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

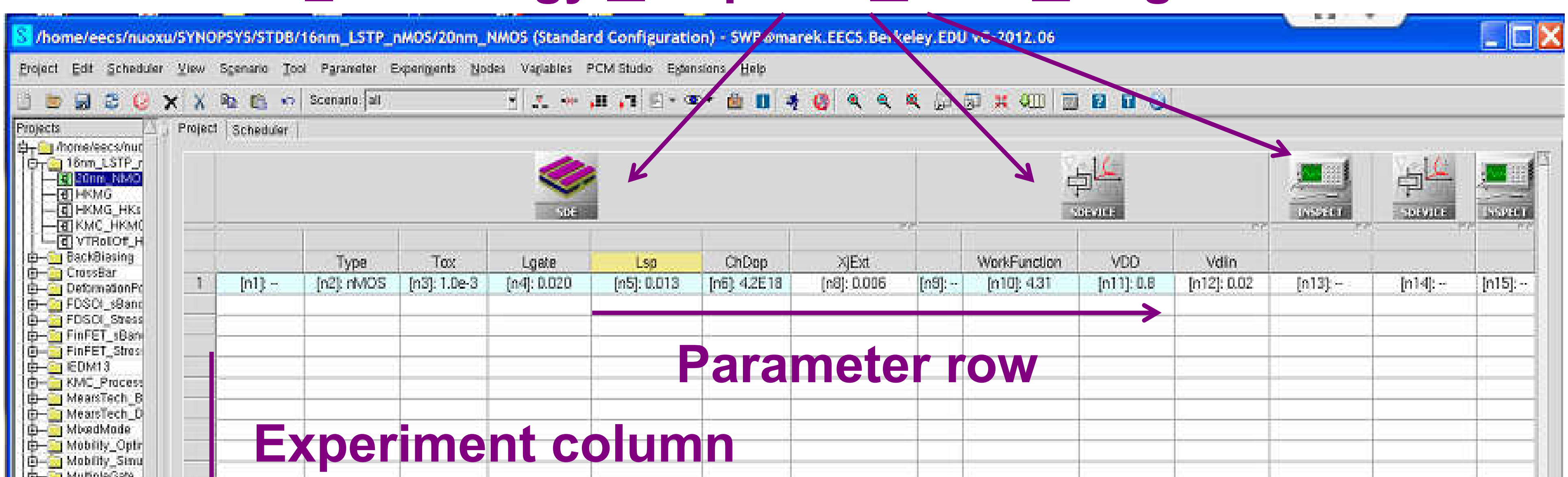
Drift-Diffusion Model: Physical Effects

Physics	Models
Mobility	Concentration-dependent mobility (fit to experimental data), Parallel field dependent mobility (fit to experimental saturation velocities)
Generation recombination and trapping	Modified concentration dependent Shockley-Read-Hall Generation/recombination (for treatment of defects)
Impact ionization	Selberherr's impact ionization model
Tunneling	Band-to-band tunneling, Trap-Assisted tunneling
Oxide physics	Fowler-Nordheim tunnelling, interface charge accumulation

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**

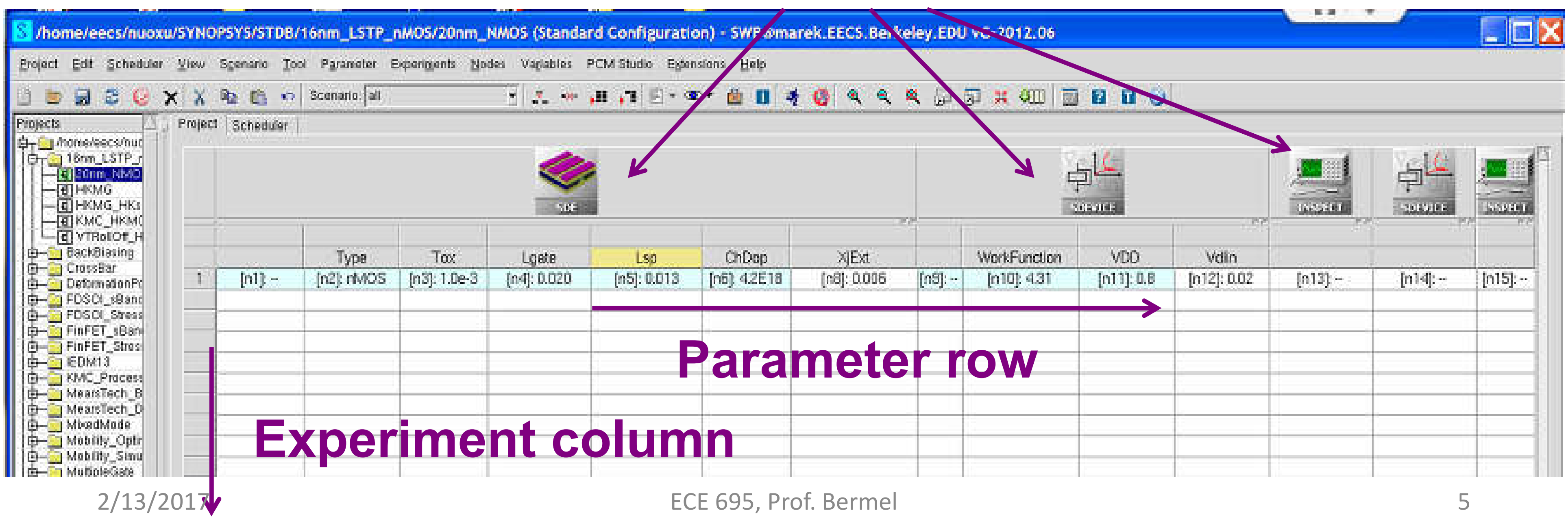
Technology Computer-Aided-Design Tools



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



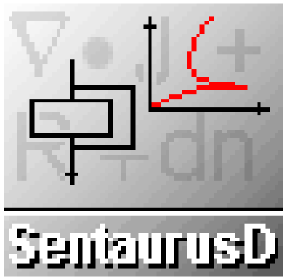
Sentaurus Structure Editor

- 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:

Vt_lin	Id_lin	
Vt_sat	Id_sat	I_OFF

- Also used to plot the I_d-V_g and I_d-V_d curves

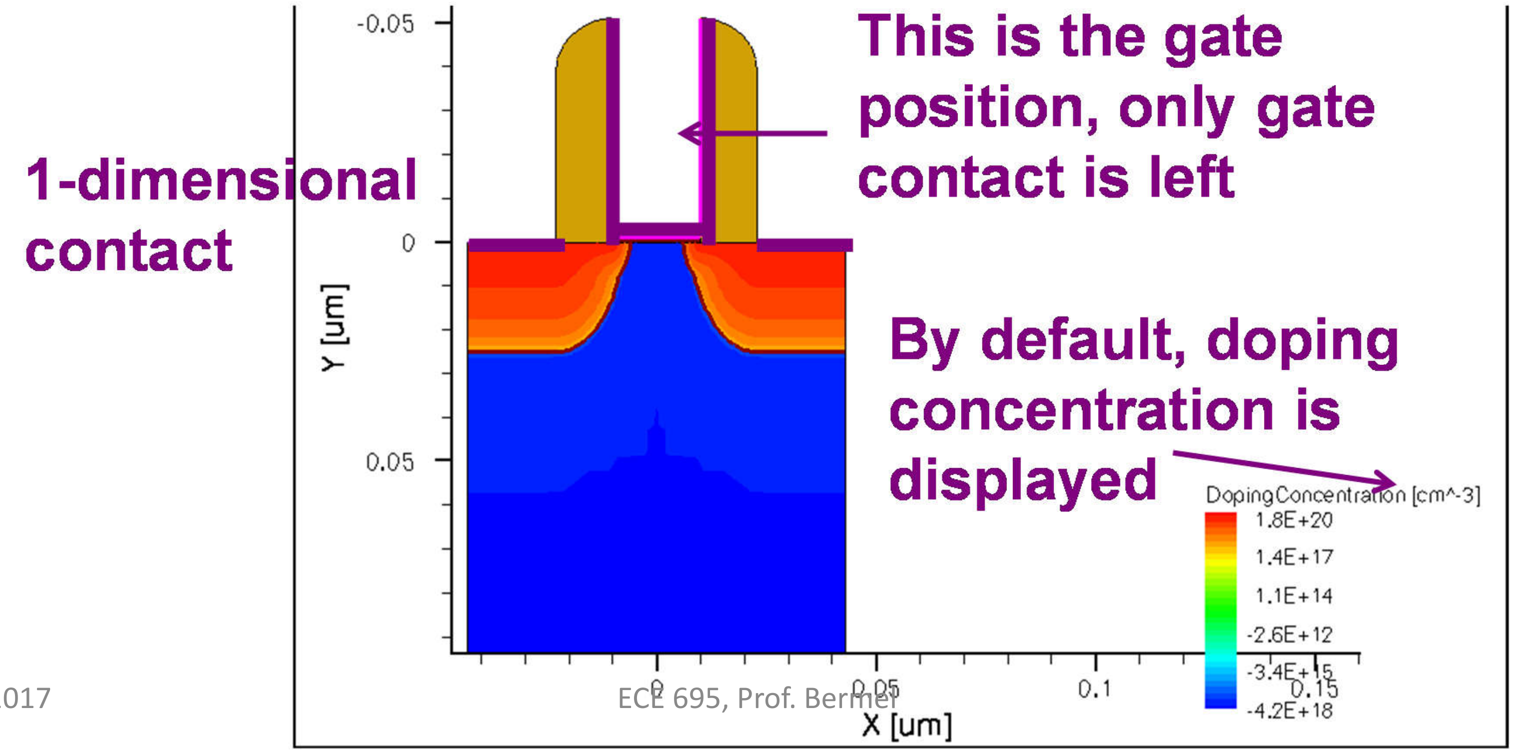
Simulation Status

- 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”.

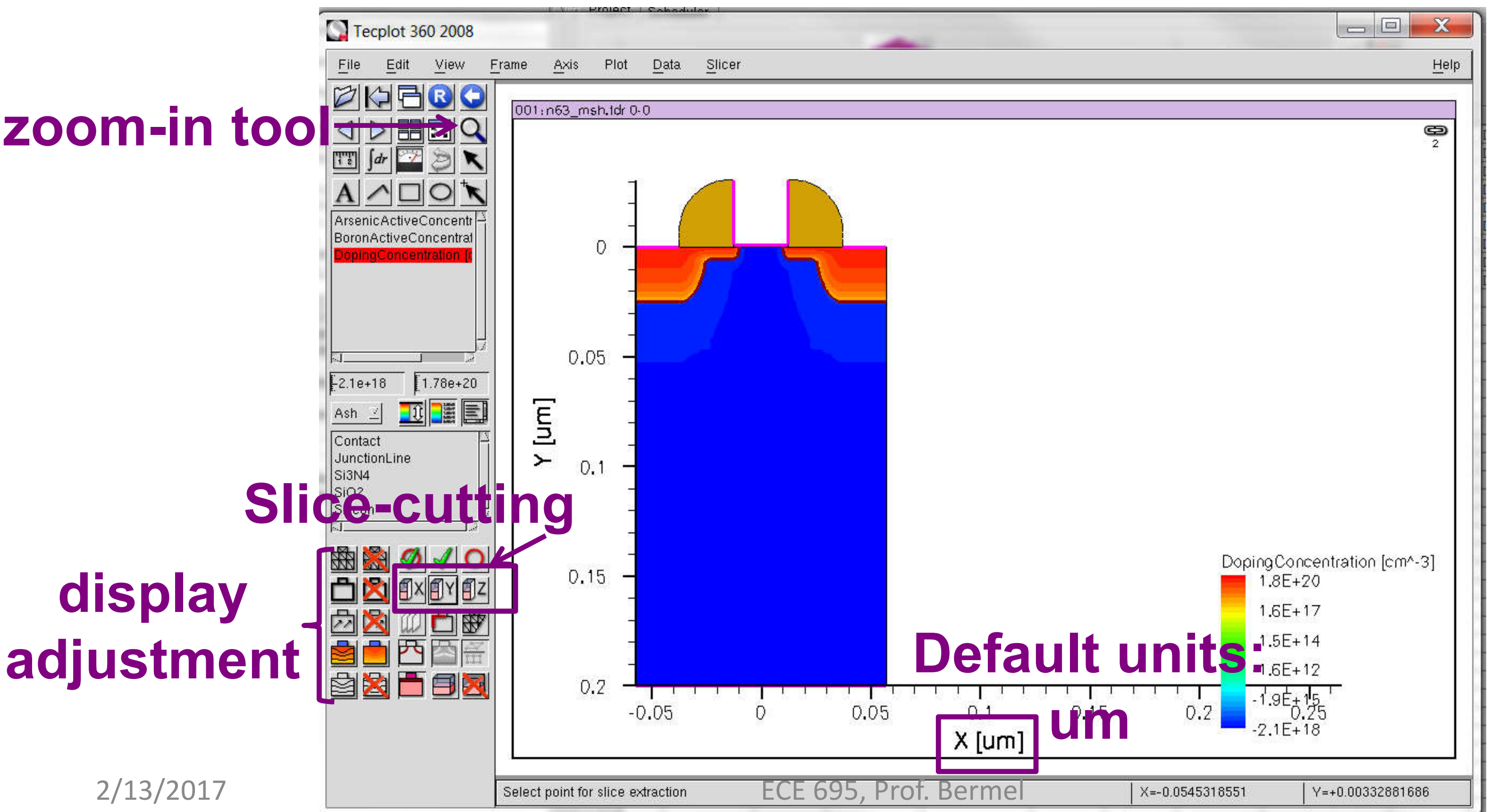
Basic Operations for Sentaurus Structure Editor

- **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.**



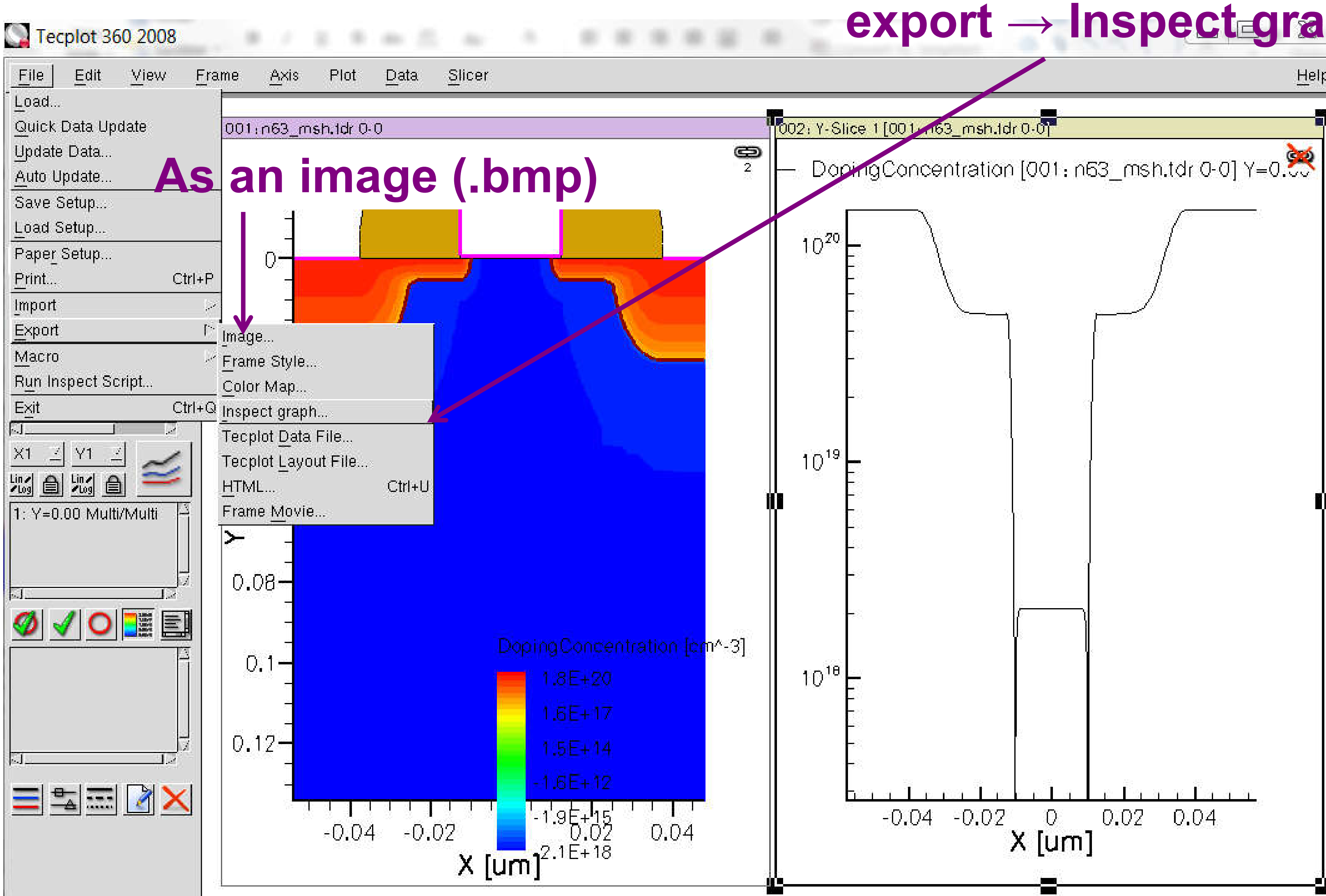
Basic Operations for Sentaurus Tecplot

- **This slide help you familiarize the usage of Sentaurus Tecplot, this tool is for the visualization and profiles/contours extraction purposes.**



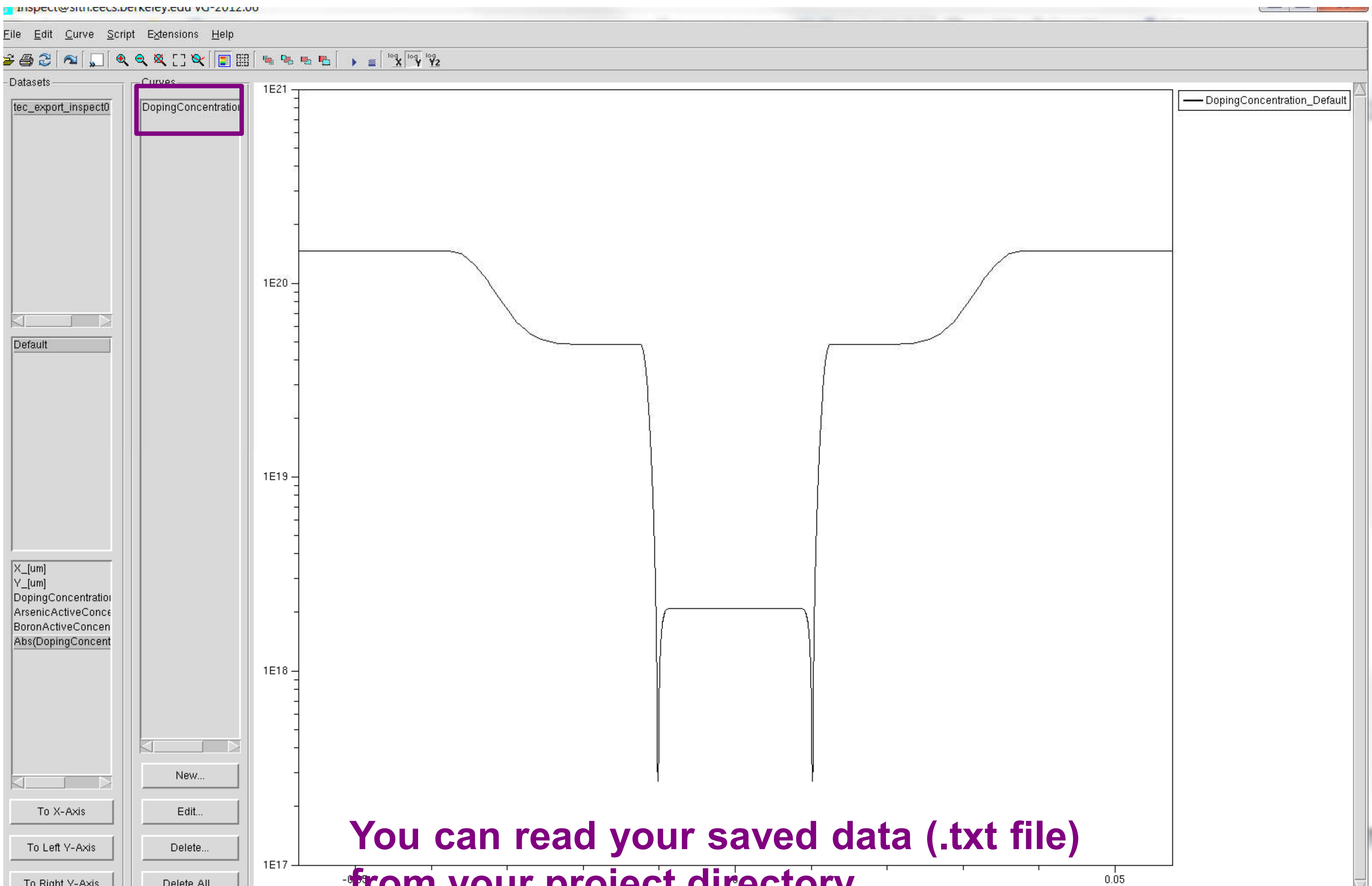
Export the results from Tecplot:

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

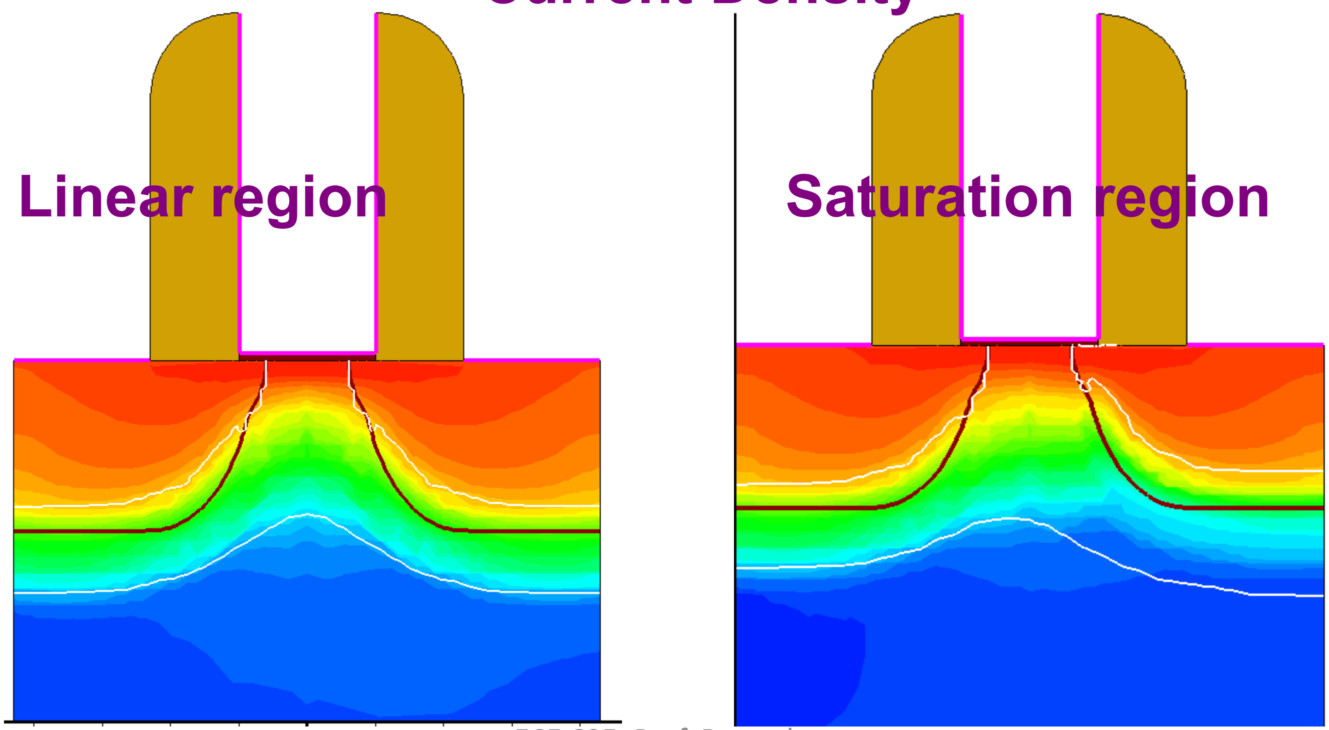


You can read your saved data (.txt file) from your project directory

Basic Operations for Sentaurus Device

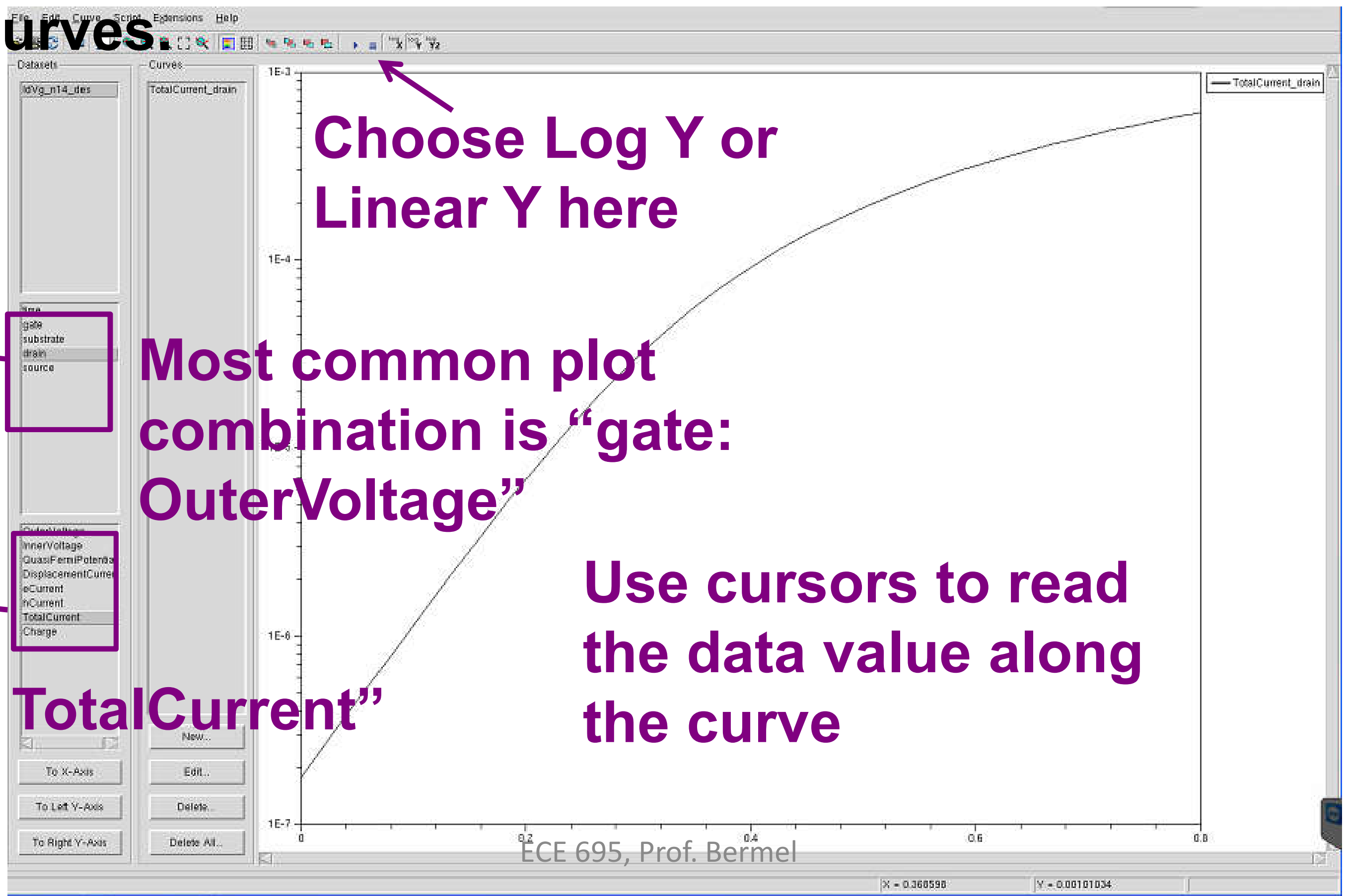
- **Right-click the “done” node in Structure Device, select Visualize → Tecplot SV (Select File) and choose des.tdr file to view your device performance contours (vector fields).**

Current Density



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

Device Terminals

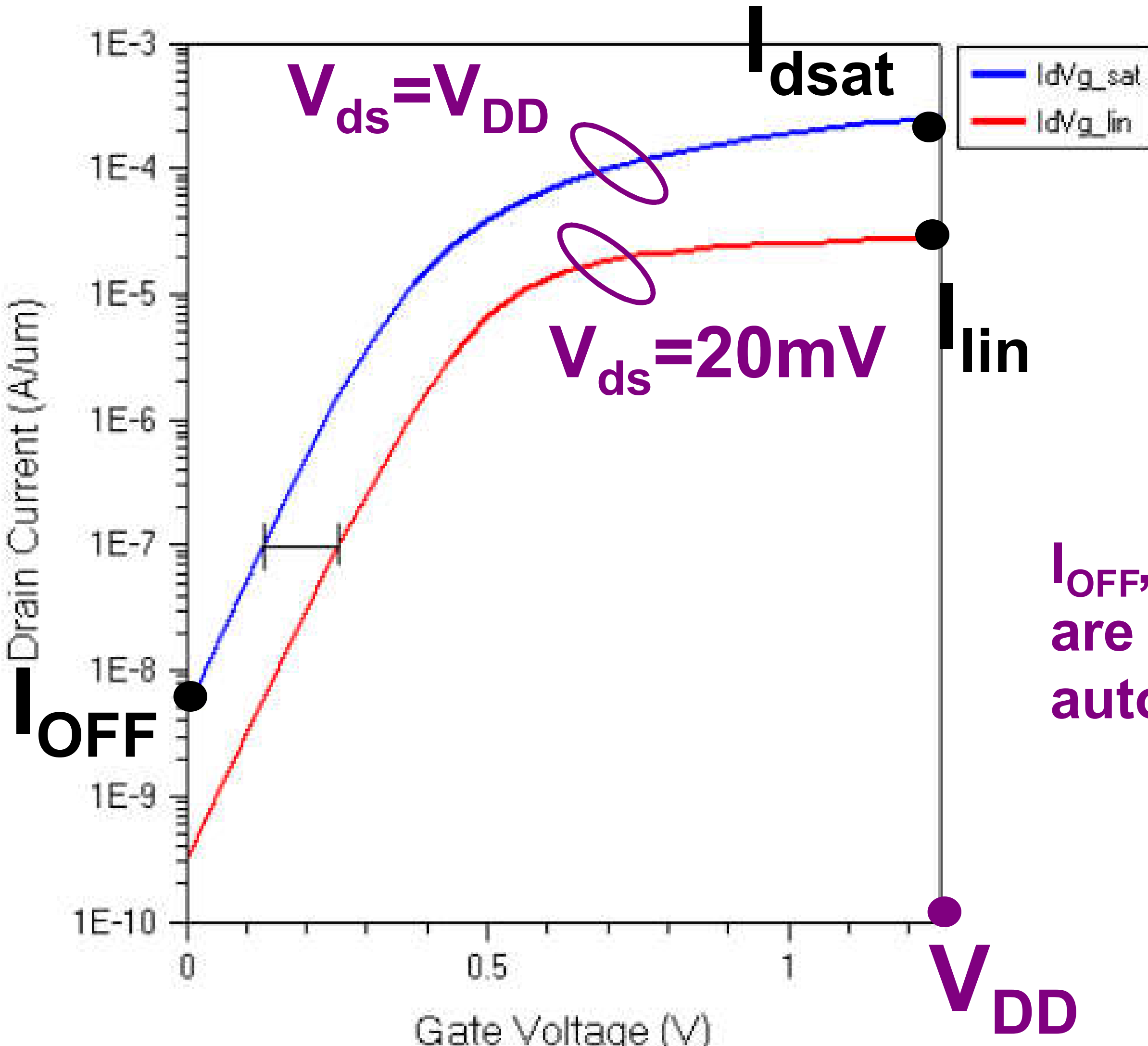
Most common plot combination is "gate: OuterVoltage"

Outputs

"drain: TotalCurrent"

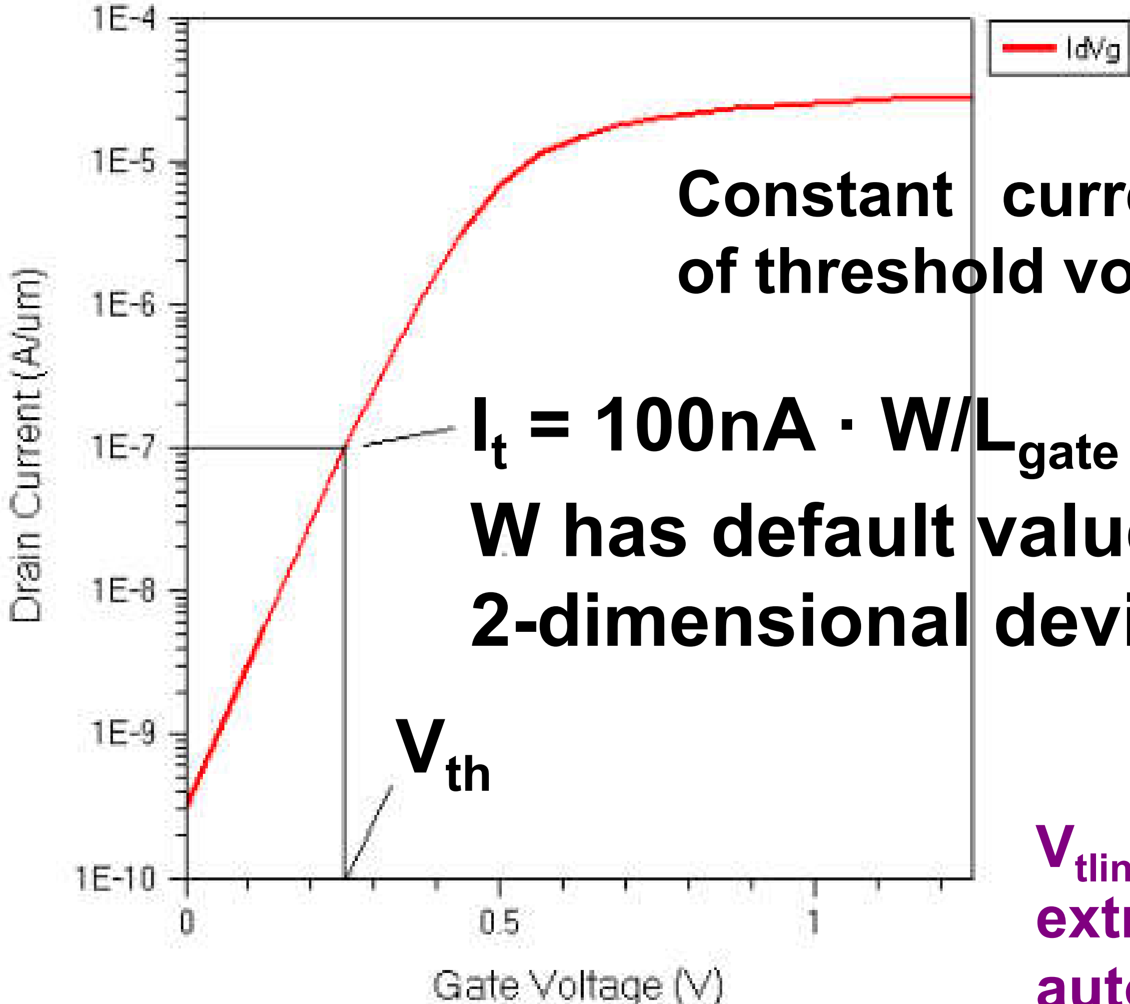
Use cursors to read the data value along the curve

I_{dsat}, I_{lin} and I_{OFF}



I_{OFF}, I_{dsat} and I_{dlin} are extracted automatically

Threshold Voltage (V_t)



Constant current definition of threshold voltage

I_t = 100nA · W/L_{gate}

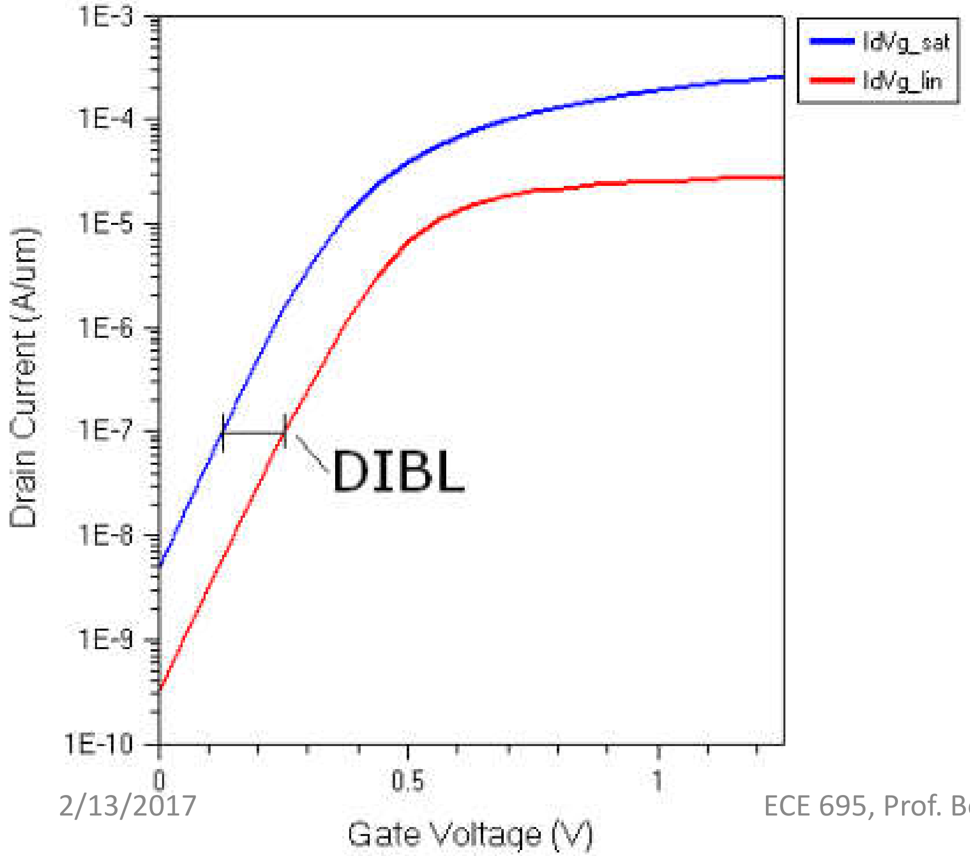
W has default value of 1um for 2-dimensional device simulation

V_{th}

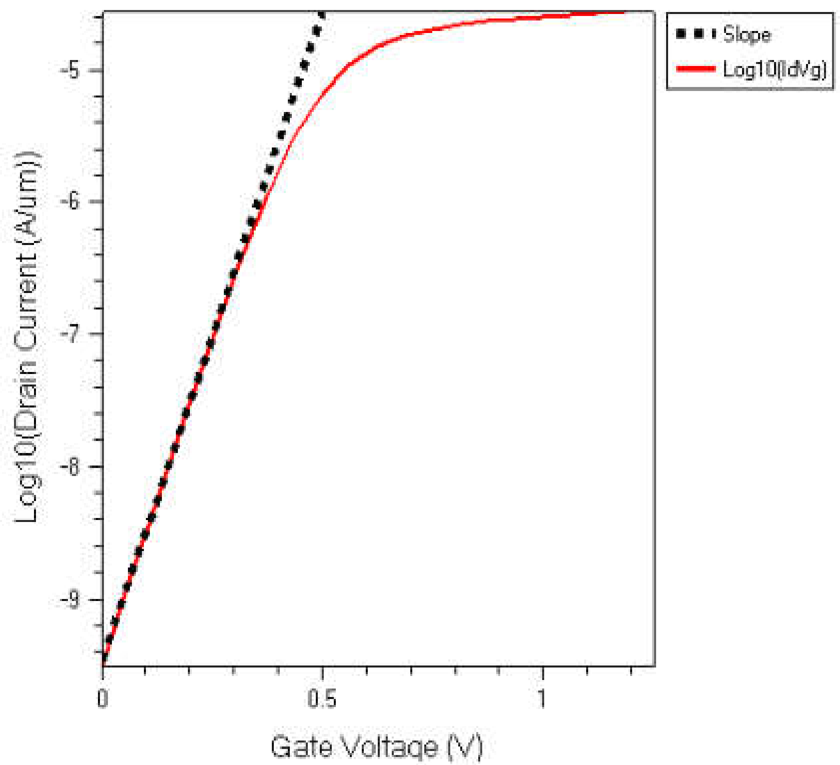
V_{tlin} and V_{tsat} are extracted automatically

DIBL and SS

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



Sub-threshold Swing



Generation/Recombination

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

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

$$R_i = \frac{pn - n_i^2}{\tau_{ni}\left(p + \Gamma n_i e^{(Ef-Ei)/kT}\right) + \tau_{pi}\left(n + \frac{n_i e^{(Ei-Ef)/kT}}{\Gamma}\right)}$$

Generation/Recombination

- Transient behaviour of traps

$$\frac{dN_{tD}^{+}}{dt} = \rho_t \left\{ \overbrace{v_p \sigma_p (p(1-F_{tD})}^{\text{hole capture}} \overbrace{- F_{tD} n_i \Gamma e^{E_i - E_t / kT}}^{\text{hole emission}}) - \overbrace{v_n \sigma_n}^{\text{electron capture}} (nF_{tD} - \overbrace{\frac{(1-F_{tD}) n_i}{\Gamma} e^{E_t - E_i / kT}}^{\text{electron emission}}) \right\}$$

$$\frac{dN_{tA}^{-}}{dt} = \rho_t \left\{ \underbrace{v_n \sigma_n (n(1-F_{tA})}_{\text{Electron capture}} - \underbrace{F_{tA} n_i \Gamma e^{E_t - E_i / kT}}_{\text{Electron emission}}) - v_p \sigma_p \underbrace{(pF_{tA}}_{\text{Hole capture}} - \underbrace{\frac{(1-F_{tA}) n_i}{\Gamma} e^{E_i - E_t / kT}}_{\text{Hole emission}}) \right\}$$

$\sigma_{n,p}$ is trap capture cross-section

$v_{n,p}$ is thermal velocity

n_i is intrinsic concentration

$F_{tA,TD}$ the probability of ionization

$N_{tA,TD}$ space charge density

$$\sigma_n = \frac{1}{\rho_{trap} \tau_n v_n} \quad \sigma_p = \frac{1}{\rho_{trap} \tau_p v_p}$$

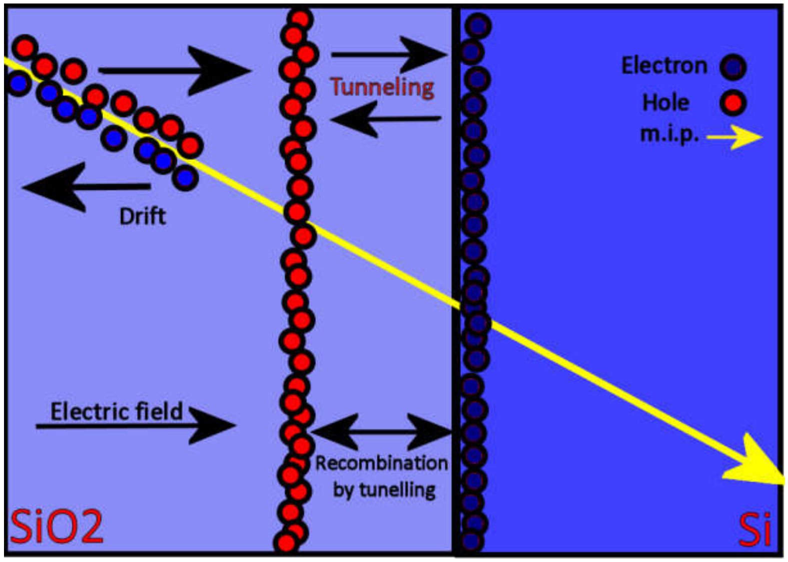
Radiation damage

P-TYPE RADIATION DAMAGE MODEL

Non-ionizing Energy loss

Defect's energy (eV)	Introduction rate (cm^{-1})	Electron capture cross-section (cm^{-2})	Hole capture cross-section (cm^{-2})
$E_c - 0.42$	1.613	2.e-15	2e-14
$E_c - 0.46$	0.9	5e-15	5e-14
$E_c - 0.10$	100	2e-15	2.5e-15
$E_v + 0.36$	0.9	2.5e-14	2.5e-15

Ionizing Energy loss



D. Menichelli, M. Bruzzi, Z. Li, and V. Eremin, "Modelling of observed double-junction effect," *Nucl. Instrum. Meth. A, vol. 426, pp.* 135–139, Apr. 1999.

F. Moscatelli *et al.*, *"An enhanced approach to numerical modeling of* heavily irradiated silicon devices," *Nucl. Instrum. Meth. B, vol. 186,* no. 1-4, pp. 171–175, Jan. 2002.

F. Moscatelli *et al.*, *"Comprehensive device simulation modeling of* heavily irradiated silicon detectors at cryogenic temperatures," *IEEE Trans. Nucl. Sci., vol. 51, no. 4, pp. 1759–1765, Aug. 2004.*

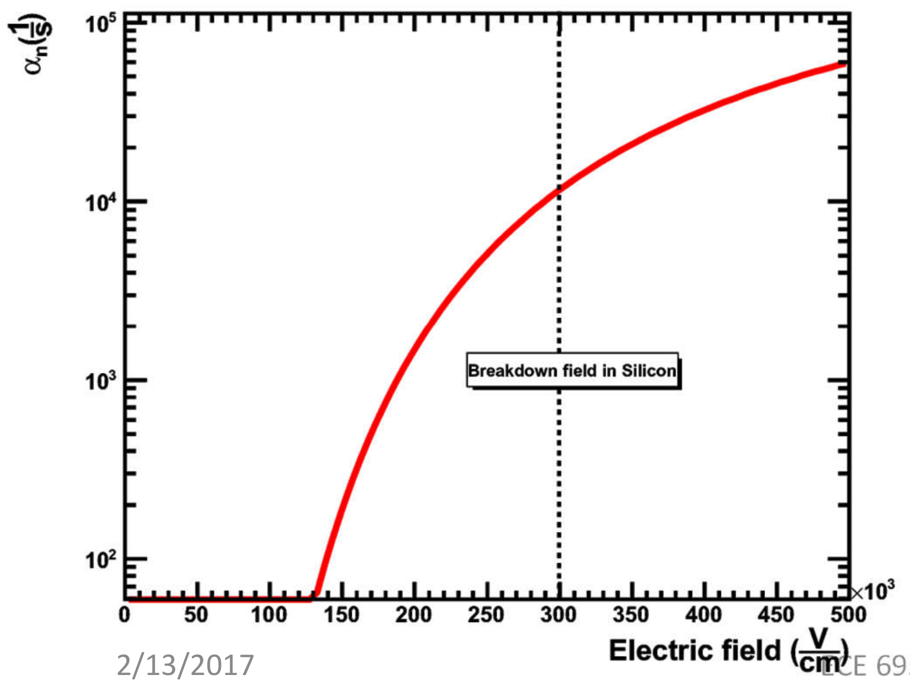
M. Petasecca, F. Moscatelli, D. Passeri, G. Pignatel, and C. Scarpello, "Numerical simulation of radiation damage effects in p-type silicon detectors," *Nucl. Instrum. Meth. A, vol. 563, no. 1, pp. 192–195, 2006.*

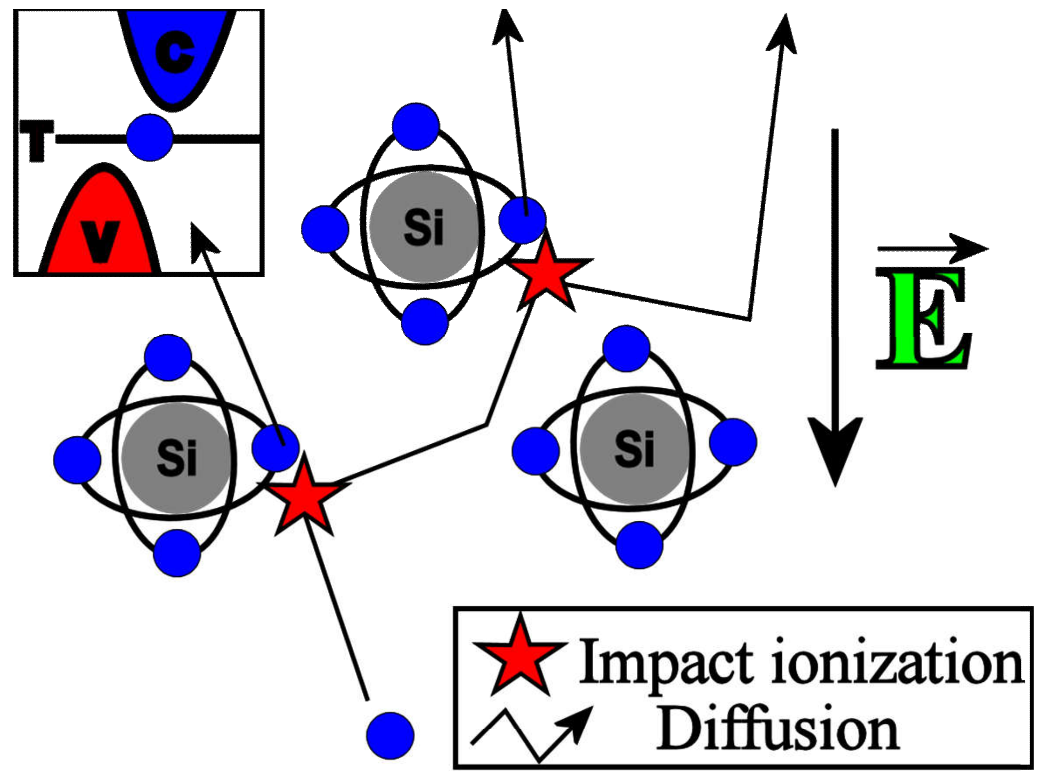
Impact ionization

$$G = \alpha_n(E)J_n + \alpha_p(E)J_p$$

$$\alpha_n = A_n e^{-\left(B_n/E\right)^{\beta_n}}$$

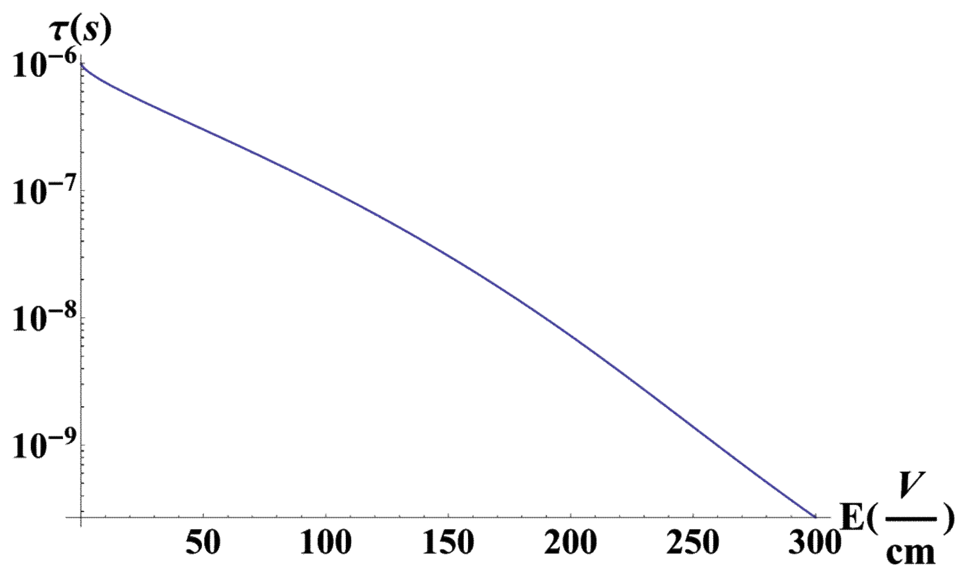
$$\alpha_p = A_p e^{-\left(B_p/E\right)^{\beta_p}}$$

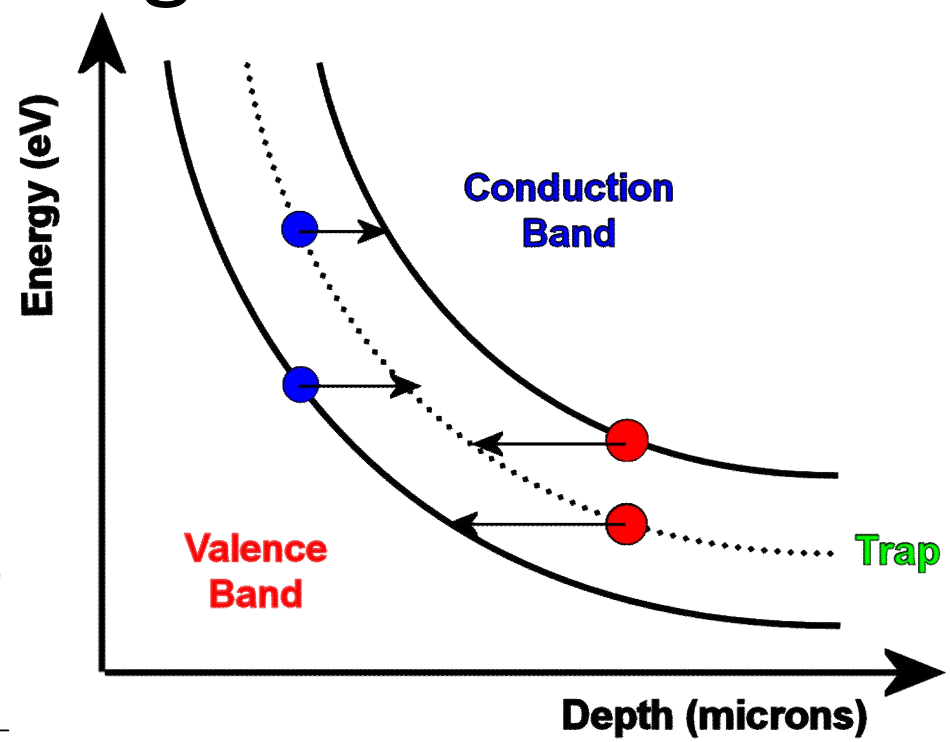




Selberherr, S., **"Analysis and Simulation of Semiconductor Devices"**, Springer-Verlag Wien New York, ISBN 3-211-81800-6, 1984.

Phonon-assisted trap-to-band tunneling





$$R_i = \frac{pn - n_i^2}{\frac{\tau_{n0}}{1+\Gamma_n^{DIRAC}}\left(p + \Gamma n_i e^{(Ef-Ei)/kT}\right) + \frac{\tau_{p0}}{1+\Gamma_p^{DIRAC}}\left(n + \frac{n_i e^{(Ei-Ef)/kT}}{\Gamma}\right)}$$

$$\Gamma_n^{DIRAC} = \frac{\Delta E_n}{kT_L}\int_0^1 e^{\left(\frac{\Delta E_n}{kT_L}u - K_n u^{3/2}\right)} du \qquad K_n = \frac{4}{3}\frac{\sqrt{2 m_0 m_{tunnel} \Delta E_n^3}}{3 q\hbar |E|}$$

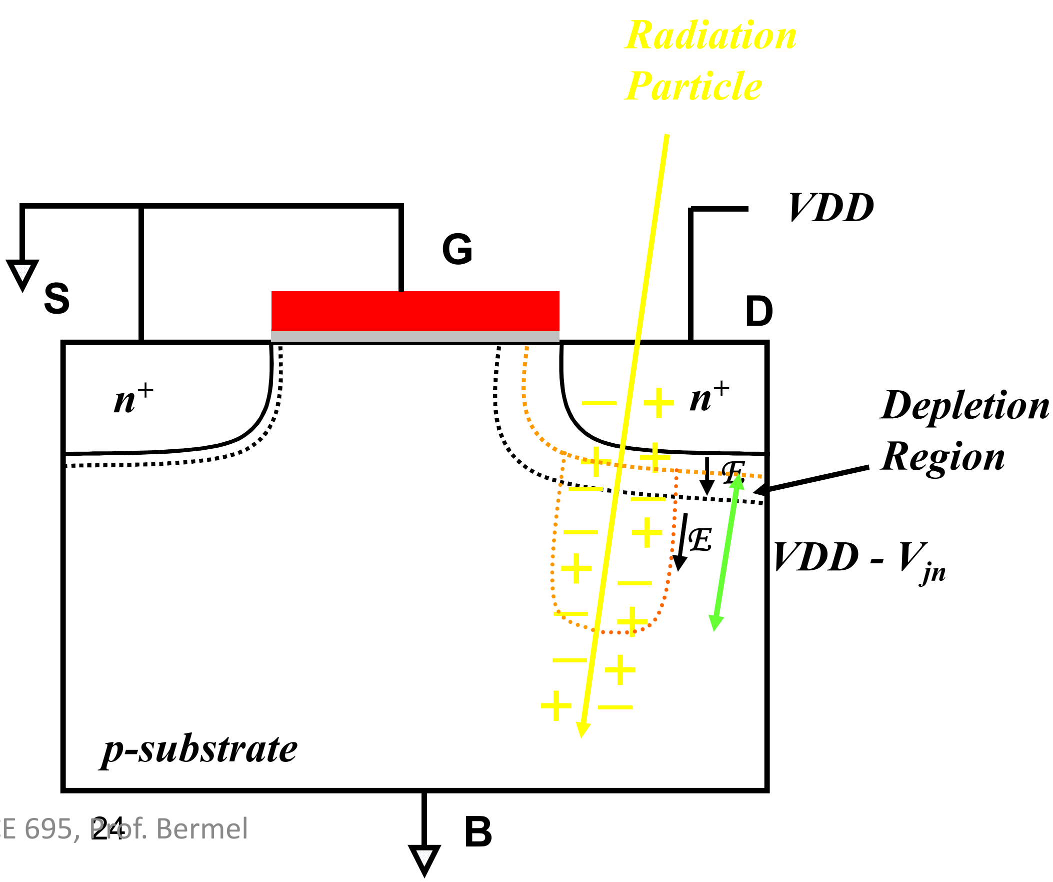
$$\Gamma_p^{DIRAC} = \frac{\Delta E_p}{kT_L}\int_0^1 e^{\left(\frac{\Delta E_p}{kT_L}u - K_p u^{3/2}\right)} du \qquad K_p = \frac{4}{3}\frac{\sqrt{2 m_0 m_{tunnel} \Delta E_p^3}}{3 q\hbar |E|}$$

Hurkx, G.A.M., D.B.M. Klaasen, M.P.G. Knuvers, and F.G. O'Hara, **"A New Recombination Model Describing Heavy-Doping Effects and Low Temperature Behaviour",** *IEDM Technical Digest(1989): 307-310.*

Charge Deposition by a Radiation Particle

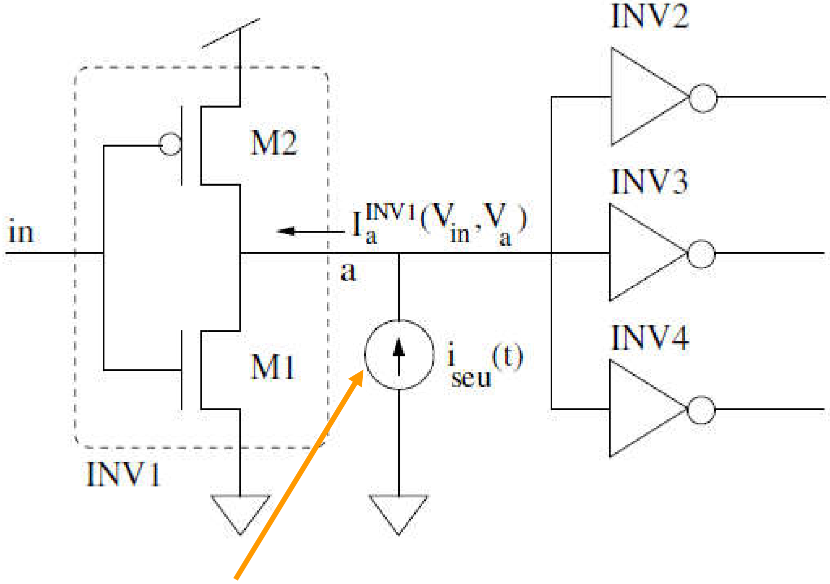
- Radiation particles - protons, neutrons, alpha particles and heavy ions
- Reverse biased *p-n* junctions are most sensitive to particle strikes

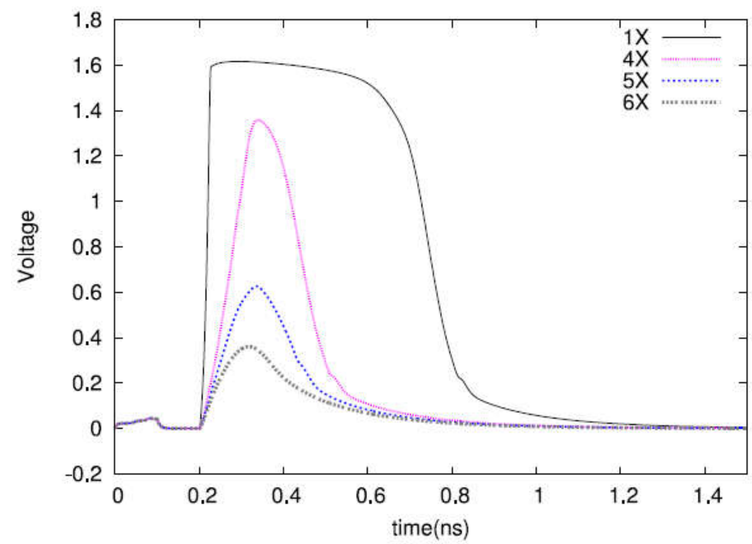
- Charge is collected at the drain node through *drift and diffusion*
- Results in a voltage glitch at the drain node
- System state may change if this voltage glitch is captured by at least one memory element
  - This is called an SEU
  - May cause system failure



Radiation Particle Strikes

- Radiation particle strike at the output of INV1
- Implemented using 65nm PTM with VDD=1V
- Radiation strike: Q=100fC, τ_α=200ps & τ_β=50ps

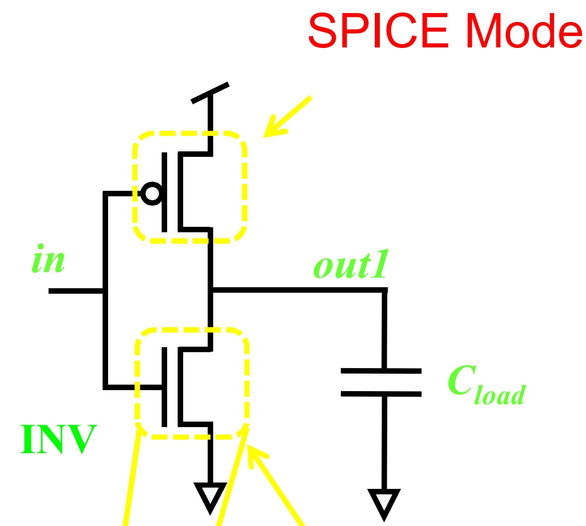


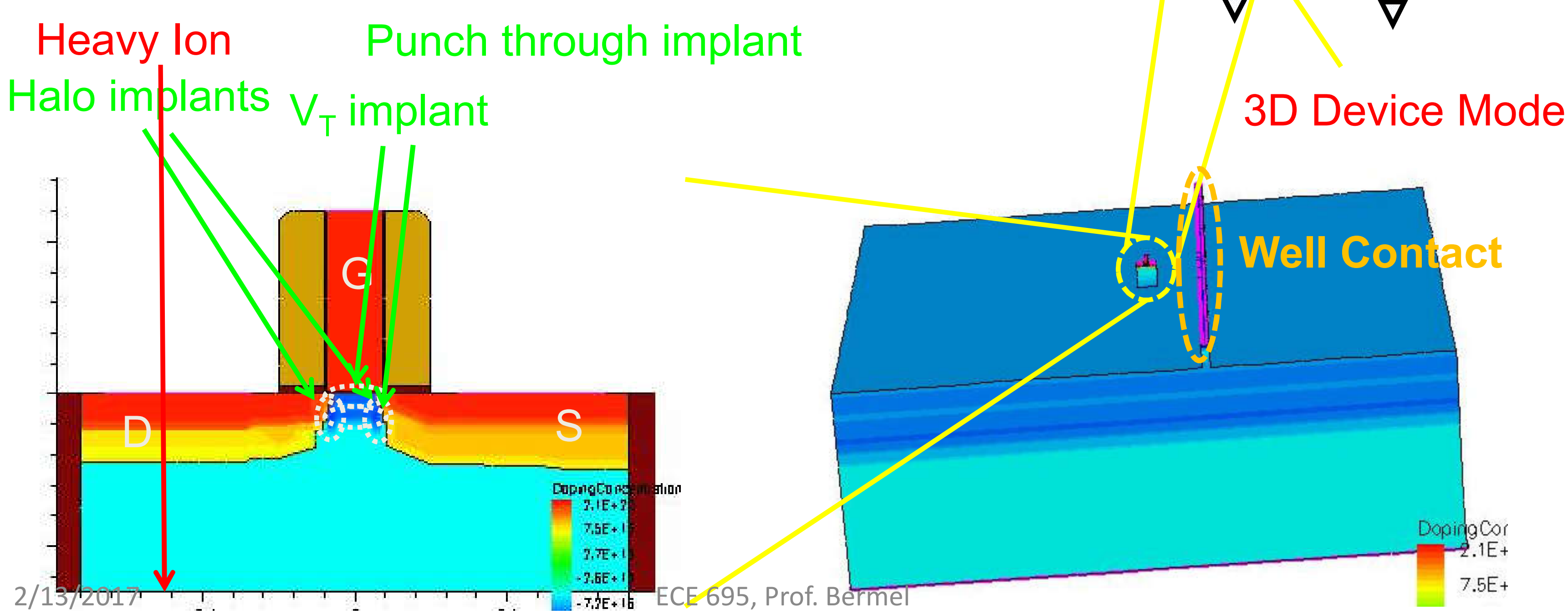


Models Radiation Particle Strike

NMOS Device Modeling

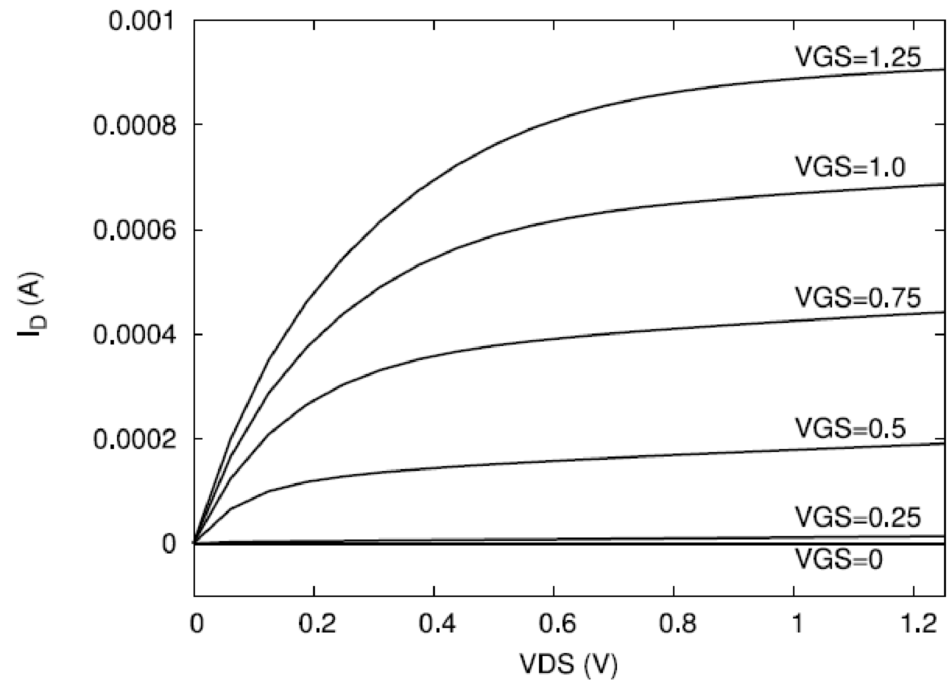
- Constructed NMOS transistors using Sentaurus-Structure editor tool
- Gate length 35nm, T_{ox} = 1.2nm spacer width = 30nm
- A heavy ion strikes at the center of the drain



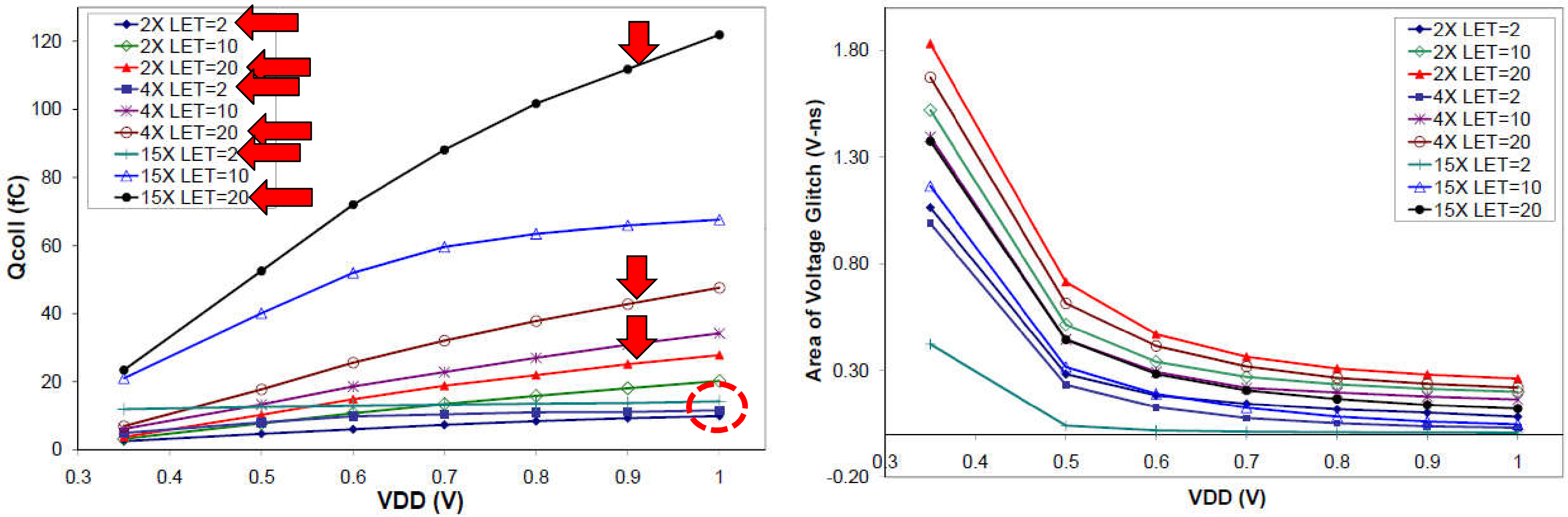


NMOS Device Characterization

- 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