ECE 695
Numerical Simulations
Lecture 15: Advanced Drift-Diffusion Simulations

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Outline

• Drift Diffusion Model Physical Effects
• Sentaurus
• Applications:
  – Transistor Modeling
  – Introduction of Trap States
  – Effects of Radiation Strikes
Drift-Diffusion Model: Physical Effects

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Sentaurus Workbench

- Run command: swb
- Graphical user interface to unify all simulation tools into a single experiment project flow
- Used to organize projects and set up experiments for both structure generation and device simulation
Unlocking Workbench

- Double click 20nm-NMOS: the simulation modules will show up on the work bench
- If you cannot edit the value in the cell, then Right click 20nm-NMOS → project → unlock: This will unlock the project for modification of values.

Technology Computer-Aided-Design Tools

Parameter row

Experiment column
Sentaurus Structure Editor

- Recommended to run in workbench
  - Run command (under putty): sde
- Structure Editor (1) generates the device structure (including the doping profiles) (2) Defines the electrical contact and (3) generates the meshing for numerical simulations.

Parameters you may need to change/optimize for this project
- Gate oxide thickness (Xo, Units: um)
- MOSFET gate length (Lgate, Units: um)
- Spacer length (Lsp, Units: um)
- Channel Doping Concentration (ChanDoping, Units: cm⁻³)
- Source/Drain extension depth (XjExt, Units: um)
Sentaurus Device

• Recommended to run in workbench
  • Run command (under putty): sdevice
• Sentaurus Device simulates the device performance by solving multiple, coupled physical equations based on the meshing.
• Inputs: gate voltage ($V_{gs}$), drain voltage ($V_{ds}$), workfunction value

Common Physical models:
• Si band structure ($E_{c/v}$, $N_{c/v}$ and bandgap narrowing)
• Fermi-Dirac Statistics
• Poisson equation, continuity equation
• Band-to-band tunneling, R-G current
• Drift-Diffusion current, carrier mobility, velocity saturation
Sentaurus Inspect

- Recommended to run in workbench
- Used to automatically extract critical device performance parameters such as:
  - $V_{t\_lin}$
  - $I_{d\_lin}$
  - $V_{t\_sat}$
  - $I_{d\_sat}$
  - $I_{OFF}$

- Also used to plot the $I_d$-$V_g$ and $I_d$-$V_d$ curves
Simulation Status

• Start Sentaurus, first select from the left project column, right-click to “preprocess”.
• Then you will find the nodes will display different colors, suggesting they have different properties. Here is a summary. Only colorful nodes will give you the simulation output.

• “Ready” means the current tool is free of syntax errors (You should see this since you are not allowed to modify the scripts).
• Right-click a certain Ready nodes to run, after a short period of time, you will find it changes to “done” or “failed”.
Basic Operations for Sentaurus Structure Editor

• Now you can view your simulation results if the nodes are done.

• Right-click the node in Structure editor, select Visualize → Tecplot SV (Select File) and choose msh.tdr file to view your device structure.

![Diagram showing gate position and 1-dimensional contact]

This is the gate position, only gate contact is left.

By default, doping concentration is displayed.
Basic Operations for Sentaurus Tecplot

- This slide helps you familiarize the usage of Sentaurus Tecplot; this tool is for visualization and profiles/contours extraction purposes.
Export the results from Tecplot:

As an image (.bmp)

To get the data field, first, use Y-cut to get the 1-D slice; then select export → Inspect graph
Then Inspect will be started.

Select the data field herein; Click File → Export → txt file

You can read your saved data (.txt file) from your project directory
Basic Operations for Sentaurus Device

- Right-click the “done” node in Structure Device, select Visualize → Tecplot SV (Select File) and choose des.tdr file to view your device performance contours (vector fields).
Basic Operations for Sentaurus Device Cont.’d

- Right-click the “done” node in Structure Device, select Visualize → Inspect (Select File) and choose IdVg_des.plt file to view your device performance curves.

Choose Log Y or Linear Y here

Most common plot combination is “gate: OuterVoltage”

“drain: TotalCurrent”

Use cursors to read the data value along the curve
$I_{\text{dsat}}$, $I_{\text{lin}}$ and $I_{\text{OFF}}$

$V_{\text{ds}} = V_{\text{DD}}$

$V_{\text{ds}} = 20\text{mV}$

$\text{IOFF}$, $I_{\text{dsat}}$ and $I_{\text{dlin}}$ are extracted automatically
Threshold Voltage ($V_t$)

**Constant current definition of threshold voltage**

$$I_t = 100 \text{nA} \cdot \frac{W}{L_{\text{gate}}}$$

$W$ has default value of 1um for 2-dimensional device simulation

$V_{th}$

$V_{tlin}$ and $V_{tsat}$ are extracted automatically
DIBL and SS

DIBL is defined as the threshold voltage difference divided by the drain bias between linear and saturation region.

Sub-threshold Swing

![Graph showing DIBL and Sub-threshold Swing](image)
Generation/Recombination

• Modified Shockley-Read-Hall G/R
  – A sum of SRH contribution by each trap
  – May be temperature, doping & field dependent
  – $\Gamma$ is the degeneracy of the trap, $n_i$ the intrinsic concentration of carriers

$$R_{n,p} = \sum R_i$$

$$R_i = \frac{pn - n_i^2}{\Gamma (E_i - E_f) / kT} + \tau_{ni} (p + \Gamma n_i e^{(E_f - E_i) / kT}) + \tau_{pi} (n + \frac{n_i e}{\Gamma})$$
Generation/Recombination

- Transient behaviour of traps

\[
\frac{dN_{tD}^+}{dt} = \rho_t \left\{ \nu_p \sigma_n \left( p(1-F_{tD}) - F_{tD} n_i \frac{E_i-E_t}{kT} \right) - \nu_n \sigma_n \left( nF_{tD} - \frac{(1-F_{tD})n_i}{\Gamma} \frac{E_i-E_t}{kT} \right) \right\}
\]

\[
\frac{dN_{tA}^-}{dt} = \rho_t \left\{ \nu_n \sigma_n \left( n(1-F_{tA}) - F_{tA} n_i \frac{E_i-E_t}{kT} \right) - \nu_p \sigma_n \left( pF_{tA} - \frac{(1-F_{tA})n_i}{\Gamma} \frac{E_i-E_t}{kT} \right) \right\}
\]

- \( \sigma_{n,p} \) is trap capture cross-section
- \( \nu_{n,p} \) is thermal velocity
- \( n_i \) is intrinsic concentration
- \( F_{tA,TD} \) the probability of ionization
- \( N_{tA,TD} \) space charge density

\[
\sigma_n = \frac{1}{\rho_{trap} \tau_n \nu_n} \quad \sigma_p = \frac{1}{\rho_{trap} \tau_p \nu_p}
\]
Radiation damage

P-TYPE RADIATION DAMAGE MODEL

<table>
<thead>
<tr>
<th>Defect’s energy (eV)</th>
<th>Introduction rate ($cm^{-1}$)</th>
<th>Electron capture cross-section ($cm^{-2}$)</th>
<th>Hole capture cross-section ($cm^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_c - 0.42$</td>
<td>1.613</td>
<td>2.e-15</td>
<td>2e-14</td>
</tr>
<tr>
<td>$E_c - 0.46$</td>
<td>0.9</td>
<td>5e-15</td>
<td>5e-14</td>
</tr>
<tr>
<td>$E_c - 0.10$</td>
<td>100</td>
<td>2e-15</td>
<td>2.5e-15</td>
</tr>
<tr>
<td>$E_v + 0.36$</td>
<td>0.9</td>
<td>2.5e-14</td>
<td>2.5e-15</td>
</tr>
</tbody>
</table>

Non-ionizing Energy loss

Ionizing Energy loss


Impact ionization

\[ G = \alpha_n(E)J_n + \alpha_p(E)J_p \]

\[ \alpha_n = A_n e^{-\frac{B_n}{E}\beta_n} \]

\[ \alpha_p = A_p e^{-\frac{B_p}{E}\beta_p} \]

Phonon-assisted trap-to-band tunneling

\[ R_i = \frac{p n - n_i^2}{1 + \Gamma_n^{\text{DIRAC}}(p + \Gamma_n i e (E_f - E_i) / kT) + \frac{\tau_p^0}{1 + \Gamma_p^{\text{DIRAC}}(n + n_i e (E_i - E_f) / kT)}} \]

\[ \Gamma_n^{\text{DIRAC}} = \frac{\Delta E_n}{kT_L} \int_0^1 e^{\frac{\Delta E_{n,tunnel} - K_n u^{3/2}}{kT_L}} du \]

\[ \Gamma_p^{\text{DIRAC}} = \frac{\Delta E_p}{kT_L} \int_0^1 e^{\frac{\Delta E_{p,tunnel} - K_p u^{3/2}}{kT_L}} du \]

\[ K_n = \frac{4}{3} \sqrt{\frac{2m_e m_{tunnel} \Delta E_n^3}{3q h |E|}} \]

\[ K_p = \frac{4}{3} \sqrt{\frac{2m_p m_{tunnel} \Delta E_p^3}{3q h |E|}} \]

Charge Deposition by a Radiation Particle

- Radiation particles - protons, neutrons, alpha particles and heavy ions
- Reverse biased $p$-$n$ junctions are most sensitive to particle strikes

- Charge is collected at the drain node through drift and diffusion
- Results in a voltage glitch at the drain node
- System state may change if this voltage glitch is captured by at least one memory element
  - This is called an SEU
  - May cause system failure
Radiation Particle Strikes

- Radiation particle strike at the output of INV1
- Implemented using 65nm PTM with VDD=1V
- Radiation strike: $Q=100\text{fC}$, $\tau_\alpha=200\text{ps}$ & $\tau_\beta=50\text{ps}$
NMOS Device Modeling

- Constructed NMOS transistors using Sentaurus-Structure editor tool
- Gate length 35nm, $T_{ox} = 1.2$nm
  spacer width = 30nm
- A heavy ion strikes at the center of the drain
NMOS Device Characterization

- Characterized the NMOS device using Sentaurus-DEVICE
- Width = 1µm
- Good MOSFET characteristics
Results and Discussions

- **O1** – Small devices collect less charge compared to large devices
  - Reverse biased electric field is present for shorter duration in small devices
  - Lower drain area – less charge is collected through diffusion

- **G1** – If we upsize a gate to harden it, a higher value of $Q_{coll}$ should be used
  - Extremely important for low voltage operation
- **O1.1** – For low energy strikes, $Q_{coll}$ remains roughly constant across different gate sizes for nominal voltage operation
Next Class

Will cover band structure theory and modeling techniques