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

Prof. Peter Bermel
February 13, 2017
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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<th>Models</th>
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<td>Concentration-dependent mobility (fit to experimental data), Parallel field dependent mobility (fit to experimental saturation velocities)</td>
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<td>Generation recombination and trapping</td>
<td>Modified concentration dependent Shockley-Read-Hall Generation/recombination (for treatment of defects)</td>
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<td>Impact ionization</td>
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<td>Tunneling</td>
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<td>Fowler-Nordheim tunnelling, interface charge accumulation</td>
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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

Technology Computer-Aided-Design Tools

Parameter row  
Experiment column
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.
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”.

2/13/2017
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.
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
$I_{dsat}$, $I_{lin}$ and $I_{OFF}$

$V_{ds} = V_{DD}$

$V_{ds} = 20mV$

$I_{OFF}, I_{dsat}$ and $I_{dlin}$ 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

$V_{th}$

$V_{t\text{lin}}$ 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

[Graphs showing the relationship between drain current and gate voltage in linear and saturation regions, with annotations indicating DIBL.]
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

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

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

- Transient behaviour of traps

\[
\frac{dN_{tD}^+}{dt} = \rho_t \left\{ v_p \sigma_p (p(1 - F_{tD}) - F_{tD} n_i \Gamma e^{E_i - E_f / kT}) - v_n \sigma_n (nF_{tD} - \frac{(1 - F_{tD}) n_i}{\Gamma} e^{E_i - E_f / kT}) \right\}
\]

\[
\frac{dN_{tA}^-}{dt} = \rho_t \left\{ v_n \sigma_n (n(1 - F_{tA}) - F_{tA} n_i \Gamma e^{E_i - E_f / kT}) - v_p \sigma_p (pF_{tA} - \frac{(1 - F_{tA}) n_i}{\Gamma} e^{E_i - E_f / kT}) \right\}
\]

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

\[
\sigma_n = \frac{1}{\rho_{\text{trap}} \tau_n v_n} \quad \sigma_p = \frac{1}{\rho_{\text{trap}} \tau_p v_p}
\]

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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 - 0.1)</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

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

\[ \alpha_n = A_n e^{-(B_n/E)\beta_n} \]

\[ \alpha_p = A_p e^{-(B_p/E)\beta_p} \]

Phonon-assisted trap-to-band tunneling

\[ R_i = \frac{pn - n_i^2}{1 + \frac{\tau_{n0}^{\text{DIRAC}}}{\Gamma_n} + \frac{\tau_{p0}^{\text{DIRAC}}}{\Gamma_p}} \]

\[ \tau(s) = \frac{1}{1 + \frac{\tau_{n0}^{\text{DIRAC}}}{\Gamma_n} + \frac{\tau_{p0}^{\text{DIRAC}}}{\Gamma_p}} \]

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: $Q=100fC$, $\tau_\alpha=200ps$ & $\tau_\beta=50ps$
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

Heavy Ion  Halo implants  $V_T$ implant
Punch through implant

SPICE Model

INV

3D Device Model

Well Contact

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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