Mixed Circuit-Device Simulation
Outline

- Why Mixed-mode?
- Introduction of Crosslight Mixed-mode
- How to Run a Mixed Circuit-Device Simulation?
- IGBT Switching Characteristics Simulation
- Highlights of Crosslight Mixed-mode
1. Why mixed-mode?

**Compact Model:**
Based on empirical formula;
Applied to IC simulation;
Difficult to obtain complex devices or complex physical events in circuit simulation;

**Numerical Device Model:**
Based on physical models;
Applied to discrete device simulation;
Incredible complex calculations when used to replace compact model in circuit simulation;

**Mixed Mode:**
Include one or more numerical devices in a circuit simulation;
Include several compact devices in a device simulation;
2. Introduction of Crosslight Mixed-mode

- Device Simulation Equations
- Circuit Simulation Equations
- Device-Circuit Interface Equations
2.1. Device Simulation Equations

The non-linear system of equations for the device simulation is based on Shockley equations.

A numerical device mesh
Mesh size=M

At each node,
\[ F(\phi, N, P) = 0 \]
Where \( \phi \) is node voltage, \( N \) is electron density and \( P \) is hole density at each node.

Jacobian matrix for Shockley equations:

\[
J(V) = \begin{bmatrix}
\frac{\partial F_1}{\partial \phi_1} & \frac{\partial F_1}{\partial \phi_2} & \cdots & \frac{\partial F_1}{\partial \phi_N} \\
\frac{\partial F_1}{\partial N_1} & \frac{\partial F_1}{\partial N_2} & \cdots & \frac{\partial F_1}{\partial N_N} \\
\frac{\partial F_1}{\partial P_1} & \frac{\partial F_1}{\partial P_2} & \cdots & \frac{\partial F_1}{\partial P_N} \\
\vdots & \vdots & \ddots & \vdots \\
\end{bmatrix}
\]

(3M x 3M)

For Newton iteration:

\[
(V, N, P)^{i+1} = (V, N, P)^i - J^{-1}((V, N, P)^i)F((V, N, P)^i)
\]
2.2. Circuit Simulation Equations

The non-linear system of equations for the circuit simulation is based on Kirchoff’s current law: the sum of the currents into each node is zero.

At each node,

\[ F(V) = 0 \]

Where \( V \) is the node voltage and \( F \) represent the sum of the currents into each node.

Jacobian Matrix for node current equations,

\[
J(V) = \begin{bmatrix}
\frac{\partial F_1}{\partial V_1} & \frac{\partial F_1}{\partial V_2} & \frac{\partial F_1}{\partial V_3} \\
\frac{\partial F_2}{\partial V_1} & \frac{\partial F_2}{\partial V_2} & \frac{\partial F_2}{\partial V_3} \\
\vdots & \vdots & \vdots \\
\frac{\partial F_N}{\partial V_1} & \frac{\partial F_N}{\partial V_2} & \frac{\partial F_N}{\partial V_3}
\end{bmatrix}
\]

\((N \times N)\)

For Newton iteration:

\[
V^{i+1} = V^i - J^{-1}(V^i) F(V^i)
\]
2.3. Device-Circuit Interface Equations

The function for the extra node is based on conservation law: the sum of the currents from circuit into the node and from mesh device into the node is zero.

- Circuit node size = N
- Device node size = M
- Connection node size = L
- Jacobian matrix order for mixed-mode = (N + 3M + L)

\[ F(V) = 0 \]
\[ F(V, \phi, N, P) = 0 \]
\[ F(\phi, N, P) = 0 \]
3. How to Run a Mixed Circuit-Device Simulation?

1. Build the process structure by CSUPREM

2. Set parameters for device simulation in *.sol
   Define circuit following Standard SPICE-like syntax in *.cir

3. Include the external circuit(*.cir) into the device simulation file (*.sol) and link device electrodes to circuit nodes

4. Run *.sol by APSYS simulator

5. Plot simulation results by GSVIEW or CrosslightView
4. IGBT switching characteristics simulation

- Build a IGBT structure by CSUPREM
- Define IGBT dynamic test circuit
- Link device electrodes to the circuit nodes
- Plot simulation results
- Analysis of IGBT switching characteristics
4.1. Build a IGBT structure by CSUPREM

Contact1=cathode
Contact2=gate
Contact3=anode
Parameters of the Simulation Structure

N drift: 1000Ω-cm, 120um. Field Stop IGBT
Gate oxide thickness: 1500A
P well, 2E13, 80KeV, depth: 5um (after diffusion)
Trench depth: 6um, trench width: 1.5um
N+: Ph, 5E15, 150KeV
P+: Boron, 1E15, 150KeV
N buffer: 3Ω-cm, 30um
P anode, doping 1e18, 2um
4.2. Define IGBT dynamic test circuit

```plaintext
# An IGBT switching test circuit(igbt_switching.cir)
VG 1 0 pulse(0 15 1e-6 1e-9 1e-9 2e-6 4e-6)
RG 1 2 40
Zigbt 3 2 0 IGBT
Lstray 3 4 0.02u
Lload 3 5 0.5u
VDD 5 0 100

TD = 1e-6
TF = 1e-9
PW = 0.5e-6
PER = 1e-6
V1 = 0
TR = 1e-9
V2 = 15
```
4.3. Link Device Electrodes to Circuit Nodes

- **contact1=emitter**
- **contact2=base**
- **contact3=collector**

**Commands in *.sol file**

```plaintext
minispice circuit_file=IGBT_switching.cir &&
z_dim=1e6 &&
spice_device_to_tcadmesh=zigbt &&
contact1_to_spice_node=0 &&
contact2_to_spice_node=2 &&
contact3_to_spice_node=3
```
4.4. Plot Simulation Results

“plot_minispice” is used to plot mixed-mode simulation results, which is defined in *.plt file as follow:

```
plot_minispice variable=voltage node=1
plot_minispice variable=voltage node=2
plot_minispice variable=voltage node=3
plot_minispice variable=voltage node=4
plot_minispice variable=voltage node=5
plot_minispice variable=current node=1 element=Vg
plot_minispice variable=current node=1 element=Rg
plot_minispice variable=current node=4 element=VDD
plot_minispice variable=current node=3 element=Lload
plot_minispice variable=current node=3 element=Dfwd
plot_minispice variable=current node=3 element=Qigbt
plot_minispice variable=current node=2 element=Qigbt
plot_minispice variable=current node=5 element=Qigbt
plot_minispice variable=current node=5 element=Rs
```

- When plotting the current, the name of the element should be the same as the one defined in the circuit layout (case insensitive).
- Sign convention for current: current flowing INTO a node is positive.
4.5. Analysis of IGBT Switching Characteristics

Typical turn off behavior

Typical turn on behavior

Turn off from here!

Turn on from here!
5. Highlights of Crosslight Mixed-mode

1. Ability to link a spice circuit to any APSYS device
2. DC and transient analysis supported
3. High speed and good convergence
   This IGBT switching case cost 15 minutes in this PC. Mesh size: 8000

<table>
<thead>
<tr>
<th>Processor:</th>
<th>Intel(R) Core(TM) i7-2670QM CPU @ 2.20GHz 2.20 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed memory (RAM):</td>
<td>8.00 GB</td>
</tr>
<tr>
<td>System type:</td>
<td>64-bit Operating System</td>
</tr>
</tbody>
</table>

4. User friendly: Standard SPICE-like syntax