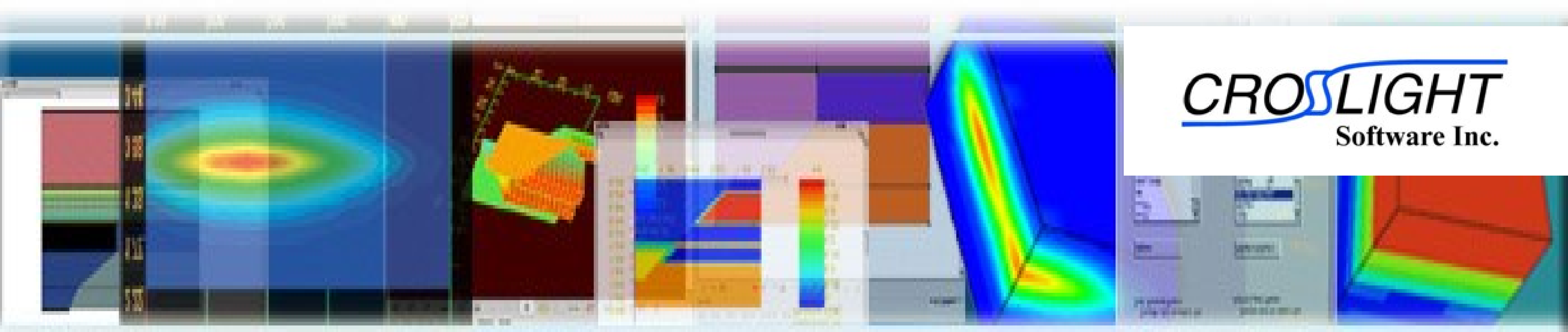


Mixed Circuit-Device Simulation

CROSSLIGHT Software Inc.

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;

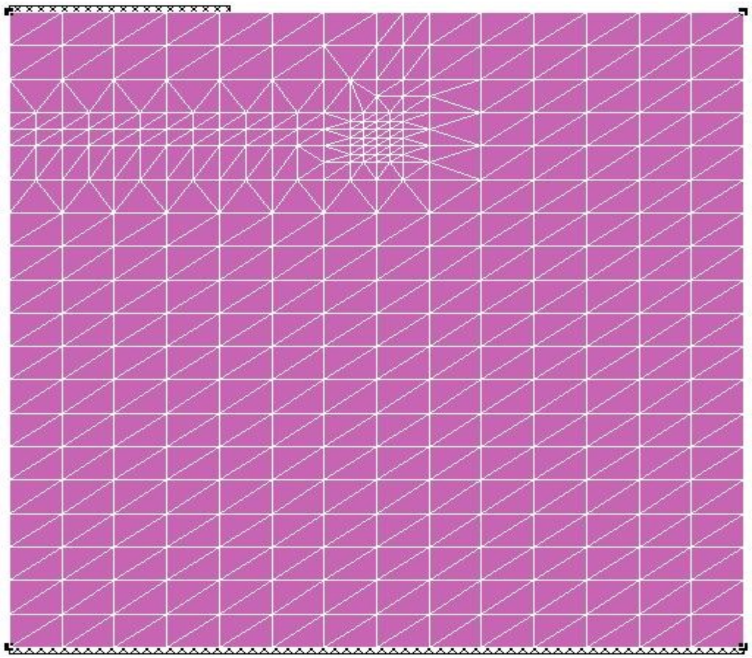
2. Introduction of Crosslight Mixed-mode

- **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,

$$F(\phi, \mathrm{N}, \mathrm{P}) = 0$$

Where Φ is node voltage, N is electron density and P is hole density at each node.
Jacobian matrix for Shockley equations:

$$J(\mathrm{V}) = \begin{bmatrix} \frac{\partial F_1}{\partial \phi_1} & \frac{\partial F_1}{\partial \phi_2} & \cdots & \frac{\partial F_1}{\partial \phi_N} \\ \frac{\partial F_1}{\partial N_1} & \frac{\partial F_1}{\partial N_2} & \cdots & \frac{\partial F_1}{\partial N_3} \\ \frac{\partial F_1}{\partial P_1} & \frac{\partial F_1}{\partial P_2} & \cdots & \frac{\partial F_1}{\partial P_N} \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

(3M x 3M)

For Newton iteration:

$$(V,N,P)^{i+1} = (V,N,P)^{i} - J^{-1}((V,N,P)^{i})\mathrm{F}((V,N,P)^{i})$$

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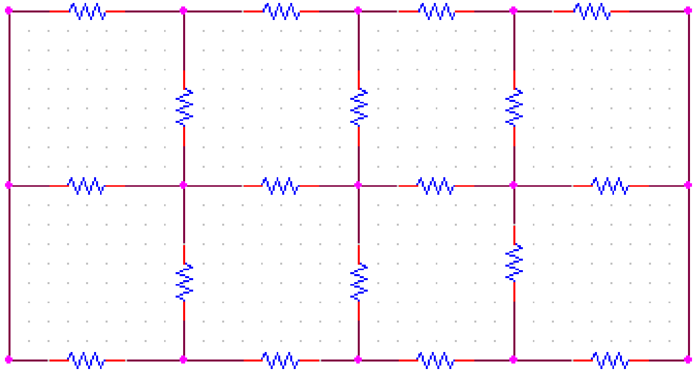
2.2. Circuit Simulation Equations

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.

A circuit network
Node size=N



At each node,

$$F(\mathrm{V}) = 0$$

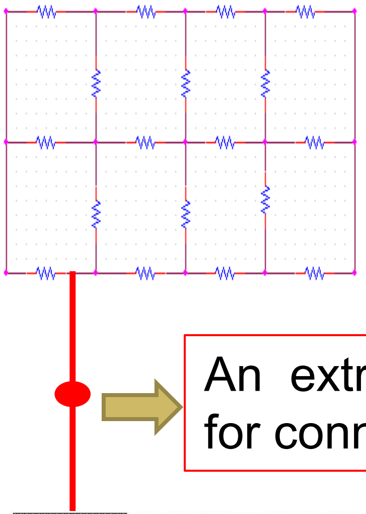
Where V is the node voltage and F represent the sum of the currents into each node.
Jacobian Matrix for node current equations,

$$J(\mathrm{V}) = \begin{bmatrix} \frac{\partial F_1}{\partial V_1} & \frac{\partial F_1}{\partial V_2} & \frac{\partial F_1}{\partial V_3} \\ \cdots & \cdots & \cdots \\ \frac{\partial F_N}{\partial V_1} & \frac{\partial F_N}{\partial V_2} & \frac{\partial F_N}{\partial V_3} \end{bmatrix}$$ (N x N)

For Newton iteration:

$$V^{i+1} = V^i - J^{-1}(V^i)\mathrm{F}(V^i)$$

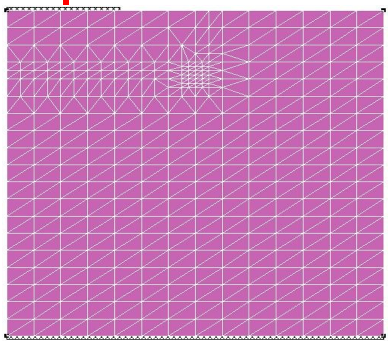
2.3. Device-Circuit Interface Equations



$$F(\mathrm{V}) = 0$$

An extra node for connection

$$F(\mathrm{V}, \phi, \mathrm{N}, \mathrm{P}) = 0$$



$$F(\phi, \mathrm{N}, \mathrm{P}) = 0$$

The function for the extra node is based on conversation 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)

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

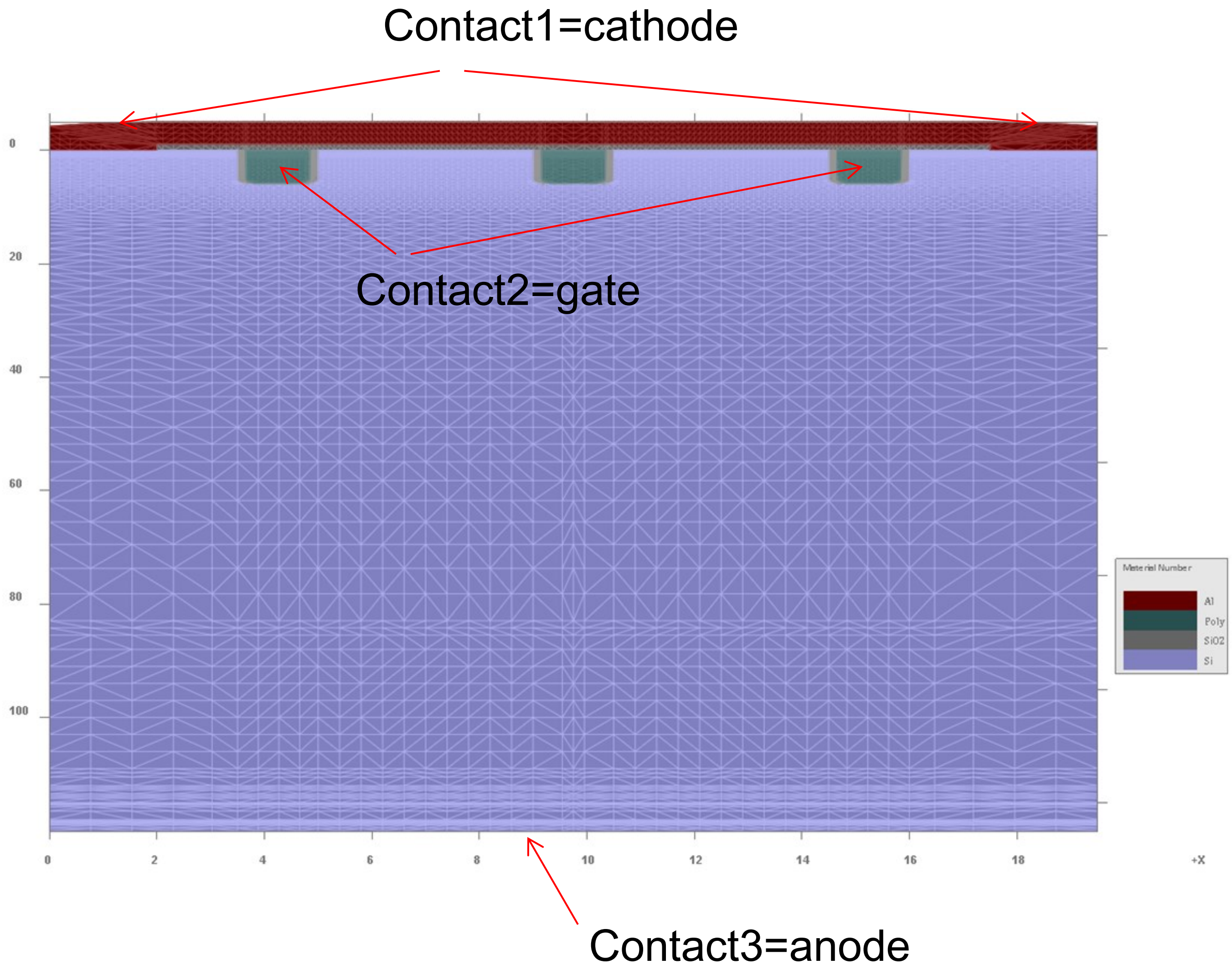
4. Run *.sol by APSYS simulator

5. Plot simulation results by GSVIEW or CrosslightView

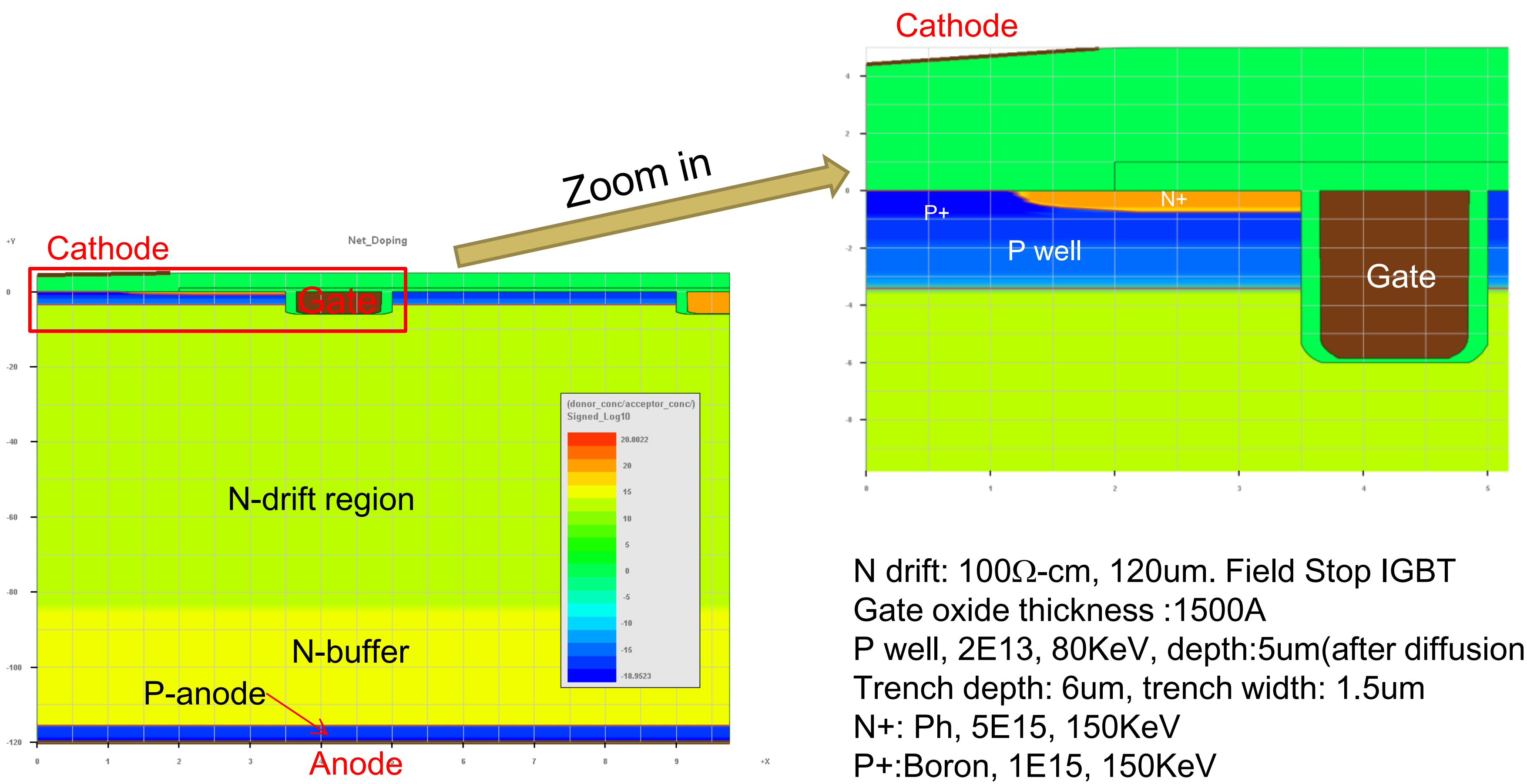
4. IGBT switching characteristics simulation

- 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

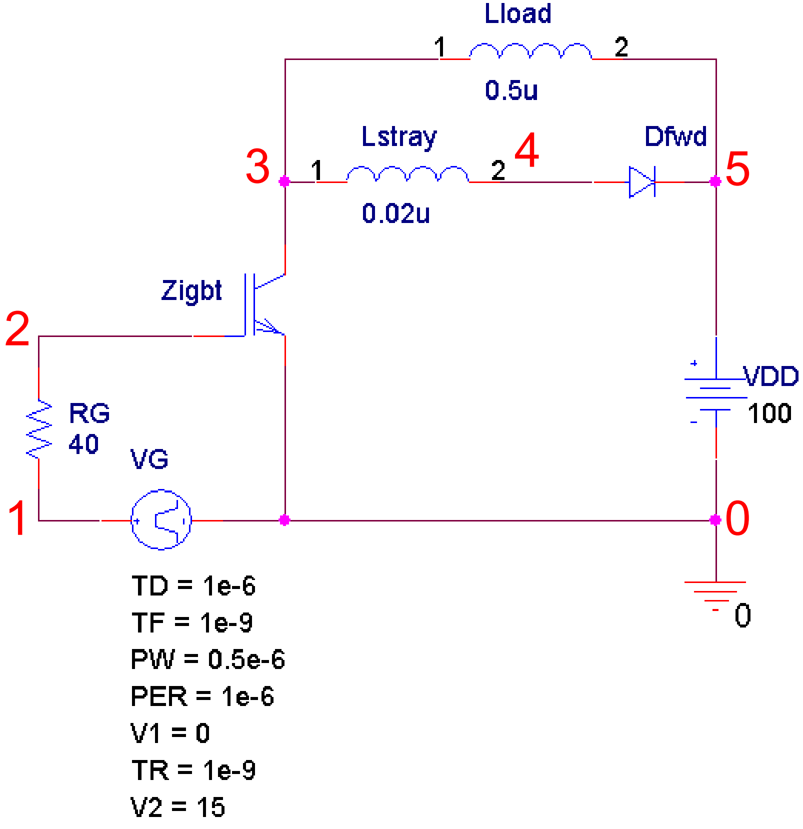


Parameters of the Simulation Structure



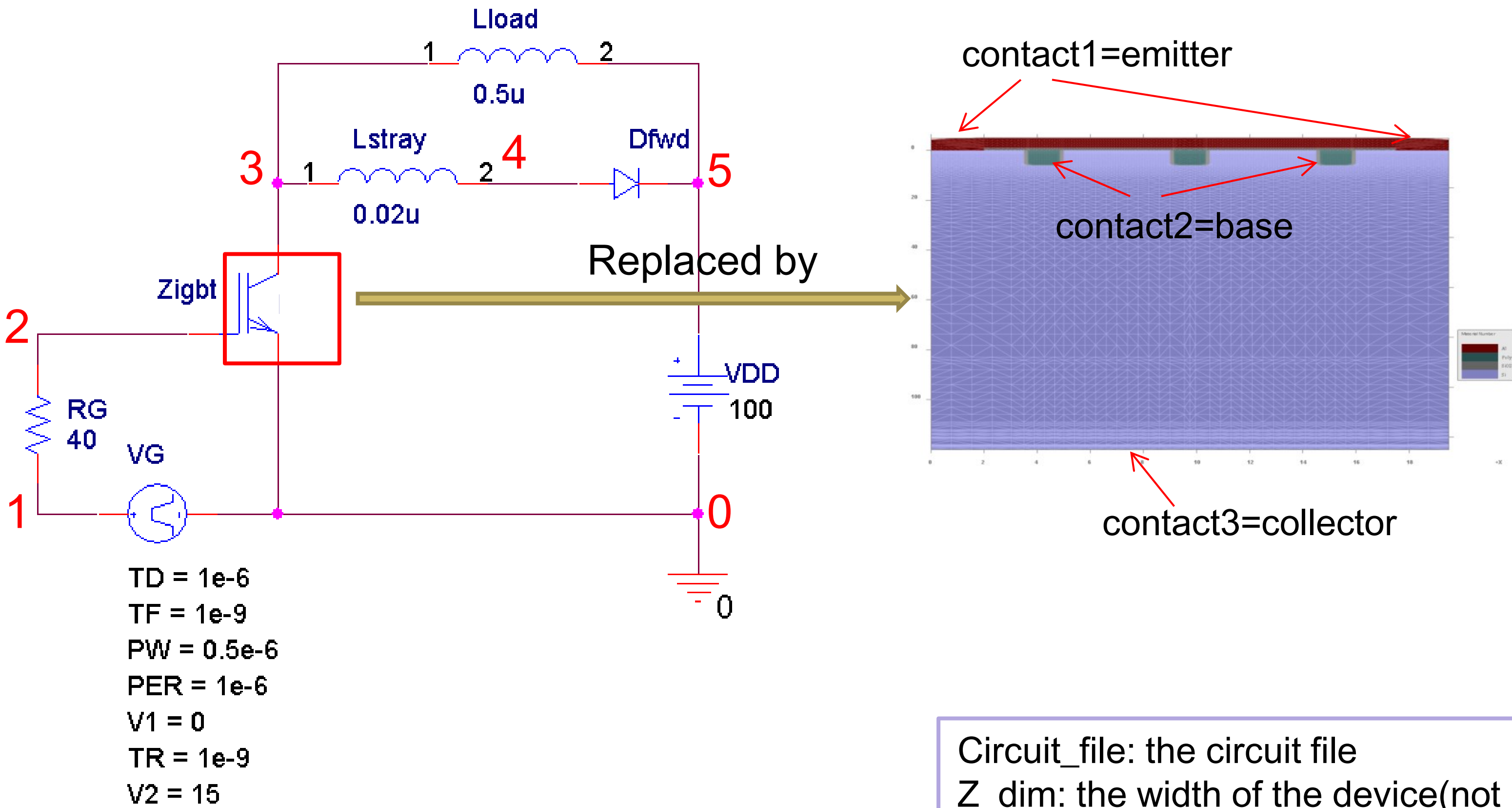
N drift: 100Ω-cm, 120um. Field Stop IGBT
Gate oxide thickness :1500A
P well, 2E13, 80KeV, depth:5um(after diffusion)
Trench depth: 6um, trench width: 1.5um
N+: Ph, 5E15, 150KeV
P+:Boron, 1E15, 150KeV
N buffer: 3Ω-cm, 30um
P anode, doping 1e18, 2um

4.2. Define IGBT dynamic test circuit




```
# 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
Dfwd   4  5  FWD 1e-5
Lload   3  5   0.5u
VDD     5  0   100
```

4.3. Link Device Electrodes to Circuit Nodes




```
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
```

Circuit_file: the circuit file
Z_dim: the width of the device(not necessary in 3D simulation)
Spice_device_to_tcadmesh: which element in the Circuit should be replaced by the mesh device
Contact#_to_spice_node: which node in the circuit should be linked with contact#.

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
```

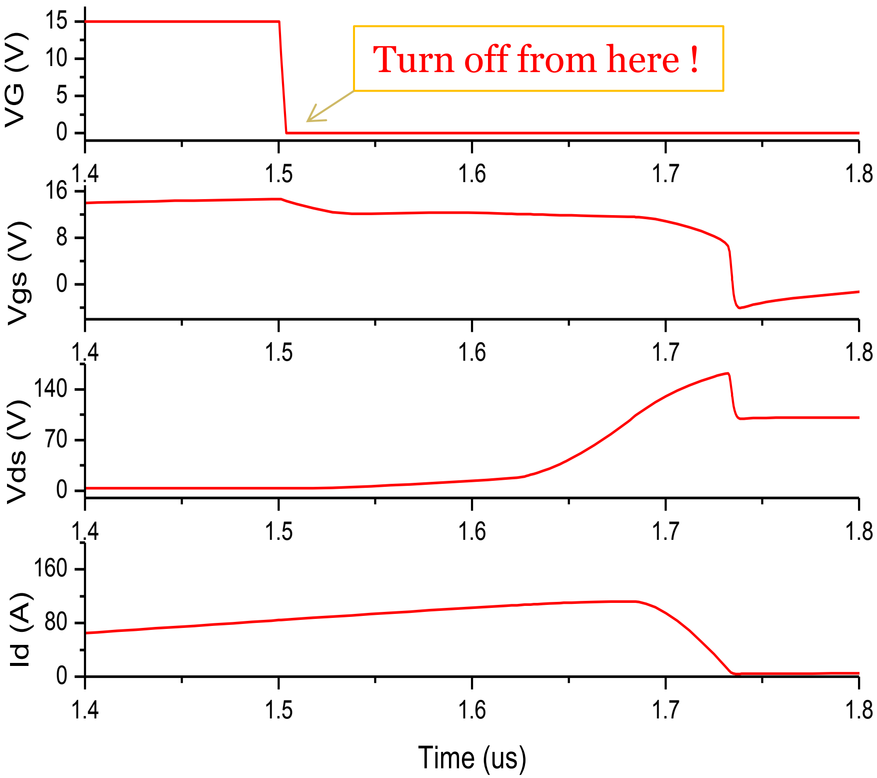
Voltage lines (node=1 to node=5):
X-axis: time
Y-axis: voltage at a given node

Current lines:
X-axis: time
Y-axis: current flowing through a given element and into the specified node.

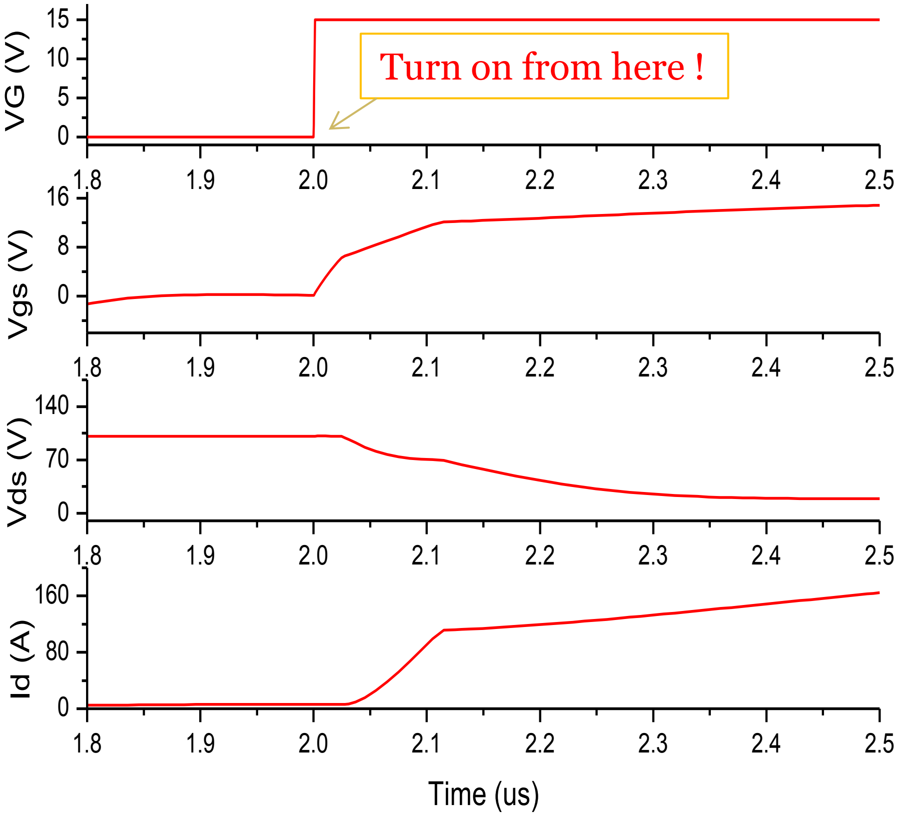
- When plotting the current, the name of the element should be the same as the one defined in the circuit layout (case insensitive).
- Sign convention for current: current flowing INTO a node is positive.

4.5. Analysis of IGBT Switching Characteristics

Typical turn off behavior



Typical turn on behavior



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

Processor:	Intel(R) Core(TM) i7-2670QM CPU @ 2.20GHz 2.20 GHz
Installed memory (RAM):	8.00 GB
System type:	64-bit Operating System

4. User friendly: Standard SPICE-like syntax

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