The Use of ISE-TCAD Package for Simulation

- General presentation of ISE-TCAD – not commercial!
- Simulation approach
- ISE-TCAD and MAPS – example
- ISE-TCAD picked up examples
- Conclusions

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General presentation of ISE-TCAD

ISE-TCAD simulation package released by: VIRTUAL FOUNDRY + PRODUCT DEVELOPMENT

software that covers whole spectrum of simulation aspects from fabrication processes of integrated circuits, semiconductor devices and circuits represented in abstract form (SPICE netlist), mixed systems (semiconductor + abstract), packaging (thermal, electromagnetic, etc.) to interaction with environmental factors (radiation), etc.

VIRTUAL FOUNDRY
+ PRODUCT DEVELOPMENT

Are there any advantages of using this software in instrumentation for high energy physics community? Particularly: detector development, front-end circuits, radiation hardness analyses...
General presentation of ISE-TCAD

Main features:

- Calibrated process simulator (interesting for developing new detector technologies),
- Advanced solid state physics models included (from standard drift-diffusion model to quantum electronics, nanoelectronics, tunneling and advanced transport models)
- True 3D device simulator !!! Finite element method solver,
- Meshing engine for 2D and 3D for planar and nonplanar devices (powerful but difficult to control and not always clearly documented),
- Si, Ge, SiGe, GaAs, heterostructures, compound semiconductors, isolation materials… (wide choice of materials),
- Optoelectronics, interaction of light with material, interaction of radiation with material (alpha particles, heavy ions, but no MIP model + statistics),

Fantastic! but...

- No Monte Carlo simulations (transport, interaction of radiation with matters, modelling of radiation sources, etc.),
- Hermeticity !!! weak influence of the user on the software, possibility of Tcl/Tk programming but difficult if not impossibly integration with existing tools…

  e.g. Output files for 3-D simulations with >10 digit precision, tons of MB, no way to change if such precision is not needed, thus simulations slow and huge physical memories needed!
General presentation of ISE-TCAD

Software tools in the package:

**Process Simulator**
- DIOS: Current 1D/2D Si and SiGe Process Simulator
- FLOOPS: Next Generation Process Simulator 1D/2D/3D

**Device Simulator**
- DESSIS: 2D/3D, Si and heterodevices, general purpose
- DESSIS-Laser: Semiconductor lasers

**Structure Generation**
- DEVISE: 2D/3D graphical structure editor
- MDRAW: 2D graphical structure editor *(boundary and doping)*
- PROLYT: Layout editor *(CIF, GDSII import)*
- PROSIT: 3D structure generator *(masks and doping profiles)*
- DIP/GIP: 3D interpolation tools *(from cross-sections to 3D structure)*

**Meshing Generation**
- MESH: 2D/3D mesh generator

**Compact Model Parameters Extraction**
- ISExtract: Compact model parameters extractor *(BSIM4)*

**Framework Tools**
- GENESIS: Graphical front end, organization of simulation projects
- LIGAMENT: Process simulation environment
- OptimISE: Parametric and statistical analysis, and optimization
- Tecplot-ISE: Advanced visualization, 1D/2D/3D
- INSPECT: Plotting and data analysis, X-Y

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NO SCHEMATIC EDITOR !!!

ISE TCAD, see www.ise.com
Simulation approach

2 cases: 1: process simulation,

PROCESS SIMULATION - standard approach: to create device structures through fabrication process simulations and passing to simulation of “virtual devices”,

LIGAMENT - package serving interface for process simulation (DIOS, FLOOPS) that is, as much as possible, independent of the particular process simulator and the simulation dimension.

Inputs: a process flow, process libraries, layouts, and other TCAD-related information

Outputs: process simulator command files or other translation targets.
Simulation approach

1: process simulation,
Simulation approach

## 1: process simulation

<table>
<thead>
<tr>
<th>Process</th>
<th>Comment</th>
<th>Material</th>
<th>Layer</th>
<th>Polarity</th>
<th>Temperature</th>
<th>Time</th>
</tr>
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<tbody>
<tr>
<td>poly-gate</td>
<td>text</td>
<td>poly-gate</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>deposit</td>
<td>material</td>
<td>poly</td>
<td>gate</td>
<td>light-field</td>
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<td>material</td>
<td>poly</td>
<td>oxide</td>
<td>default</td>
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<td></td>
</tr>
<tr>
<td>etch</td>
<td>material</td>
<td>resist</td>
<td></td>
<td>default</td>
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<td></td>
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<tr>
<td>poly-oxidation</td>
<td>time</td>
<td>40 sec</td>
<td></td>
<td>(700) (5300) degC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Full process flow – basic steps defined at physical level – parameterisation for multi-variant process simulation (*DoE*)

Process simulation (*DIOS, FLOOPS*) carried out basing on models of implantation, diffusion, etching, etc, 3D structure obtained or 2D cross-sections for interpolation (*DIP/GIP*)
Simulation approach

1: process simulation,

- Layout editor *(PROLYT)* CIF/GDSII import + export *(↔️ CADENCE)*,
- process simulation for selected areas of interest *(1D, 2D +3D)* → structure for *(interpolation DIP/GIP)* with contacts, meshing and electrical simulation !!!!
Simulation approach

2 cases: idealised geometries simulation,

- special circumstances: process simulation is not needed; for conceptual studies or fast parametric analysis idealized device geometries directly created with analytic doping profiles using device editor and then simulation.

  Device geometry is defined
  a) from the mask layout and the process flow (PROSIT) – process emulation,
  b) by user drawing the geometry in 2D (MDRAW) or in 3D (DEVISE).

PROSIT

Information for geometry:

- boundaries:
  resolution 0.1 5 10
  domain 13 -5 -1 15 2 15

- materials/regions:
  region Silicon Silicon
  region Oxide Oxide
  region Nitride Nitride
  region Resist Resist
  region Subst Contact Contact
  region Gate Contact Contact
  region Source Contact Contact
  region Drain Contact Contact

procedures:

proc contact (region mask) {
  deposit $region 1.0
  pattern $mask
  etch $region 2.0
  strip Resist
}

process flow:

side front
pattern well dark
implant well
strip Resist
pattern nsource dark
implant source
strip Resist

Information used by mesh generator:

- doping:
  doping substrate Boron 2e+15 Silicon
  doping pwell Boron Gauss 0 1.5e17 0.0 3e16 0.5
  doping source Arsenic Gauss 1.0 3.8e20 0.0 1e20 0.1
  doping drain Arsenic Gauss 1.0 3.8e20 0.0 1e20 0.1

- mesh refinement:
  refine default 13. -5. -9.0 100. 100. 100. 0.2 0.2 2.0 1.0
  refine drain 13. -1.3 -0.2 13.6 0.1 0.05 0.05 0.2 0.1
  refine source 13. -3.5 -0.2 13.6 -2.0 0.05 0.05 0.2 0.1
  refine channel 13. -2.3 -0.1 13.6 -1.0 0.1 0.02 0.1 0.02

Analytically defined doping profiles are used
Simulation approach

2: idealised geometries simulation,

**PROSIT**

**final device geometry:**

**MESH**

**geometry + doping + refinement** → **device model:**

- mesh generation common step for both simulation approaches –
  a) 2D geometry & doping can be obtained from DIOS, 3D needs interpolation (DIP) or FLOOPS (new),
  b) PROSIT *(with process flow)*, MDRAW, DEVISE can be used for “hand” drawn geometries.
Simulation approach

2: idealised structure,

Preparation to radiation hardness studies of MAPS

Nwell/p-epi diode
Reset transistor
Oxide charge + interface
Bulk damage parameters
Simulation approach

DESSIS - solver,

electrical behavior - single semiconductor device in isolation or several physical devices combined in a circuit. Terminal currents, voltages and charges computed based on a set of physical device equations (carrier distribution + conduction mechanisms).

<table>
<thead>
<tr>
<th>Device Physics</th>
<th>Mixed Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D, 2D, 3D, and 2D cylindrical geometries</td>
<td>Electrothermal netlists</td>
</tr>
<tr>
<td>Drift-diffusion</td>
<td>Mixed dimension physical devices</td>
</tr>
<tr>
<td>Thermodynamic</td>
<td>Device-specific physics</td>
</tr>
<tr>
<td>Hydrodynamic</td>
<td>Berkeley Spice circuit models</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td>Open compact model interface</td>
</tr>
<tr>
<td>Schrödinger solver</td>
<td></td>
</tr>
</tbody>
</table>

Heterostructures
Composition-dependent parameters
Thermionic emission

Interface Physics
Tunneling through insulators
Hot carrier injection
Interface traps

Bulk Traps
Ferroelectrics
Optical generation
Single Event Upset (SEU) (alpha particles and heavy ion)

Analysis
AC
DC
Noise
Transient
Simulation approach

DESSIS - solver,

File {
 ...
}
Electrode {
 ...
}
Thermode {
 ...
}
Physics {
 ...
}

Plot {
 ...
}
CurrentPlot {
 ...
}
Math {
 ...
}
Solve {
 ...
}

Physics section:

AreaFactor = <float>
Charge(<options>) = <float>
EffectiveIntrinsicDensity
(BandGapNarrowing (<models>))
Hydrodynamic
Hydrodynamic (<carrier>)
Mobility(<models>)

Recombination (<models>)
Temperature = <float>
Thermodynamic
Traps (<options>)

AlphaParticle (<options>)
Amorphous (<options>)
AnalyticTEP
Fermi
GateCurrent(<model>)
HeavyIon (<options>)
IncompleteIonization
MagneticField =
(<float>, <float>, <float>)

Noise (<options>)
OptBeam (<options>)
Piezo (<specifications>)
MoleFraction
[e|h]QvanDort
RecGenHeat
Radiation (<options>)
Schroedinger
**Simulation approach**

**GENESIS** – simulation environment,

Simulation projects – tool flows + parameters

Design of experiment (DOE) for analyses with varied parameters, parallel execution on several machines, interface to visualisation, extraction and optimisation tools.
ISE-TCAD and MAPS - example

From digital photography

classical 3T pixel schematics

to charged particle detection

Monolithic Active Pixel Sensors (MAPS) advantages:

decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.), small pitch (high tracking precision), low amount of material, fast readout, moderate price, SoC, etc.
ISE-TCAD and MAPS – example

Particle track

Particle track (example)

$\tau = 0$ ns

$\tau = 25$ ns

ministry carrier concentration

mixed mode device and circuit simulator DESSIS-ISE from ISE-TCAD package

$\rightarrow$ Charge collection - relaxation process $\rightarrow$ equilibrium state
(excess charge = ionising particle),

$\rightarrow$ Device in 3-D, mesh with analytical description of doping profiles and boundary definition,

$\rightarrow$ Different detector parameters investigated:

- thickness of the epitaxial layer and substrate,
- size of a pixel and collecting diodes,
- number of diodes per pixel.
ISE-TCAD and MAPS - example

Simulation background:

\[ \varepsilon_{si} \nabla^2 \psi = -q \left( p_n - n + N_D^+ - N_A^+ \right) \]
\[ \nabla J_n = q R + q \frac{\partial n}{\partial t} \quad \text{and} \quad \nabla J_p = q R + q \frac{\partial p}{\partial t} \]
\[ \overline{J}_n = -n q \mu_n \nabla \varphi_n \quad \text{and} \quad \overline{J}_p = p q \mu_p \nabla \varphi_p \]

\[ \tau_{\text{dop}}(N_i) = \tau_{\text{min}} + \left( \tau_{\text{max}} - \tau_{\text{min}} \right) \left[ 1 + \left( \frac{N_i}{N_{\text{ref},t}} \right)^\gamma \right] \]

Set of Poisson equation and electrons and holes transport equations with

\[ \mu_{\text{dop}}(N_D^+ + N_A^-) \quad \tau_{\text{dop}}(N_D^+ + N_A^-) \quad R_{\text{SRH}}^{\text{SRH}} \]
ISE-TCAD and MAPS - example

Simulation background:

- Mesh in 3-D with adapted density
- Big structures in 3-D (?)
- Plane cross-section through diodes
- Electric field
- « TOSCA » solution for electrostatic potential
ISE-TCAD and MAPS - example

Charge collected as function of impact position:

Particle impact points chosen randomly within central pixel area ...

More than 8 hours Per single impact
ISE-TCAD and MAPS - example

Transient simulations for charge collection:

Prototype with 15 µm epitaxial layer and 20 µm pitch
ISE-TCAD and MAPS - example

Charge collected as function of impact position:

5 µm epitaxial layer

15 µm epitaxial layer

Simulations supposing substrate thickness = 0 µm

370e⁻ ⇄ 250e⁻ (~32%)

780e⁻ ⇄ 670e⁻ (~14%)
ISE-TCAD and MAPS - example

Estimation of charge collection time:

- 15 µm epitaxial layer + infinite substrate

Important observations:
- charge collection time (90% of charge) < 150 ns,
- 4-diode charge collection ~ 3 times faster,
- charge collection faster for thinner epitaxial layer.
ISE-TCAD and MAPS - example

Agreement with experiments

Collected charge

- MIMOSA I – 14 µm epitaxial layer
- MIMOSA II - <5 µm epitaxial layer

Collection time

Response convolved with readout chain; deconvolution $\tau_{\text{col}} = 100-150$ ns

Collected charge

MIMOSA I:
- 4 diodes
- 1 diode

MIMOSA II:
- 1 diode
- 2 diodes

(1) most probable value for MIPs

Agreement with experiments

Collected charge

MIMOSA I – 14 µm epitaxial layer
MIMOSA II - <5 µm epitaxial layer

Collection time

Response convolved with readout chain; deconvolution $\tau_{\text{col}} = 100-150$ ns
ISE-TCAD picked up example

Radiation hardness (example)

Alpha particle in digital circuit (ISE-TCAD example)

Figure 1 Simulated SEU of a SRAM cell.

(a) The SOI NMOS “N2” is simulated as a 3D physical device. The devices “P1”, “P2”, and “N1” are simulated as 2D physical devices, or alternatively as SPICE compact models.

(b) Hole current distribution in a body tied the SOI NMOS “N2” of a SRAM cell after a heavy ion strike.

(c) SEU switching dynamics of the SRAM cell after a heavy ion strike with an LET of 0.05pC (blue) and 0.10pC (red). The cell is able to recover from the low energy strike, while the high energy strike causes a soft error.

[1] ISE TCAD, see www.ise.com
ISE-TCAD picked up example

Commercial CMOS Image Sensor - example

Figure 1: Circuit of CIS pixel; orange part was neglected in device simulation

optical – electrical interface

Simulation using OPTIK ISE and DESSIS ISE for electrical response, EMLAB ISE is used for estimation of optical crosstalk

Figure 2: Carrier generation in a CIS pixel; light propagation through the lens onto the photodiode was simulated by 3D raytracing

Figure 3: Floating diffusion voltage drop during illumination of pixel with a wavelength of 600 nm and a power of 0.1 mW/cm² compared with pixel not illuminated (dark)
Conclusions ...

ISE-TCAD – advanced, extended, from process to device simulation environment.

Continuously developed:
1) ☺ New features and tools integrated, improvements,
2) ☹ commercial licenses (v.8.0 LEPSI) 8.5, 9.0, 9.5 (10.0 announced) – cost ‼‼‼,
3) ☹ high complexity, quite often “undocumented” behaviour → stacking the user → need of technical support → support barely available for scientific and educational institutes,
4) ☹ non-standard environment – mixture of scripting languages, GUI → MsWindows,
5) ☹ no directly implemented features for detector – but ☺ yes for commercial interest sensors,
6) ☺ as close as possible to technology, ☹ not so useful ... how to obtain data if no technology development institution?