# Next Generation Stanford TCAD---PISCES 2ET and SUPREM 007

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## Abstract

Different aspects of Process and Device Simulators developed at Stanford are demonstrated. For PISCES 2ET, a new transport model is benchmarked in comparison to other simplified formulations. Support utilities related to curve tracing are demonstrated. The modular integration of standard tools such SUPREM 4GS and SPEEDIE with a heterogeneous set of other simulators using an agent-based approach (007) is demonstrated.

## Introduction

The growing use of process and device simulation to give dramatic savings in IC technology development is well documented throughout the industry. Moreover, the importance of more advanced kinetic models for all aspects of IC technology is being stressed owing to physical constraints in deep submicron devices. At the same time there are a number of problems for both TCAD developers and users that now require new effort and attention. In this demonstration we will show progress both in creating advance modeling capabilities and integrating utilities that provide more robust user support. The following discussion focuses on several sample problems that will be used in the demonstration. In addition, use of object-oriented methodology and framework-based services such as gridding and visualization will demonstrate important qualitative changes related to TCAD tool usability issues.

## Dual Energy Transport Device Analysis---PISCES 2ET

The latest version of PISCES incorporates a new dual energy transport (DUET or 2ET) formulation (1). This transport model provides full coupling of both carrier and lattice temperatures. Examples to be presented will demonstrate the predictive capabilities of DUET for deep sub-micron SOI and bulk MOS devices. In addition, there are a variety of support utilities that are useful for efficient application of TCAD for technology analysis and design. Specific examples based on MOS technology involving SOI devices and ESD phenomenon as well as microwave GaAs MESFET components modeling will be used to illustrate both advanced physical models and the curve-tracing/mixed-mode capabilities.

### *A. DUET Model Applications*

Validity of the PISCES-2ET model formulation for hot carrier phenomena in submicron devices will be demonstrated based on simulations of substrate current for submicron MOSFET devices. An energy-dependent impact ionization (II) model is implemented in the DUET formulation and the generation of electron and hole pairs by II are solved self-consistently with the transport equations. Excellent agreement with experimental results are demonstrated (see Fig. 1). In addition, the use of energy-dependent mobility model has also shown better experimental agreement than the previous DD model on advanced short-channel SOI devices (see Fig. 2)

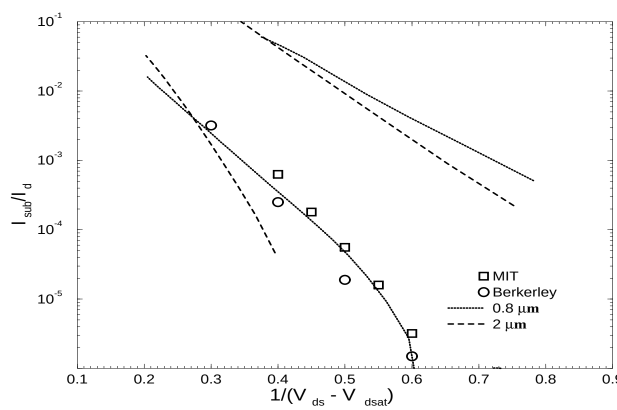



Fig. 1: Simulation results for the substrate current in MOSFET with two different channel length and the comparison is made for 0.8µm case between the PISCES-2ET-simulated and measured results (2)(3). The upper curves are simulated using the DD model.

### *B. Curve-Tracing and ESD*

The "curve-tracer" is a module which externally controls a device simulator via its input and output and can work with any simulator in which lumped resistance elements can be placed on a contact (4). It is ideal for virtual failure-analysis experiments such as latchup, BVceo, and electrostatic discharge (ESD) breakdown---phenomena distinguished by sharp break points in the I-V curves which are numerically unstable in conventional device simulation. The dynamic load

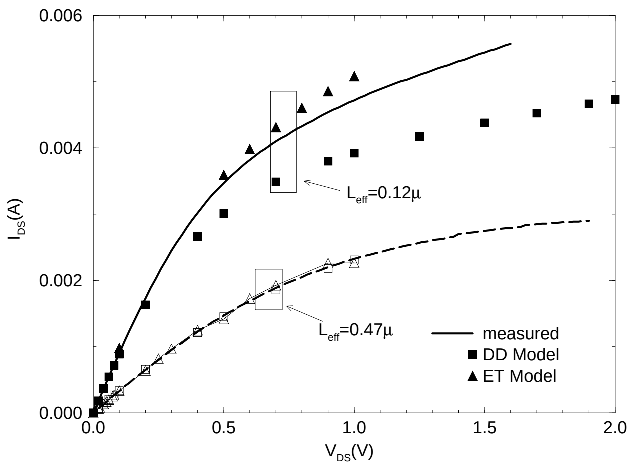



Fig. 2: Simulated and measured data (5) for SOI structure with different channel length (0.47 and 0.12 µm).

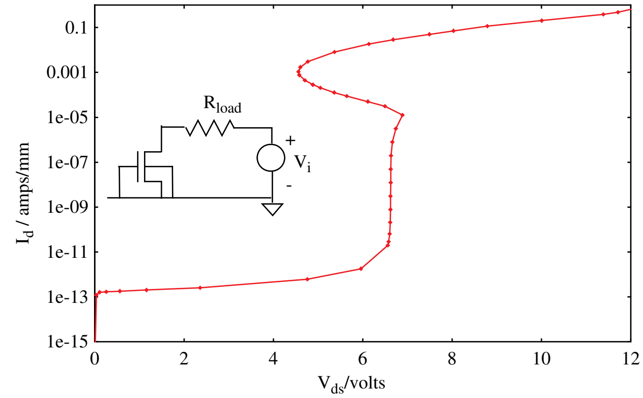



Fig. 3: A simulation of drain current vs. drain voltage for 0.5 µm NMOS transistor is swept using the curve tracer. The source, gate, and substrate nodes are grounded.

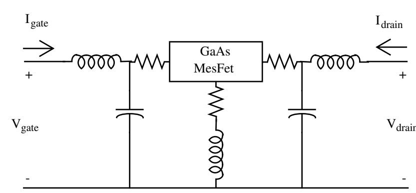
line technique used in this work makes it possible to keep the simulation stable throughout the I-V trace. The example used here is for a MOSFET device used as part of input-protection circuitry to divert large currents and to clamp the input voltage below the dielectric breakdown voltage of the thin gate oxide. A positive ESD pulse incident at the input is modeled as a dc current sweep which can be used to extract the breakdown voltage (BVdss), trigger voltage, and snapback (hold) voltage of the protection transistor. In the simulation the breakdown voltage is 6.7V, the trigger voltage is slightly higher at 6.9V, and the snapback voltage is 4.6V. Beyond the snapback point the drain voltage increases until thermal runaway occurs, a phenomenon best modeled using transient and/or 3D simulation (see Fig. 3).

### *C. Mixed-Mode Modeling*

Mixed-mode simulations are used to obtain more accurate circuit simulation results by means of numerical device models coupled to the usual SPICE compact models. Complex device effects such as self heating and photon generation can be simulated by the numerical device and hence, examined directly in the context of actual circuit operation. A generalized interface between the Berkeley SPICE tool and a numerical device simulator such as PISCES is demonstrated. To illustrate the utility of the system a MESFET simulation is presented including parasitic extraction needed in matching S-parameter results. The example involving experimental and simulated Smith chart, shown in Figs. 4a and 4b, shows data for S11 and S22 with inductive behavior in the frequency range between 28 and 36 GHz (6).

## Object-Oriented Process Modeling---SUPREM OO7

In contrast to other simulator developments that have focused on redefinition of modules above the levels of gridding and supporting numerical analysis, our efforts have centered on building an object-oriented environment that supports tight integration of heterogenous tools. For example, this demonstration will show inter-operability of standard SUPREM 4GS working with new oxidation and diffusion modules that are tightly linked but distinctly different programs. We have also demonstrated the use of this methodology to couple complete applications such as SPEEDIE, used for physical modeling of deposition and etching, with SUPREM 4GS. A robust quadtree based geometry/grid server called FOREST is also demonstrated that supports prototype standards such as SWR and HDF-Vset for procedural interfaces and persistent data storage. The use of tool agents to implicitly control object module invocation has resulted in the naming of these capabilities as SUPREM 007.




$$Y_{11} = \frac{I_{gate}}{V_{gate}} \qquad Y_{12} = \frac{I_{gate}}{V_{drain}} \qquad y_{ij} = \frac{Y_{ij}}{Y_o}$$

$$Y_{21} = \frac{I_{drain}}{V_{gate}} \qquad Y_{22} = \frac{I_{drain}}{V_{drain}}$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} 1+y_{11} & y_{12} \\ y_{21} & 1+y_{22} \end{bmatrix}^{-1} \begin{bmatrix} 1-y_{11} & y_{12} \\ y_{21} & 1-y_{22} \end{bmatrix}$$

Fig. 4a: A GaAs MESFET with parasitics is simulated in Stanford's mixed-mode simulator in order to find the S-parameters for the frequency range of 1GHz to 40GHz. First, the Y-parameters are found using the SPICE/PISCES simulation and then a simple transformation is used to determine the S-parameters.

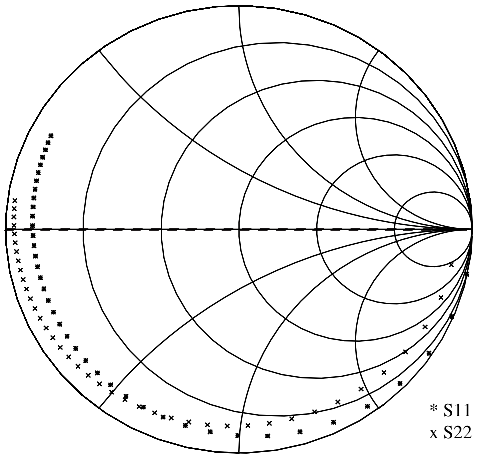



Fig. 4b: Smith chart showing inductive behavior.

### *A. Dial-an-Operator PDE Engine*

The object-oriented dial-an-operator diffusion solver allows users to simply write down the governing and constitutive equations. The equations are parsed into an object-oriented data structure which generates the element residuals and tangent matrices for a discretized solution of the system of equations. The dial-an-operator PDE formulation framework is linked in with existing solver and gridding libraries (see Fig.5). The onus of writing code for implementing a new equation set is totally removed. Moreover, this opens the way to add and experiment with advanced kinetic models for diffusion without having to revamp a process simulator such as the SUPREM 4GS code.

### *B. Automated 2D Gridding*

The grid/geometry server FOREST provides all the necessary meshing, mesh adaptation and geometry operations for both process and device simulation. Static grids with complex device geometry (PISCES) and quasi-3D structures for interconnect (FASTCAP) analysis are demonstrated in a second showcase presentation. When geometry changes at the surface, the program automatically regrids the structure to reflect the new geometry in support of other volume grid requirements. Specifically for oxidation simulation where both grid and geometry operations are used for generating a grid, FOREST supports a set of operations that include: moving the boundary, removing geometric anomalies, and regenerating the grid (See Fig. 6).

### *C. Heterogenous TCAD Tool Integration*

Heterogeneous tools can communicate with one another in the SUPREM OO7 environment using a consistent standard application interface and supporting persistent data storage.
SWR field and geometry server interfaces are demonstrated as the standard application interface (API) for FOREST and HDF-Vset format is used as the persistent storage format. Different tools with different data structures, for example SUPREM interfaced to SPEEDIE, directly read and write to this format. Thus, tool integration can support both standard file as well as procedural level interfaces (see Fig. 7).

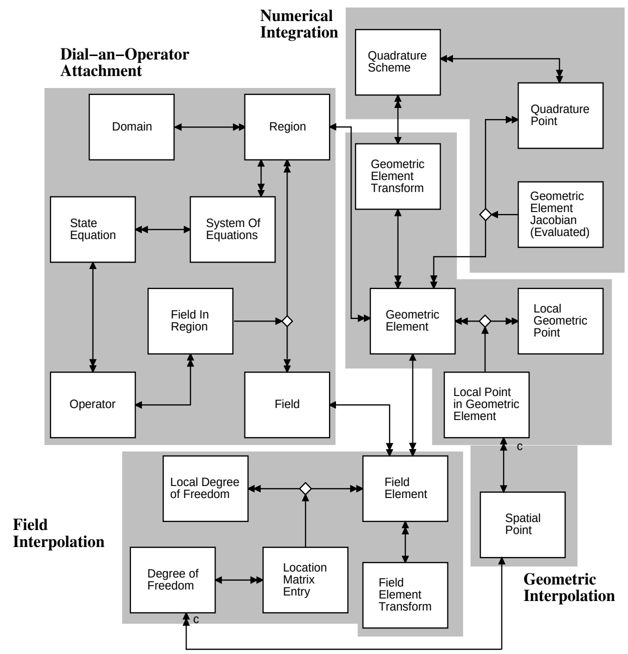



Fig. 5: Information model for dial-an-operator engine on the methodology in (7). The shaded area groups objects by functionality.

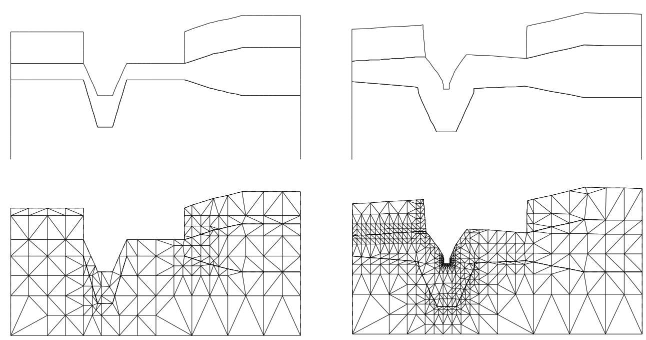


Fig. 6: Oxidation simulation using FOREST. The geometry is moved, geometric anomalies removed and the grid is generated if necessary.

### *D. "Backend" Modeling of Technology*

Two major factors affecting circuit density in submicron technologies are oxide isolation and metallization of ICs. In the examples to be presented, we consider the integrated simulation of these process modules using SUPREM 007, interacting with SPEEDIE. In the case of oxide isolation the challenge is to sequentially pattern the silicon, dope the isolation regions and to form the local oxidation structures---including the options for deep and shallow trench structures. In the course of this demonstration FOREST has a variety of geometry services to provide - including time step control, de-looping, avoiding region crashings etc. Robust gridding is also required in order to support convergent simulation of the stress-dependent oxidation of trenched structures. In the case of the metallization and planarization of ICs, the example to be presented shows the sequential deposition and etching of dielectric and metal layers using the advanced kinetic models contained in SPEEDIE. The geometry services provided by FOREST will be used to move the surface being mindful of loop formation and different layers being exposed to the ambient (See Fig. 7).

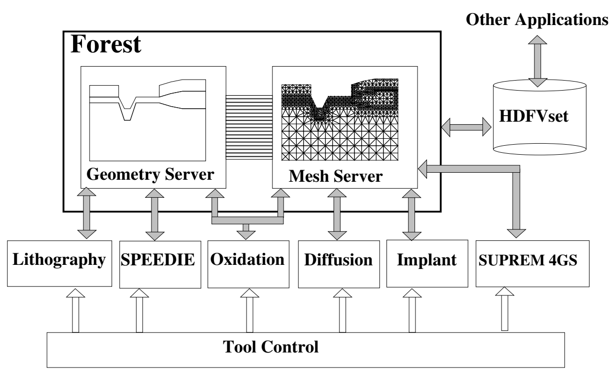



Fig. 7: File level and procedural level interfaces are provided by FOREST for integration of heterogeneous tools. Geometry and mesh data are separate yet consistent--allowing different tools to use them individually.

## Conclusion

There are a growing number of TCAD applications involving both process simulation and device analysis where more flexibility in modeling are required. The demonstrations of PISCES 2ET, including a number of support utilities, and SUPREM 007, an agent-based approach to plug-and-play modeling, are highlights of this work. In the case of device analysis, the emphasis is given to new capabilities o characterize and calibrate complex physical phenomena, including the influence of boundary conditions. For process modeling, the importance of object-oriented methodology both for geometry/grid services and in terms of tool control are key features that support an open system for tool integration.

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