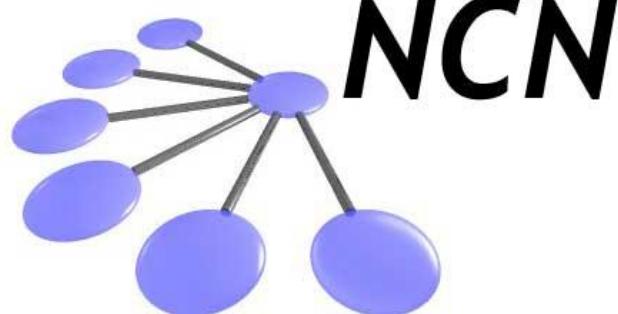


Network for Computational Nanotechnology (NCN)

Berkeley, Univ.of Illinois, Norfolk State, Northwestern, Purdue, UTEP



First-Time User Guide to MuGFET v1.1

Nov. 17, 2008

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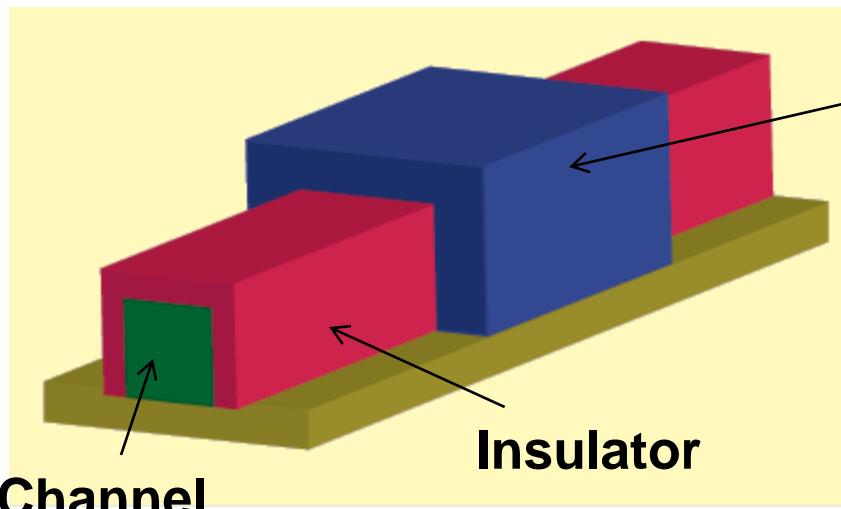
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Introduction: What is MuGFET?

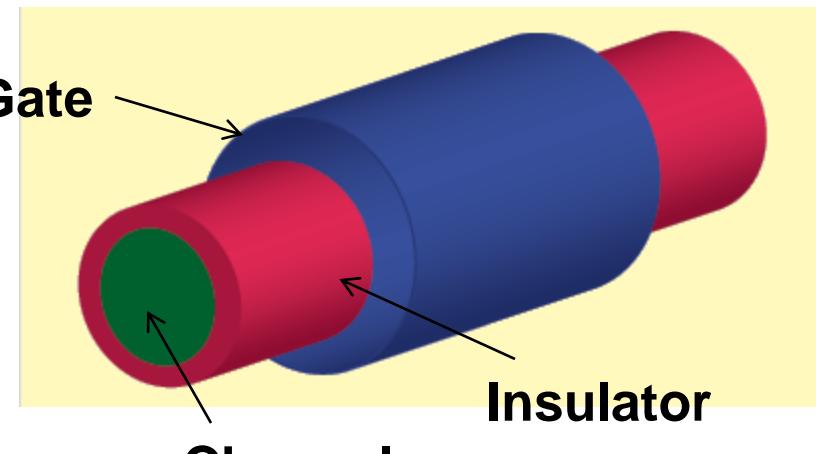
Nanoscale Multi-Gate Field Effect Transistor

Size of device decreases (Moore's Law)
→ number of gates increases for more efficient gate control

FinFET



Nanowire FET

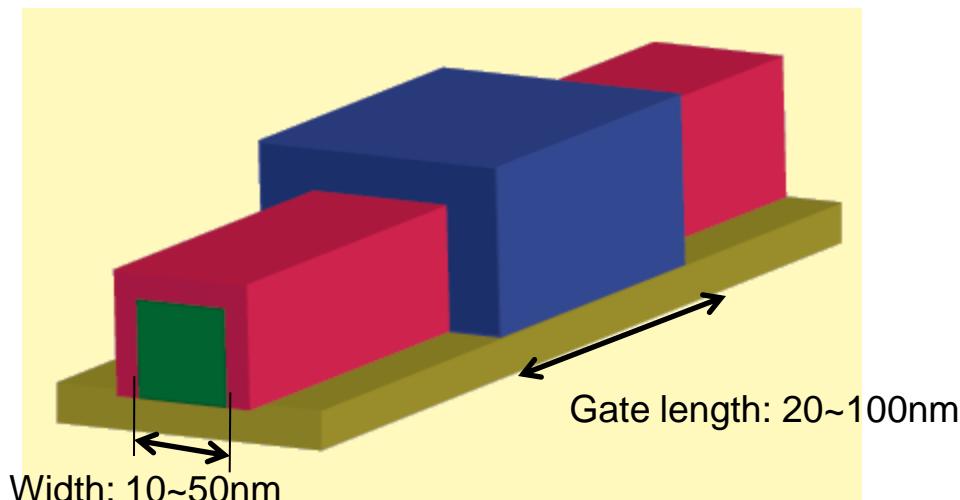


Introduction

MuGFET simulates quantum transport at the nanoscale, which is close to the atomistic dimension.

→ **Quantum transport** simulation is necessary but is not the best choice for the following reasons:

Relatively long and large device



- Computationally very **expensive**
- **Difficult** to include all of the scattering processes

Introduction

The **Drift diffusion type simulator** works well enough to demonstrate characteristics of relatively long and large devices.

In What Ways?

- QM mechanics is not dominant if the lateral dimension of the transistor is larger than 10 nm.*
- Physical insight can be provided, even if not strictly valid.
- The subthreshold characteristic is still diffusion dominated.
- The on-current can never be overestimated by the drift diffusion simulation.
- The hot carrier transport can be taken care of by solving the energy balance equation.
- The drift diffusion simulator is way faster than the quantum transport simulator.

*This statement is from a conversation with Prof. Vasileska at ASU

Introduction

***PROPHET**: general partial differential solver developed at Bell Lab

****PADRE**: device simulator developed at Bell Lab

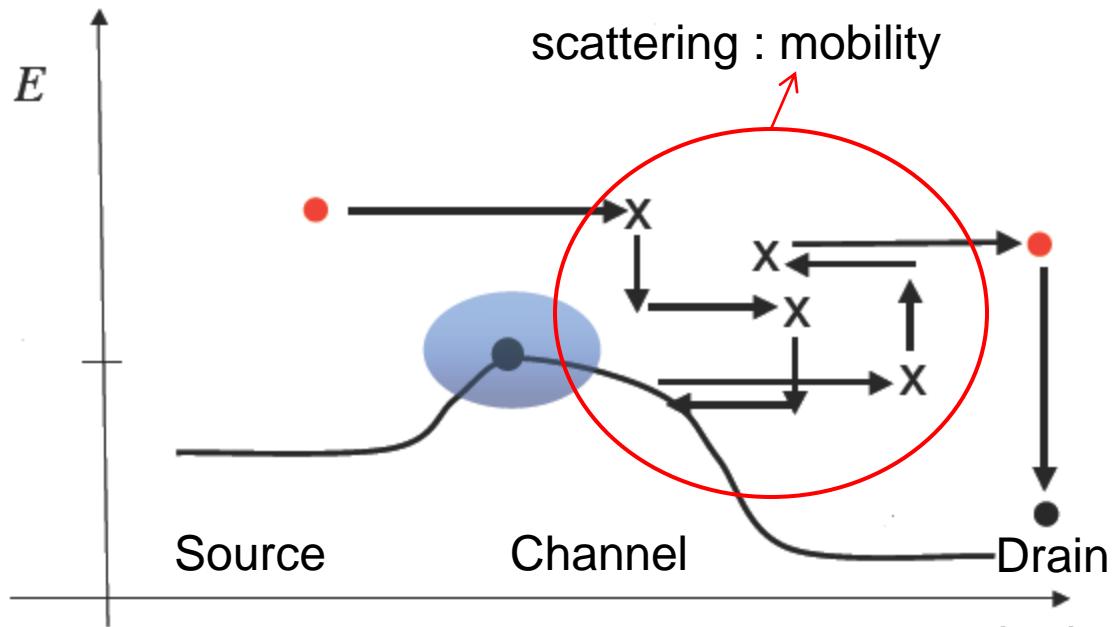


*https://www.nanohub.org/resource_files/tools/prophet/doc/guide.html

**http://www.nanohub.org/resource_files/tools/padre/doc/index.html

Theory

Drift Diffusion Picture



*ECE612 Fall2008 lecture 8 note

ε : dielectric constant

V : potential

n / p : electron/hole density

q : elementary charge

$J_{n/p}$: electron/hole current density

*R. F. Pierret, Semiconductor Device Fundamentals

T : temperature

G / R : generation/recombination rate

μ_n, μ_p : electron/hole mobility

D_n, D_p : electron/hole diffusion coefficient

Theory

$$\nabla \cdot \mathbf{S}_{n,p} = -\mathbf{J}_{n,p} \cdot \nabla \psi - W_n - \frac{3k}{2} \frac{\partial}{\partial t} (\lambda_{n,p}^* n T_{n,p}^*)$$

$$\mathbf{J}_n = q D_{n,p} \nabla n - \mu_{n,p} n \nabla \psi + q n D_{n,p}^T \nabla T_{n,p}$$

$$\mathbf{S}_n = -K_{n,p} \nabla T_{n,p} - \left(\frac{\kappa \delta_{n,p}}{q} \right) \mathbf{J}_{n,p} T_{n,p}$$

$\mathbf{S}_{n,p}$: energy flux density

$D_{n,p}$: thermal diffusivity

$W_{n,p}$: energy density loss rate

$T_{n,p}$: carrier temperature

$K_{n,p}$: thermal conductivity

$\mu_{n,p}$: electron mobility

Drift Diffusion Model

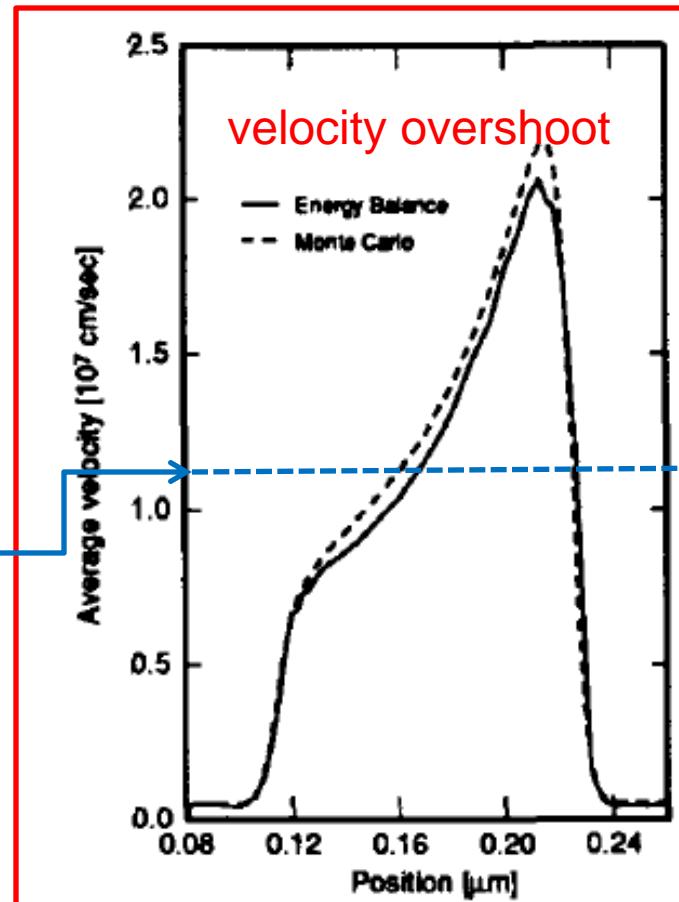
→ carrier velocity is saturated in the channel
(where electric field is larger than critical value)

Reality

→ Velocity overshoot: current gets higher

*https://www.nanohub.org/resource_files/2006/06/01581/intro_dd_patre_word.pdf

Energy Balance Equation*



M.R.Pinto et. al. IEEE, 1993



Rappture Interface

Outline of Interface

Device Type → Structure → Material → Environment → Simulator → Simulate

1 Device Type → 2 Structure → 3 Material → 4 Environment → 5 Simulator → 6 Simulate

Examples: Double Gate p-FinFET - Gate length : 45 nm, Channel width : 30nm

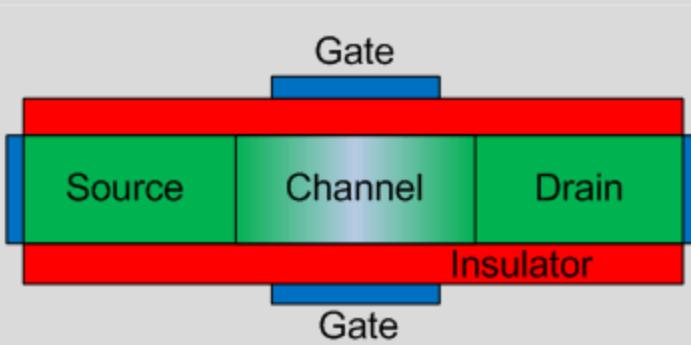
Device Type

Class: FinFET

Spec

Dimension: 2D (Double Gate)

Gate Type: Metal



Rappture Interface

MuGFET

File

1 Device Type → 2 Structure → 3 Material → 4 Environment

Examples: Double Gate p-FinFET - Gate length : 45 nm, Channel width : 100 nm

Device Type

Class: FinFET

Spec

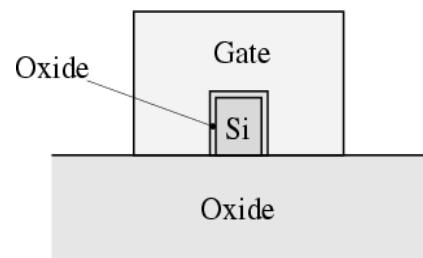
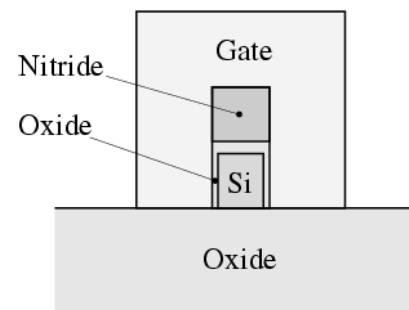
Dimension: 2D (Double Gate)

Gate Type: Metal

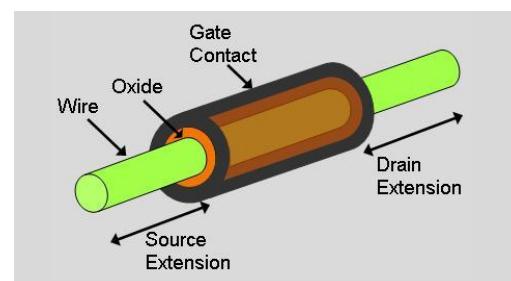
Structure >

Device Type

- Class- FinFET or Nanowire
- Dimension

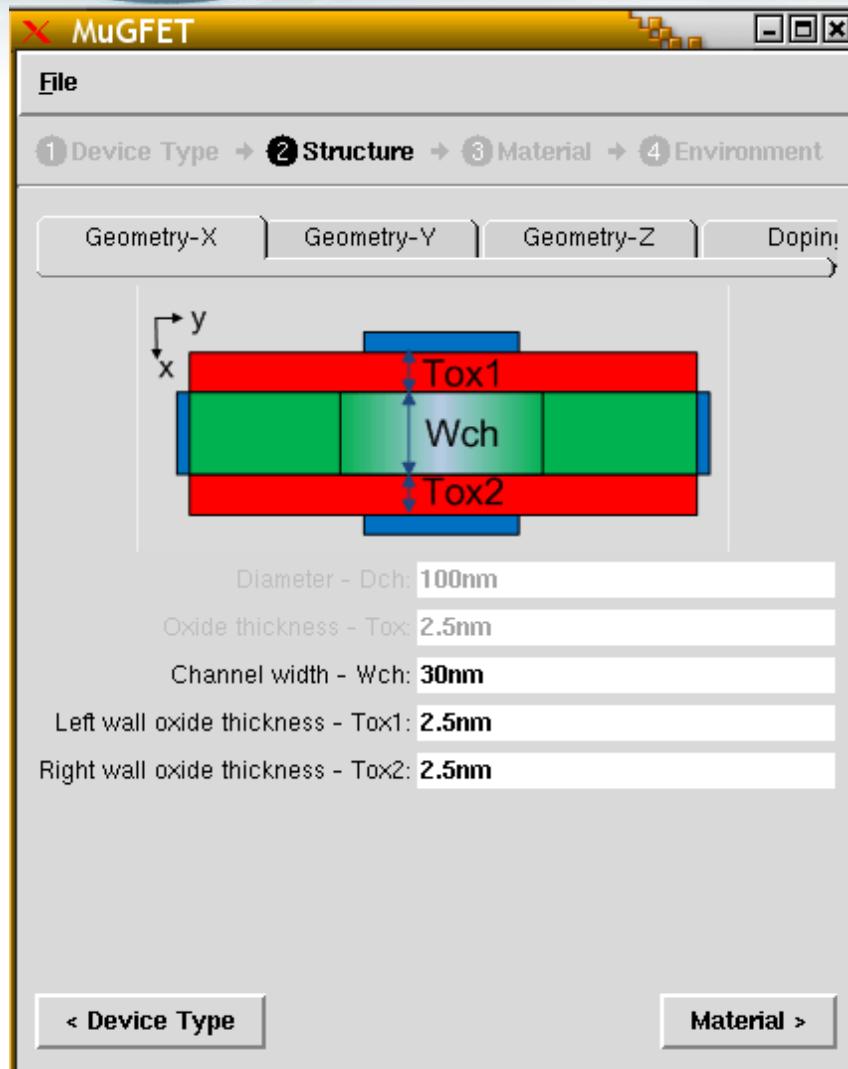


- Nanowire- no dimension



- Gate type- metal or poly (polysilicon)
(poly option is only valid in PADRE simulator)

Rappture Interface

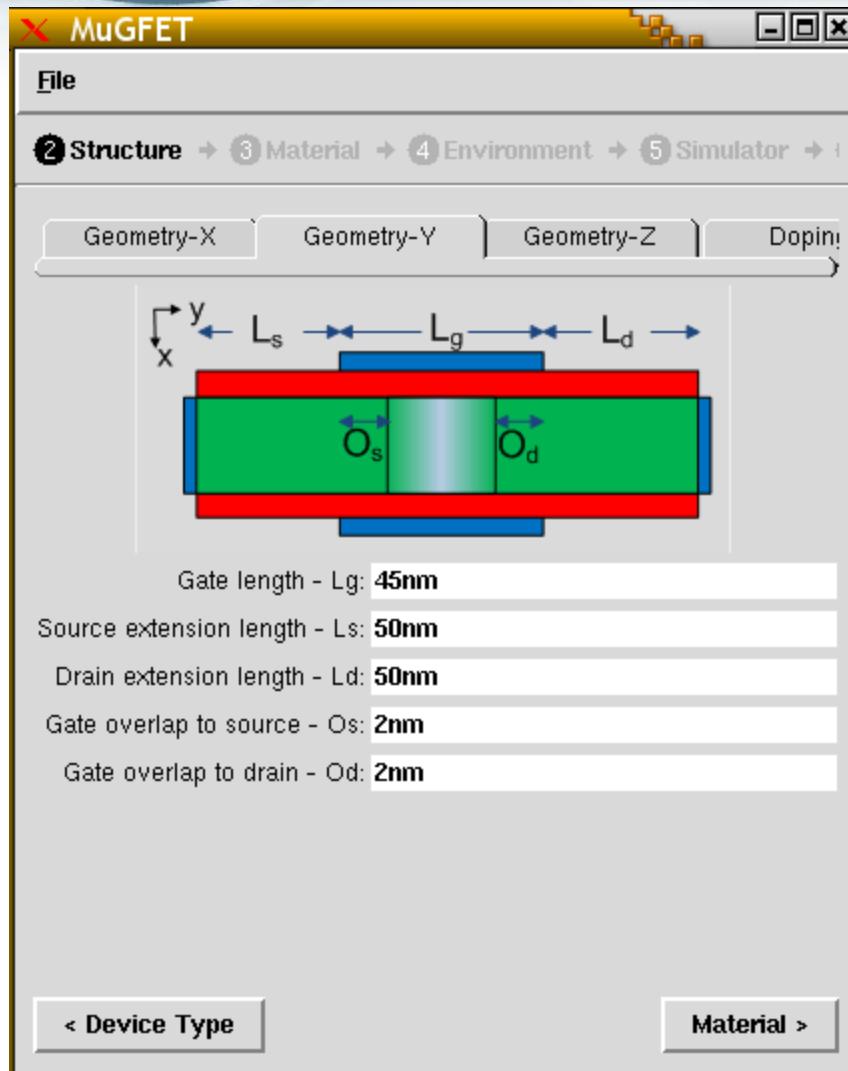


Device Structure

- Geometry-X: Lateral Direction
 - » Channel width
 - The width of silicon channel region
 - » Oxide thickness
 - Left wall
 - Right wall
 - X-direction is Radial Direction
 - » when you choose the nanowire

Note: The cross section should be large when compared to the electron wave length, so that the quantum effect will not appear to be using the Drift Diffusion Equation.

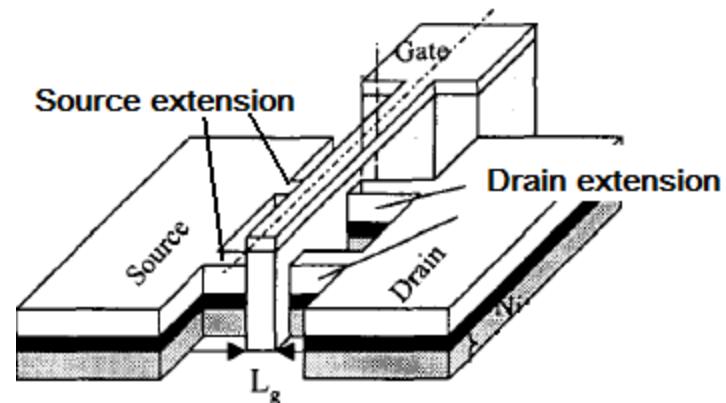
Rappture Interface



Device Structure

- **Geometry-Y**

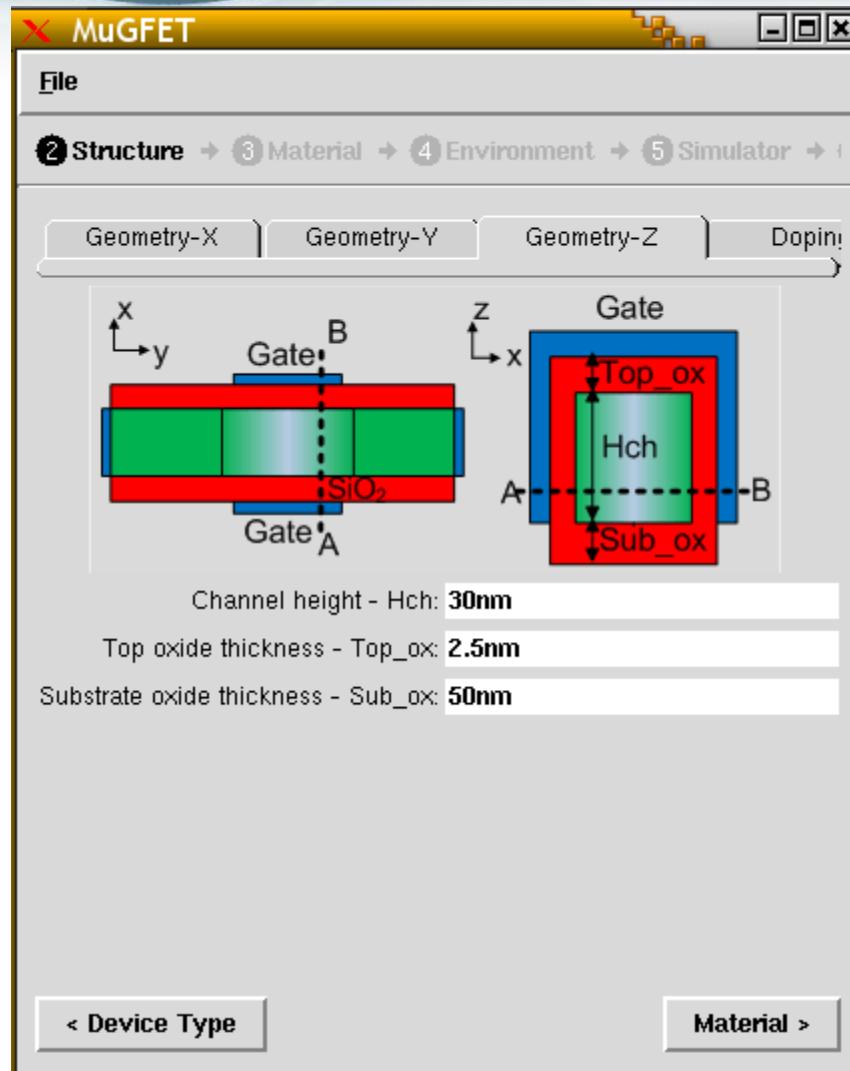
- » L_g : gate length
- » L_s : source extension length
- » L_d : drain extension length
- ✓ Extension region has same width as the channel but is doped differently



*Y.K.Choi et. al. IEEE Electron Device Letters, 2002

- » O_s/O_d : Gate overlap to source/drain

Rappture Interface

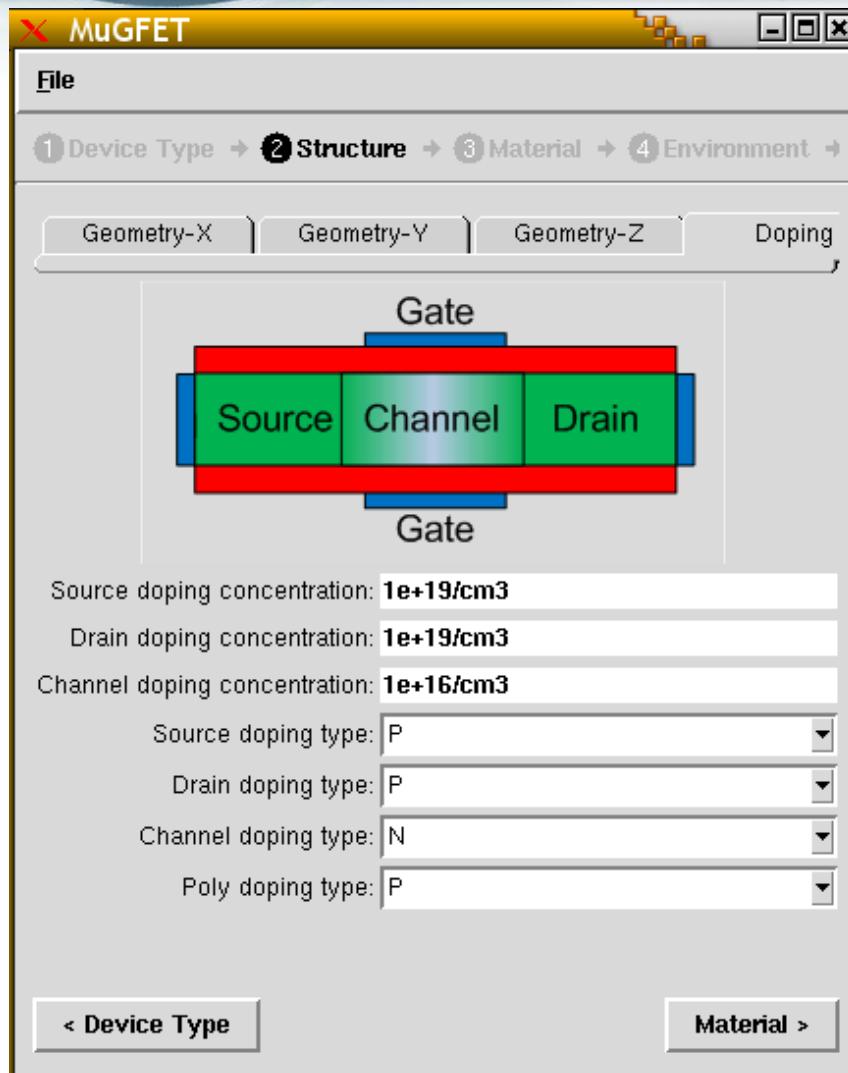


Device Structure

- **Geometry-Z**

- » Z directional geometry setting is only activated when you choose triple gate (3D) in device type
- » Hch: channel height
- » Top_ox: top oxide thickness
- » Sub_ox: substrate oxide thickness

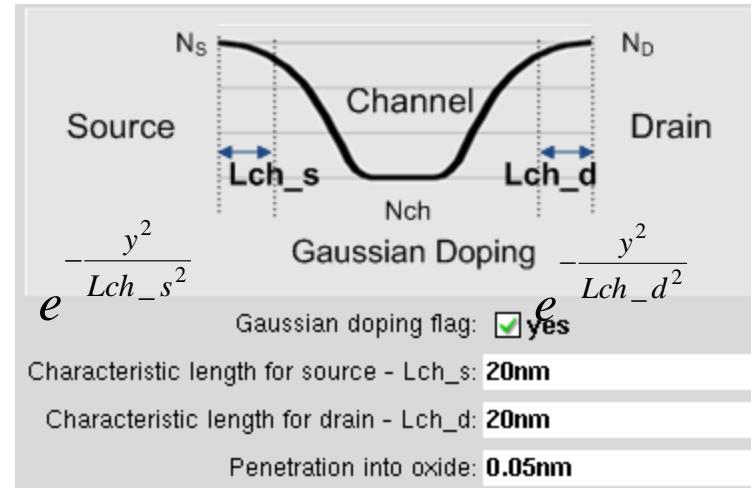
Rappture Interface - Doping



- Doping

- ✓ Doping concentration in each section
- ✓ Doping type in each section

- Gaussian Doping



- » Gaussian doping profile starts from the end of the source/drain extension region
- » Characteristic length is the length to which the doping drops by the factor $\exp(-1)$

Rappture Interface

Material Property

MuGFET

File

1 Device Type → 2 Structure → 3 Material → 4 Environment → 5 Simulator → 6 Simulate

General Bandstructure Electrons in channel Holes in Channel

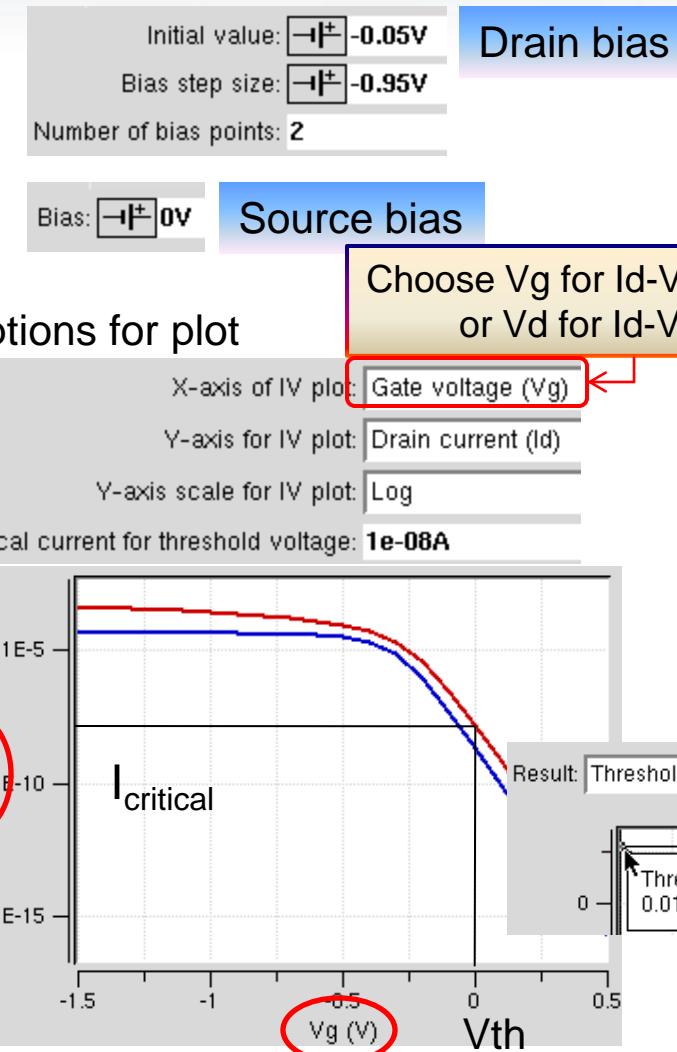
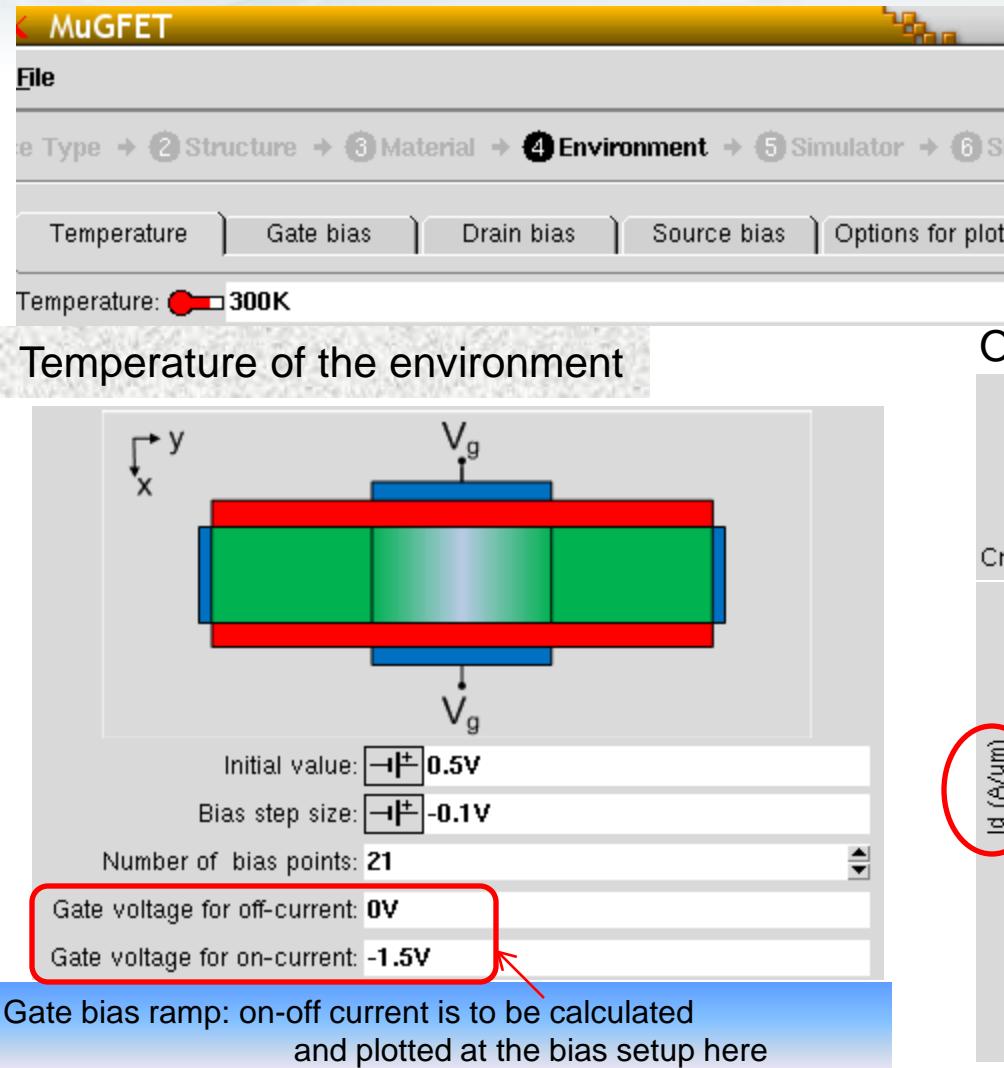
Dielectric constant in channel: Dielectric constant in insulator:

Gate Insulator Channel Insulator Gate

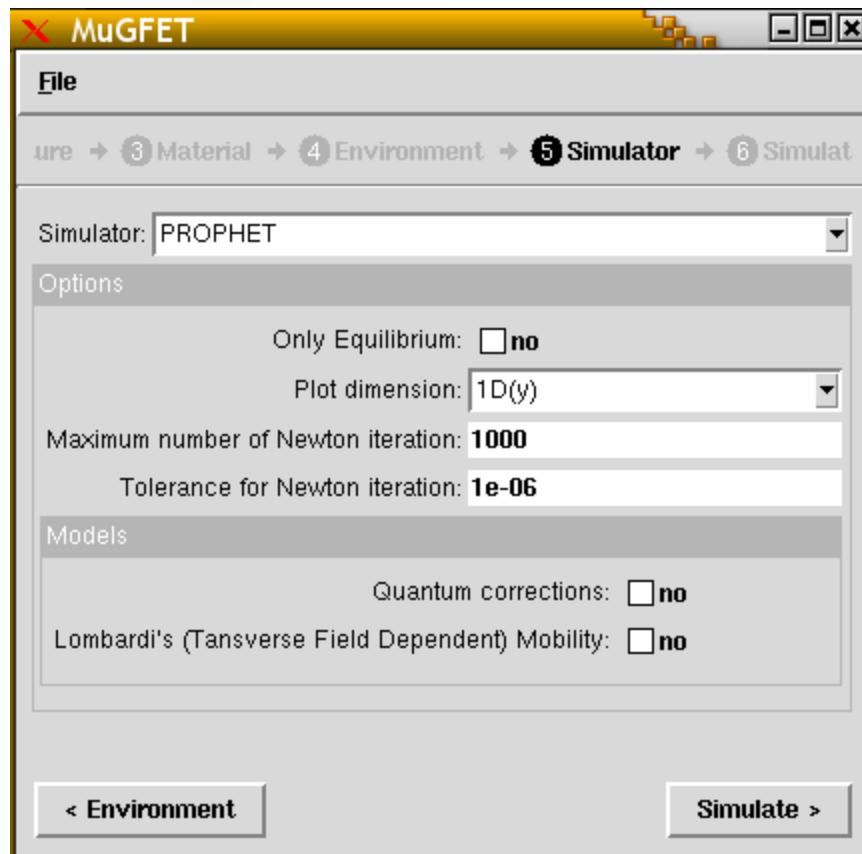
Bandgap of channel material: **1.12eV**
 Affinity of channel material: **4.05eV**
 Gate contact work function: **4.75eV**

Electron effective mass (m_0):
 Density of states effective mass (m_0):
 Mobility:
 Heavy hole effective mass (m_0):
 Density of states effective mass (m_0):
 Saturation velocity:

Rappture Interface - Environment



Simulator Options - PROPHET



** Lombardi's mobility model : http://www-tcad.stanford.edu/~prophet/user_ref/node8.html

- Only Equilibrium

- » All of the bias steps will be ignored, if simply simulating the equilibrium condition.

- Plot dimension

- » 1D(x): 1D plot across the channel
- » 1D(y): 1D plot along the channel
- » 2D: 2D plot

- Newton iteration parameters

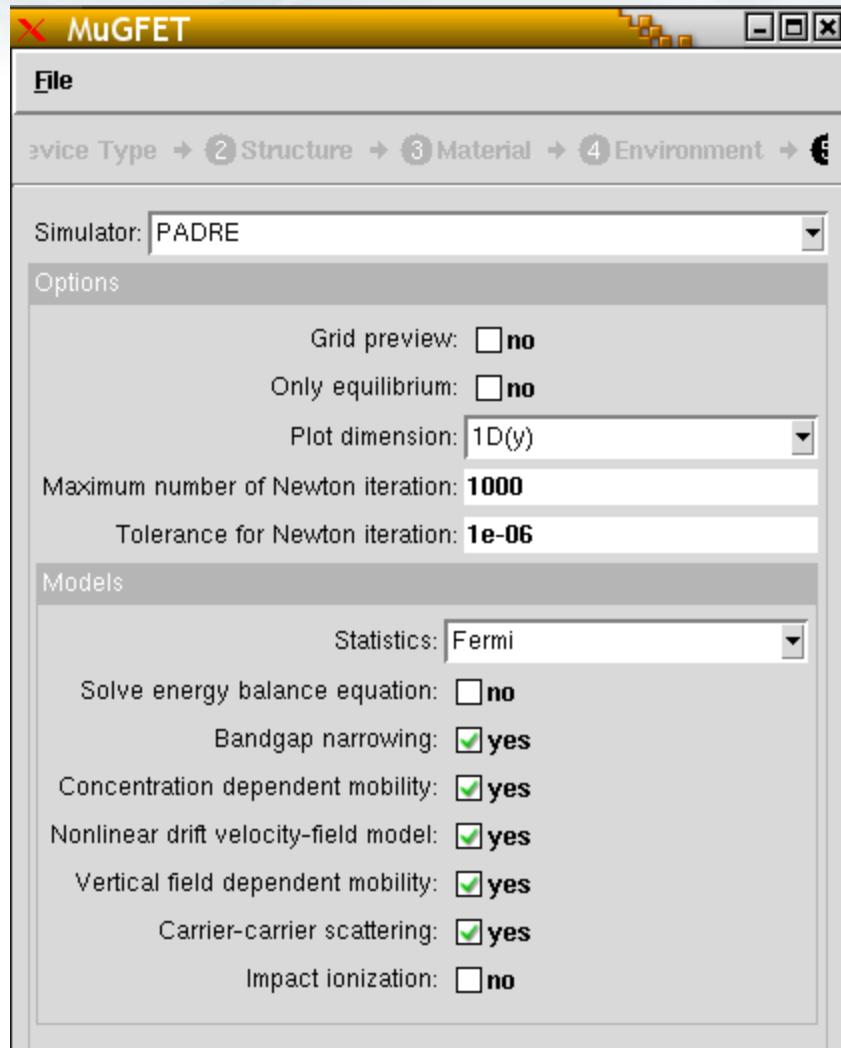
(for convergence of the continuity equation and the Poisson equation)

- » Maximum number of iteration
- » Tolerance

- Models

- » Quantum correction
- » Lombardi's transverse field dependent mobility model**

Simulator Options - PADRE



- Grid Preview

 - » The mesh structure can be seen before running the simulation.

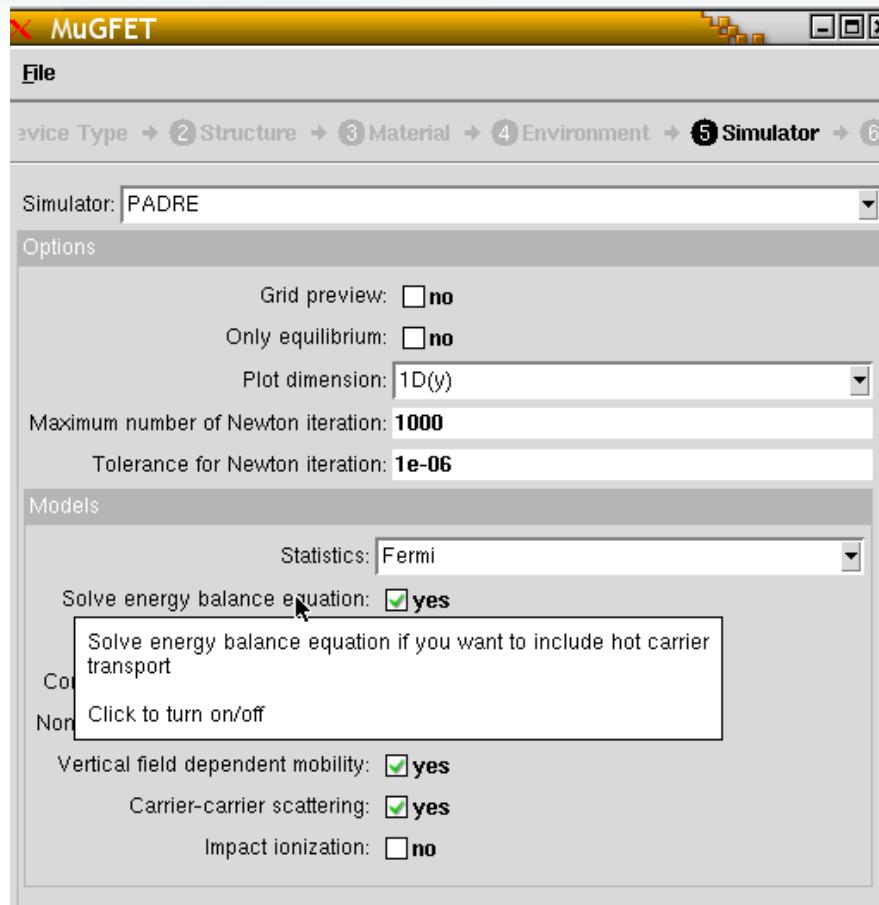
- *Models

 - » Statistics: Fermi or Boltzmann
 - » Energy balance equation
 - ✓ Includes the solve energy balance equation for the hot transport
 - » Bandgap narrowing
 - » Concentration dependent mobility
 - » Nonlinear drift velocity field model
 - » Vertical field dependent mobility model
 - » Carrier carrier scattering model
 - » Impact ionization

*http://www.nanohub.org/resource_files/tools/padre/doc/padre-ref/models.html

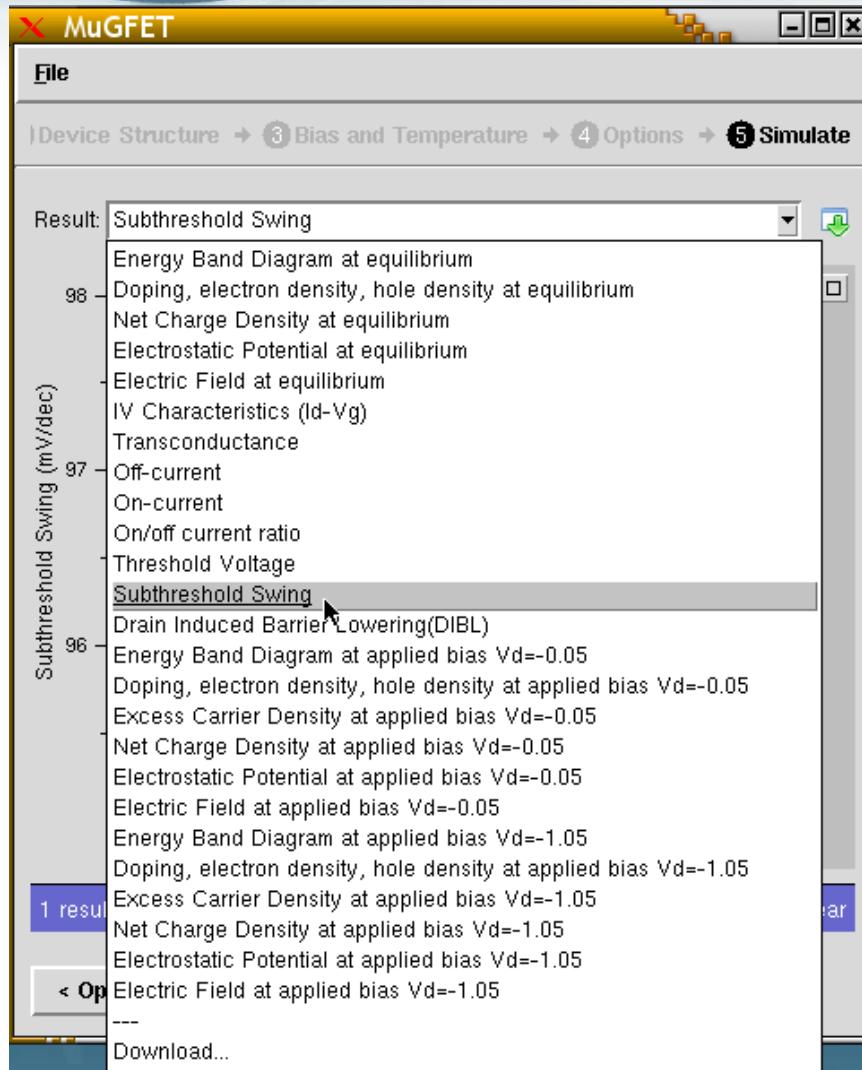
*<http://www.nanohub.org/resources/1514/>

PADRE Option - energy balance equation



- When the energy balance equation is selected for solving, the continuity equation, Poisson equation, and energy balance equation are coupled to each other and solved independently.
- The equations do not easily converge, when the energy balance equation is selected.
- The bias steps should be small when solving energy the balance equation.
- Sometimes it is best not to choose a wide range of bias.
- A good strategy is to start from zero bias and increase it gradually.

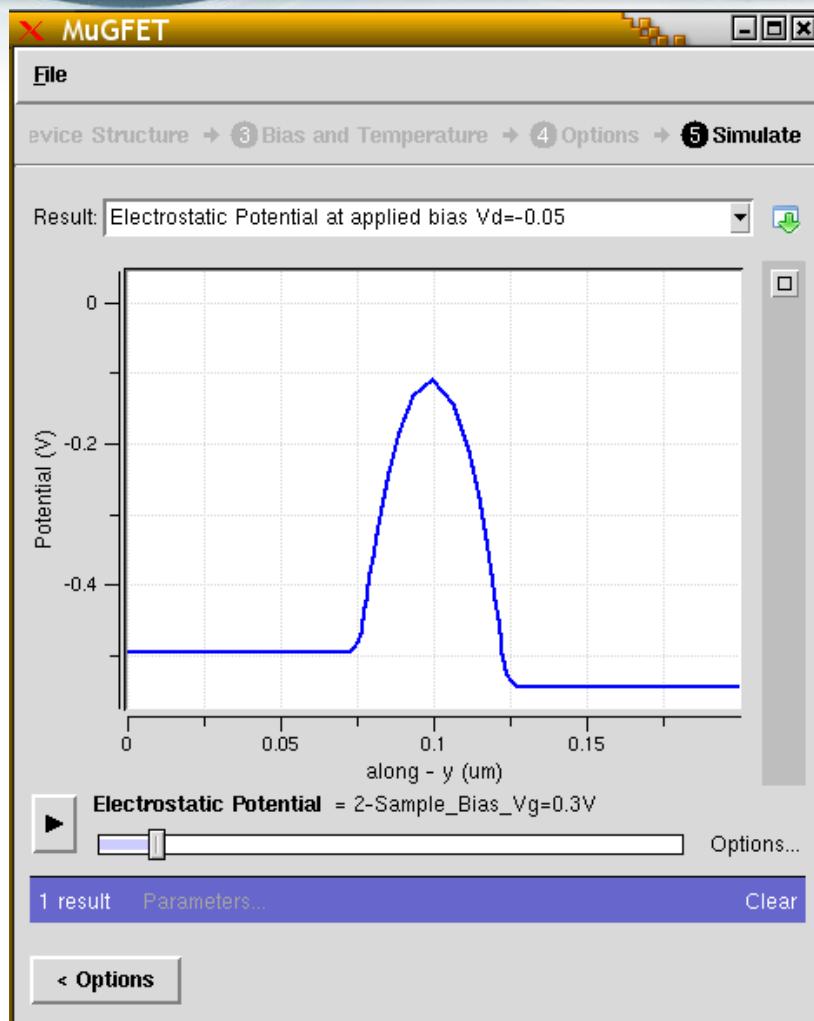
Useful Plots for Device Design (input)



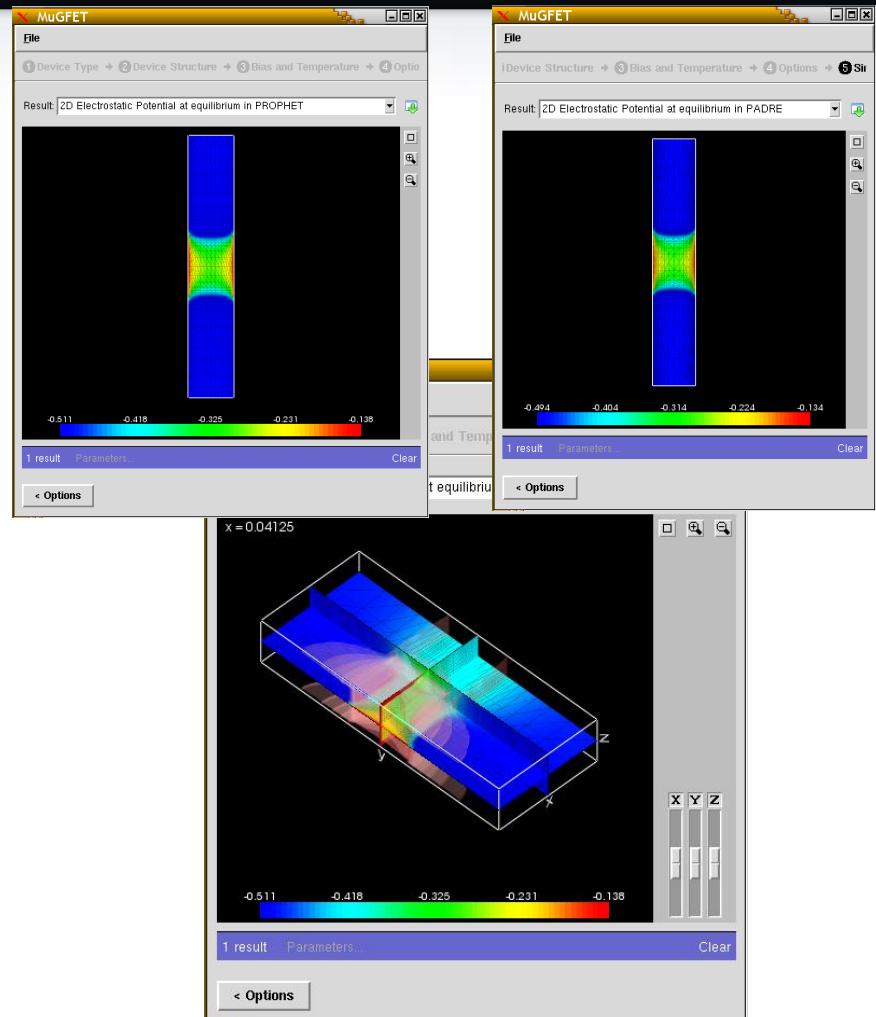
- IV characteristics
- Threshold voltage
- Subthreshold swing
- Transconductance
- Drain induced barrier lowering(DIBL)
- On/off current and its ratio
- Doping, electron, hole density
- Electrostatic potential
- Energy band diagram*
- Net charge density*
- Electric field*

*These plots are supported only in PADRE

Plots

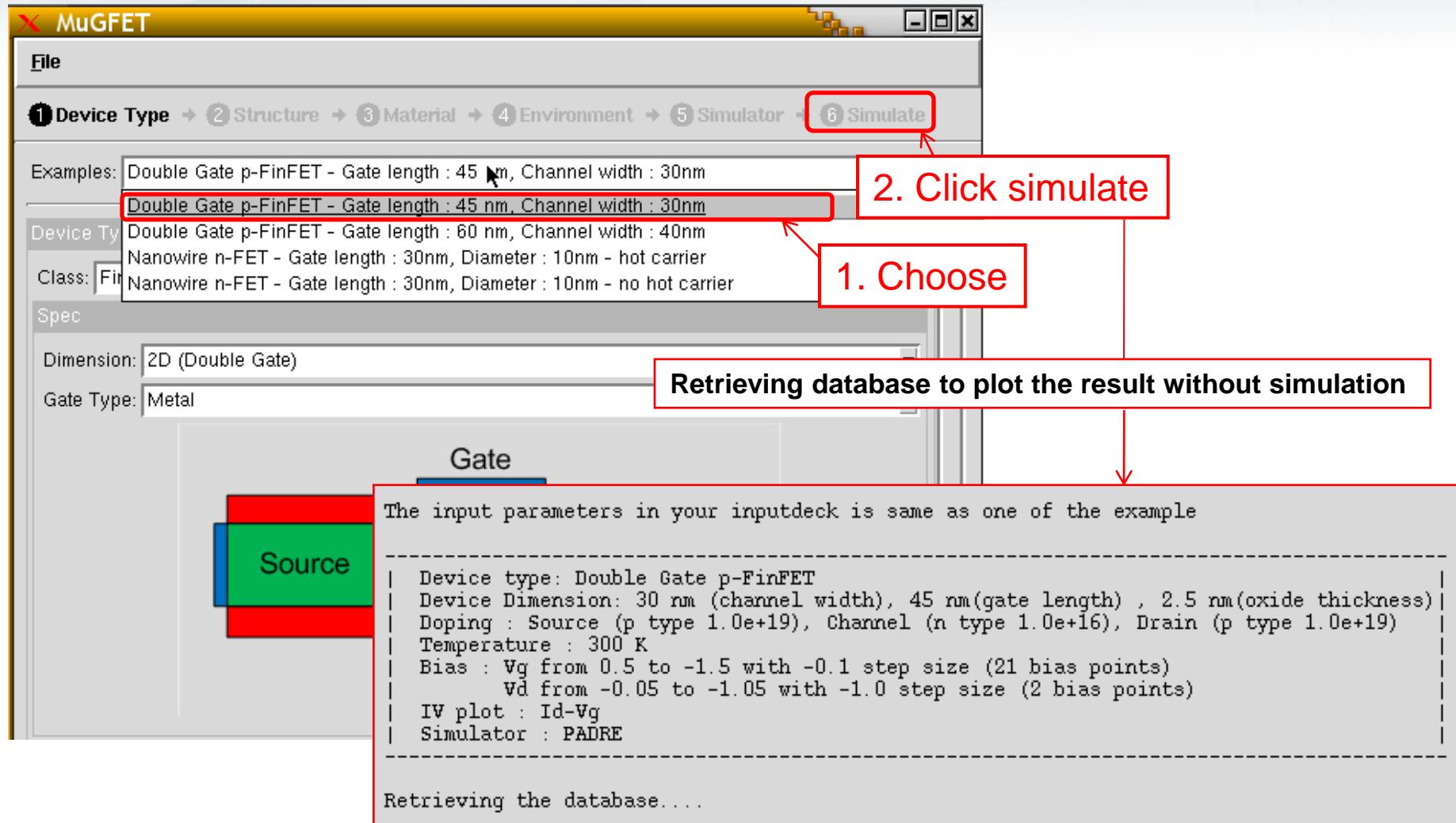


Sequence plot for applied bias

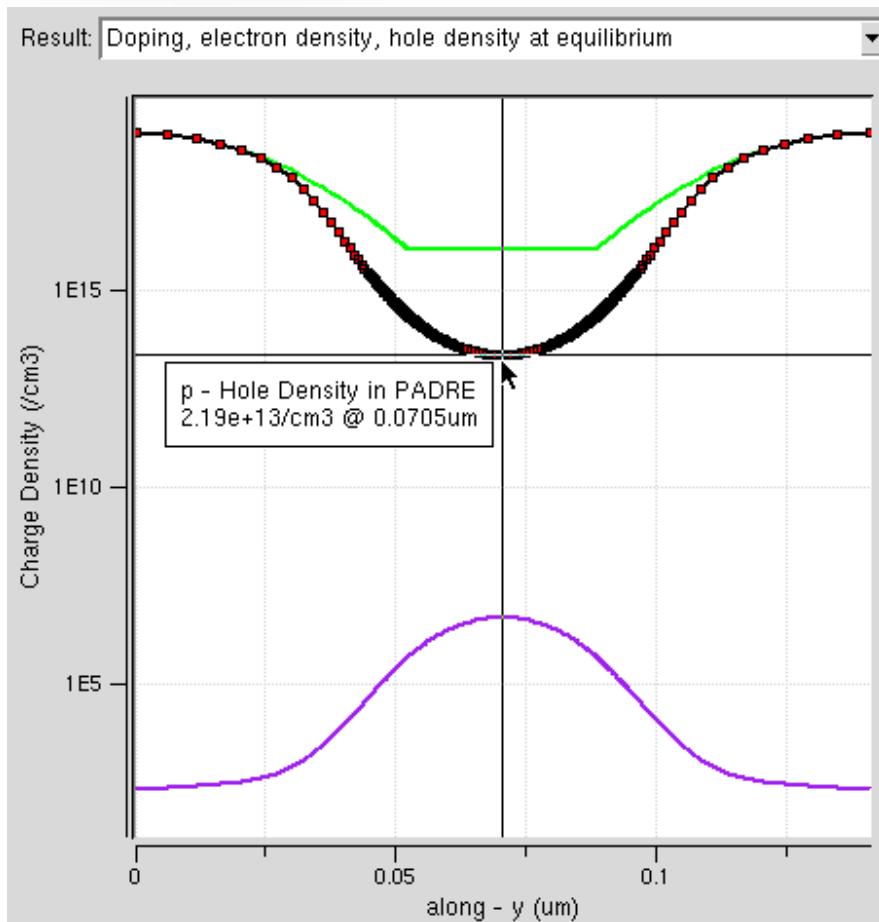


3D plots are available but appear more slowly

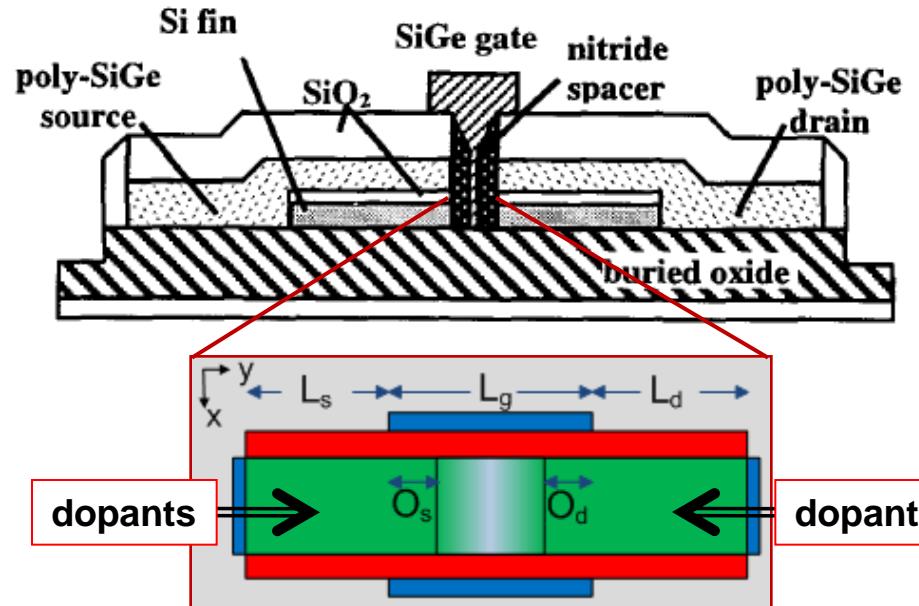
What if You Just Hit “Simulate” ?



Example p-finFET Lg=45nm, Wch=30nm, tox=2.5nm*



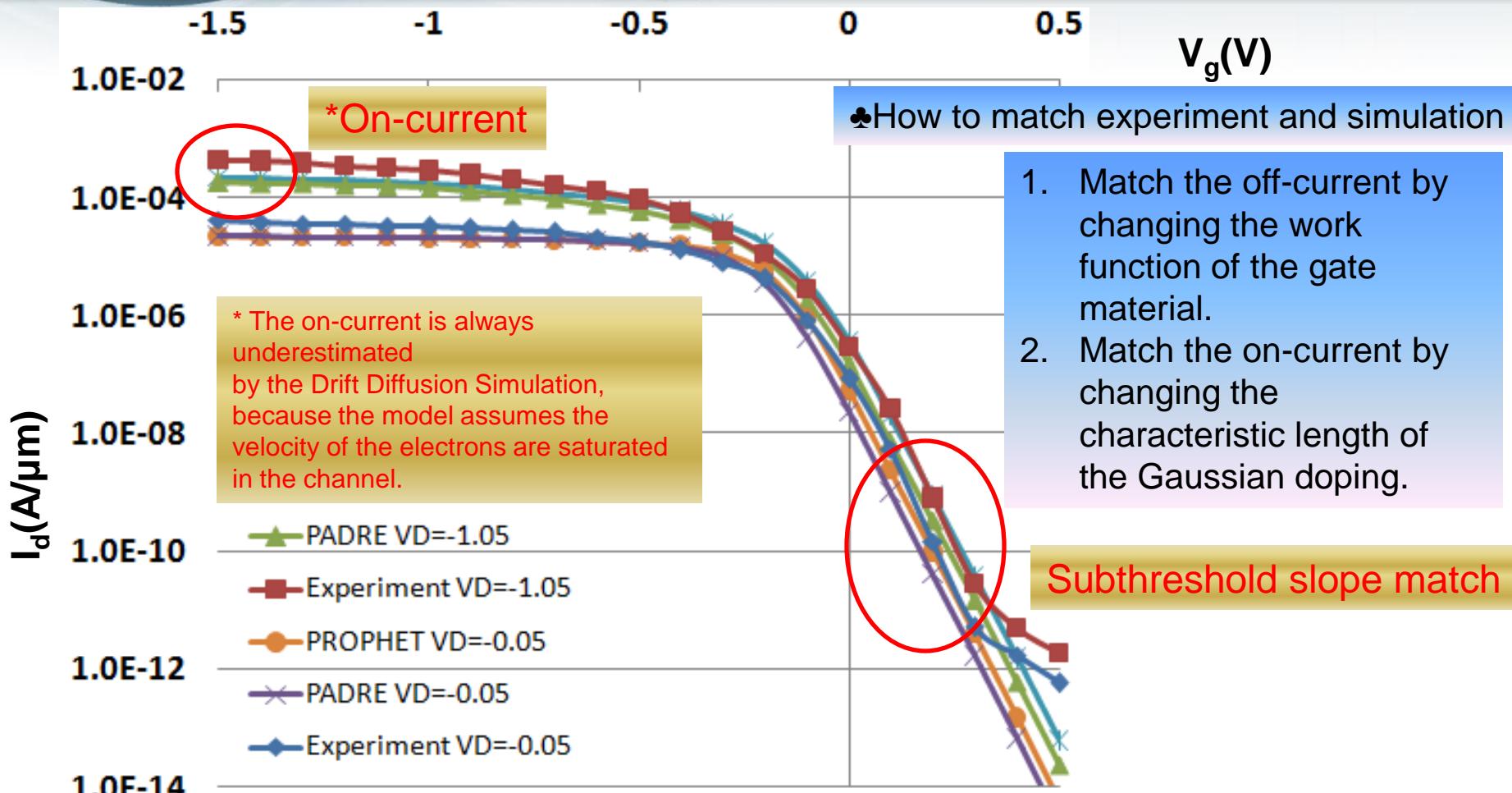
- The primitive finFET structure
- Gaussian doping - using raised source and drain, dopants diffused to the source and drain extension region



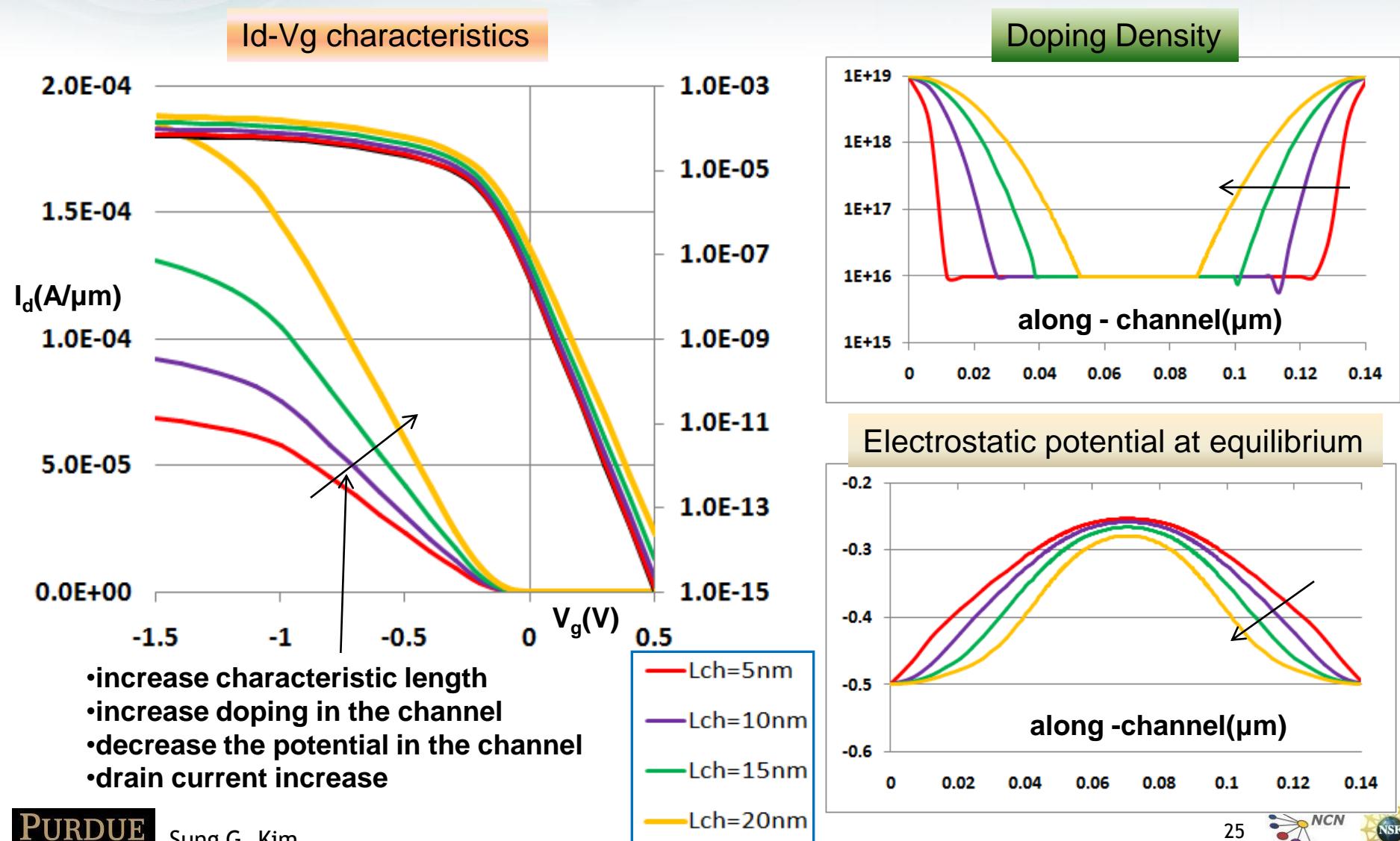
- L_s and L_d (source/drain extension length) is same as spacer width.

*Sub 50-nm finFET: PMOS - Huang, et al., IEDM, 1999

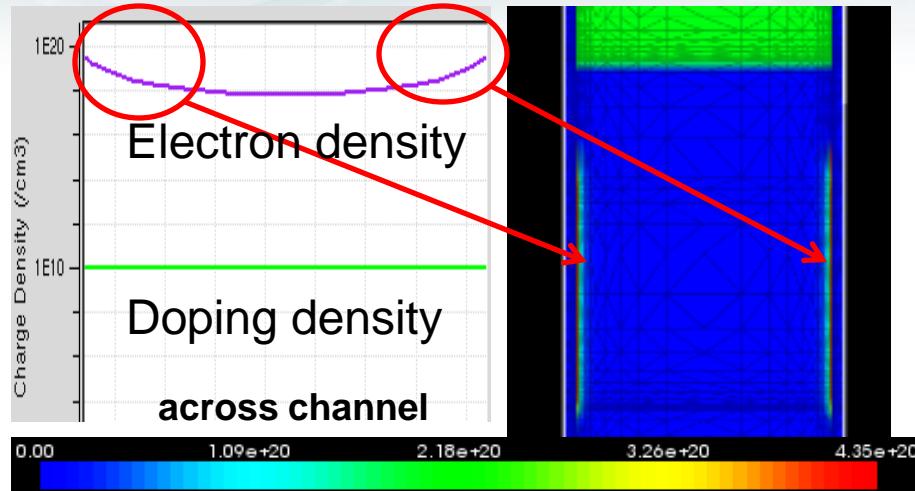
Simulation - Experiment Result Comparison Id-Vg



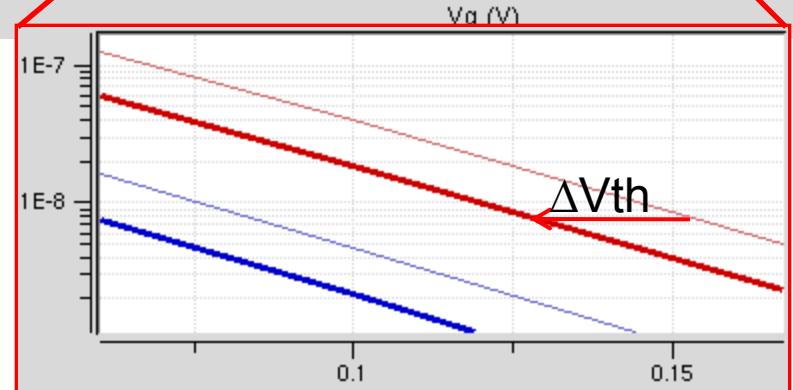
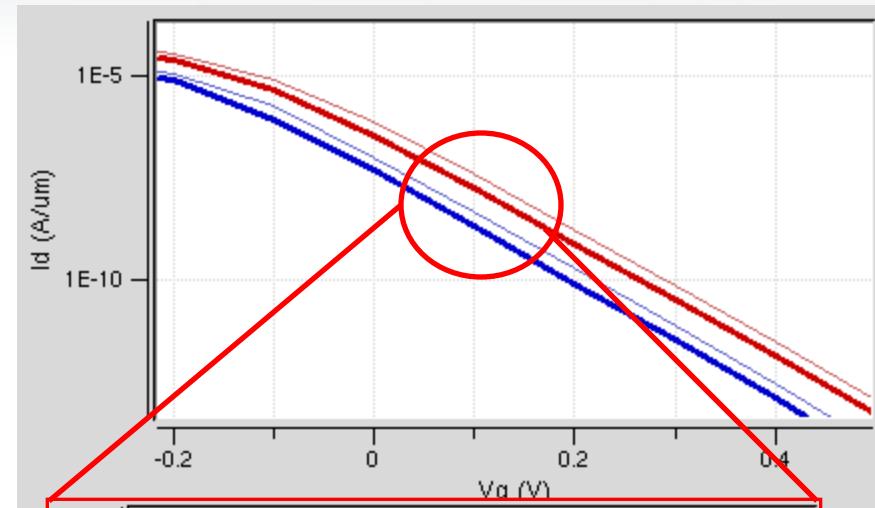
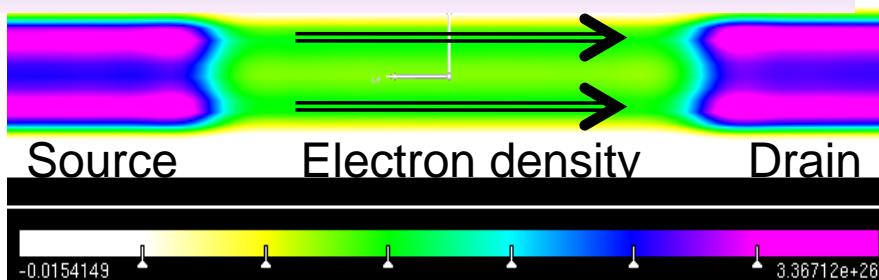
Effect of Gaussian Doping Profile



Channel Formation - Quantum Correction



In PADRE and PROPHET, the inversion charges are at the surface of the channel

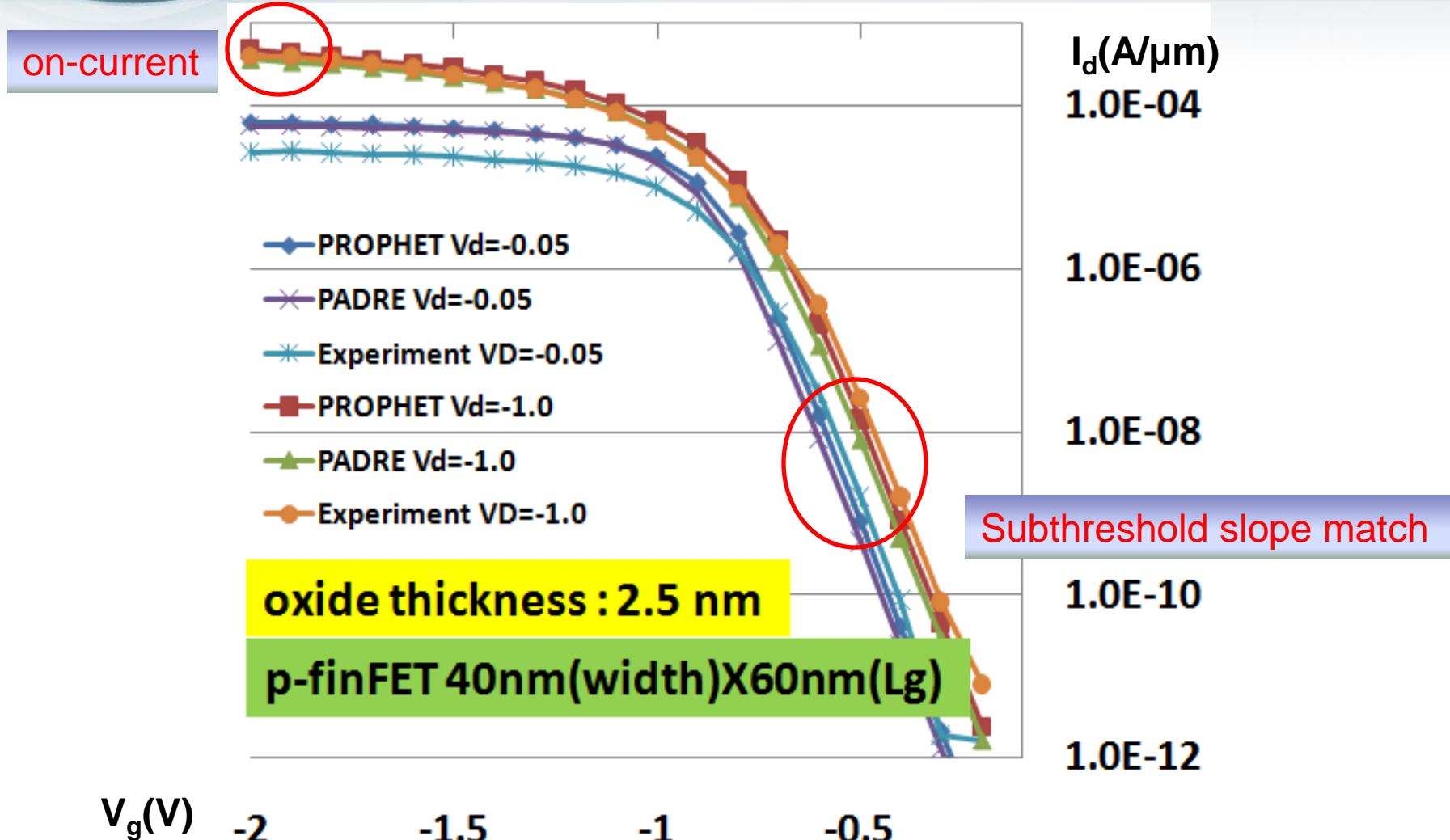


In reality, because of the quantum effect, the carriers flow at a distance from the surface → threshold voltage changes

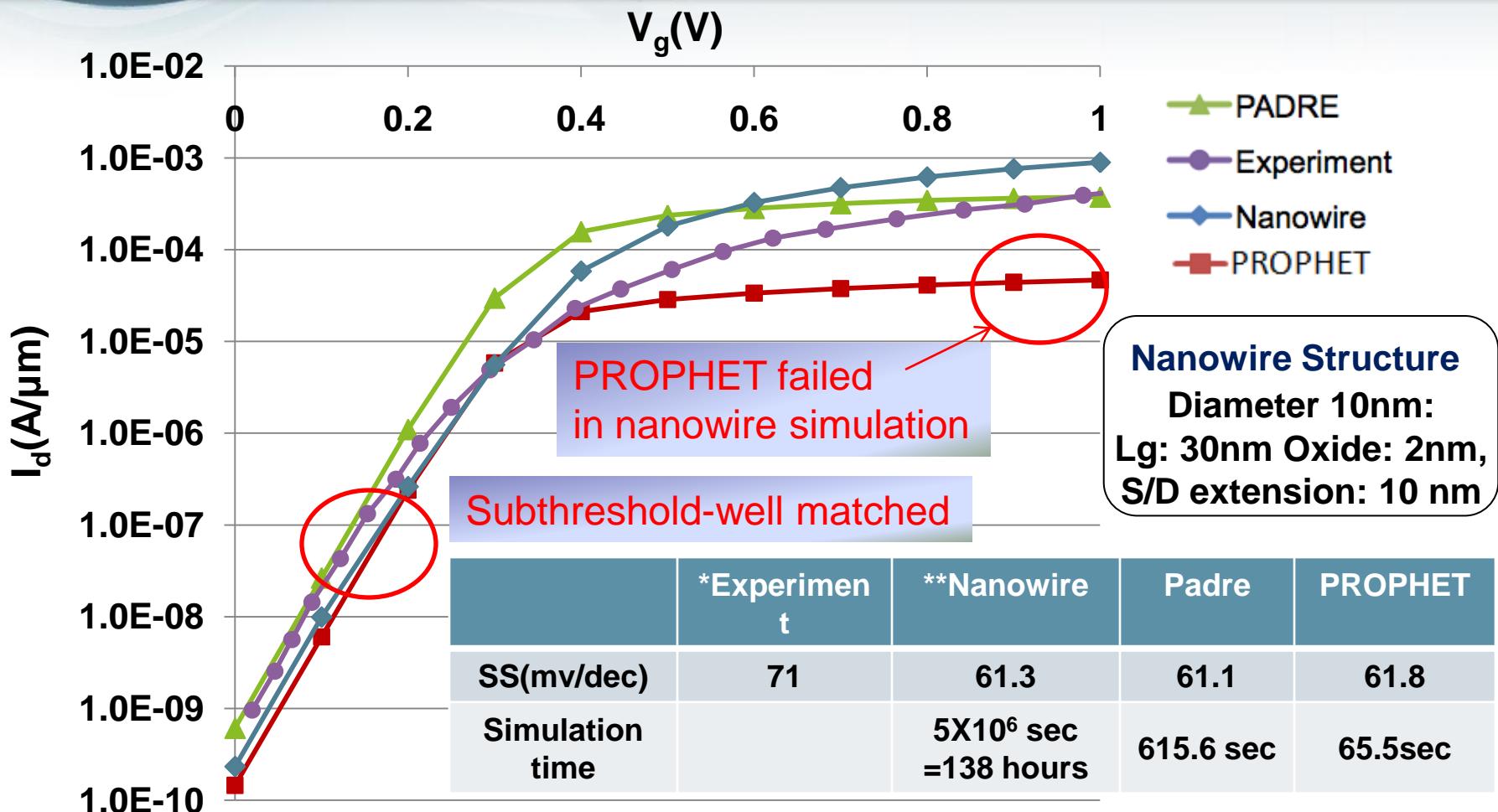
Drain Current Normalization

- Normalization of Id (finFET)
 - » Normalization to the fin height
 - ✓ This is the same as the conventional normalization, as based on the width of the channel (PADRE and PROPHET).
 - » Normalization to the fin height *2
 - ✓ Multiply 2, due to the channel formation in both of the side walls.
- Comparison with experiment
 - » Divide 2 to the PADRE and PROPHET result, if the experimental result uses normalization to the fin height *2.
- Normalization of Id (nanowireFET)
 - » The drain current is sometimes normalized to the diameter in experiment.
 - » The drain current in PADRE and PROPHET is not normalized.
- Comparison with experiment
 - » Divide by the diameter to the PADRE and PROPHET results.
 - » Change the units to $A/\mu m$ or $\mu A/\mu m$

Example p-finFET Lg=60nm, Wch=40nm, tox=2.5nm**



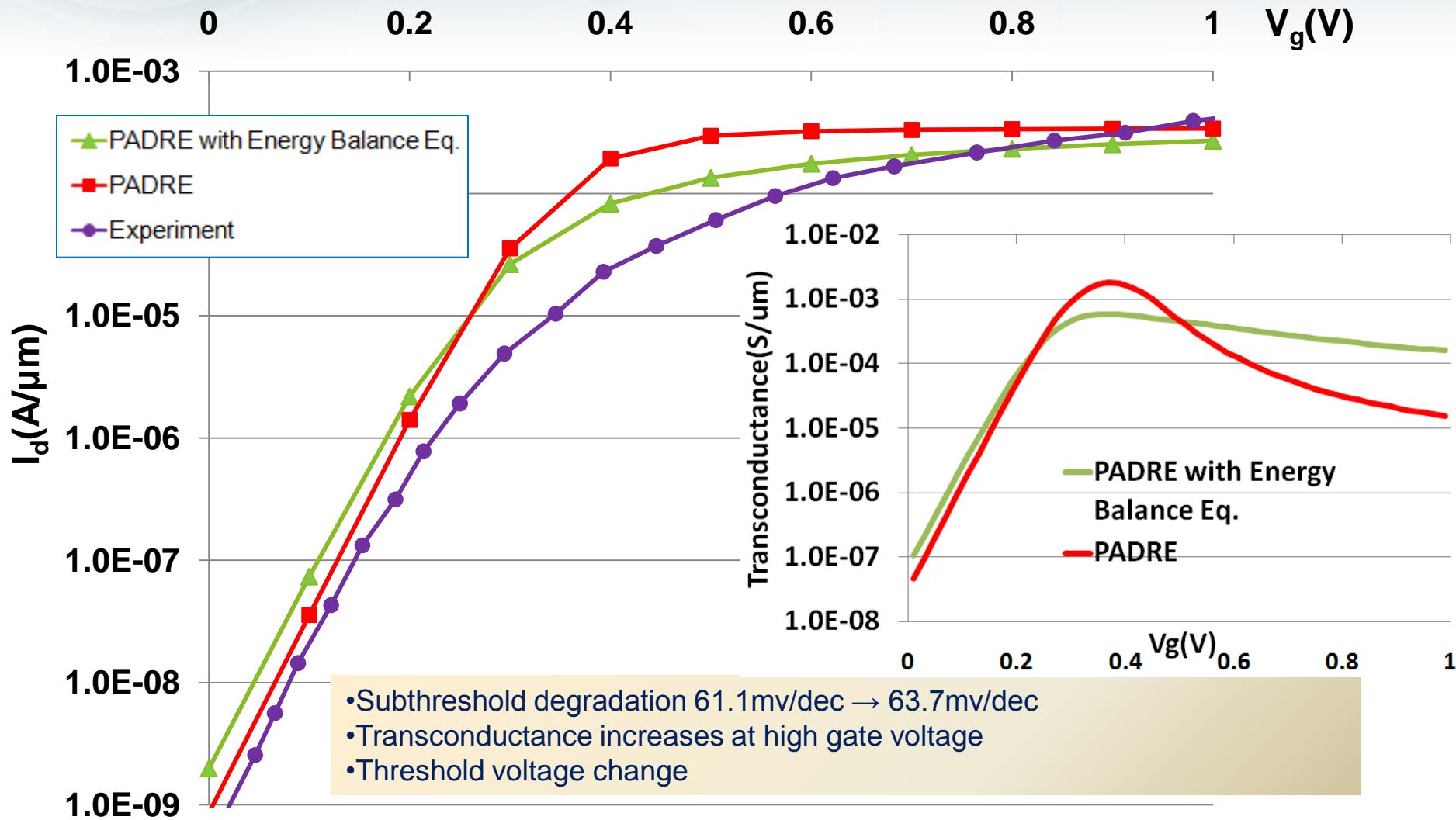
Example - Nanowire



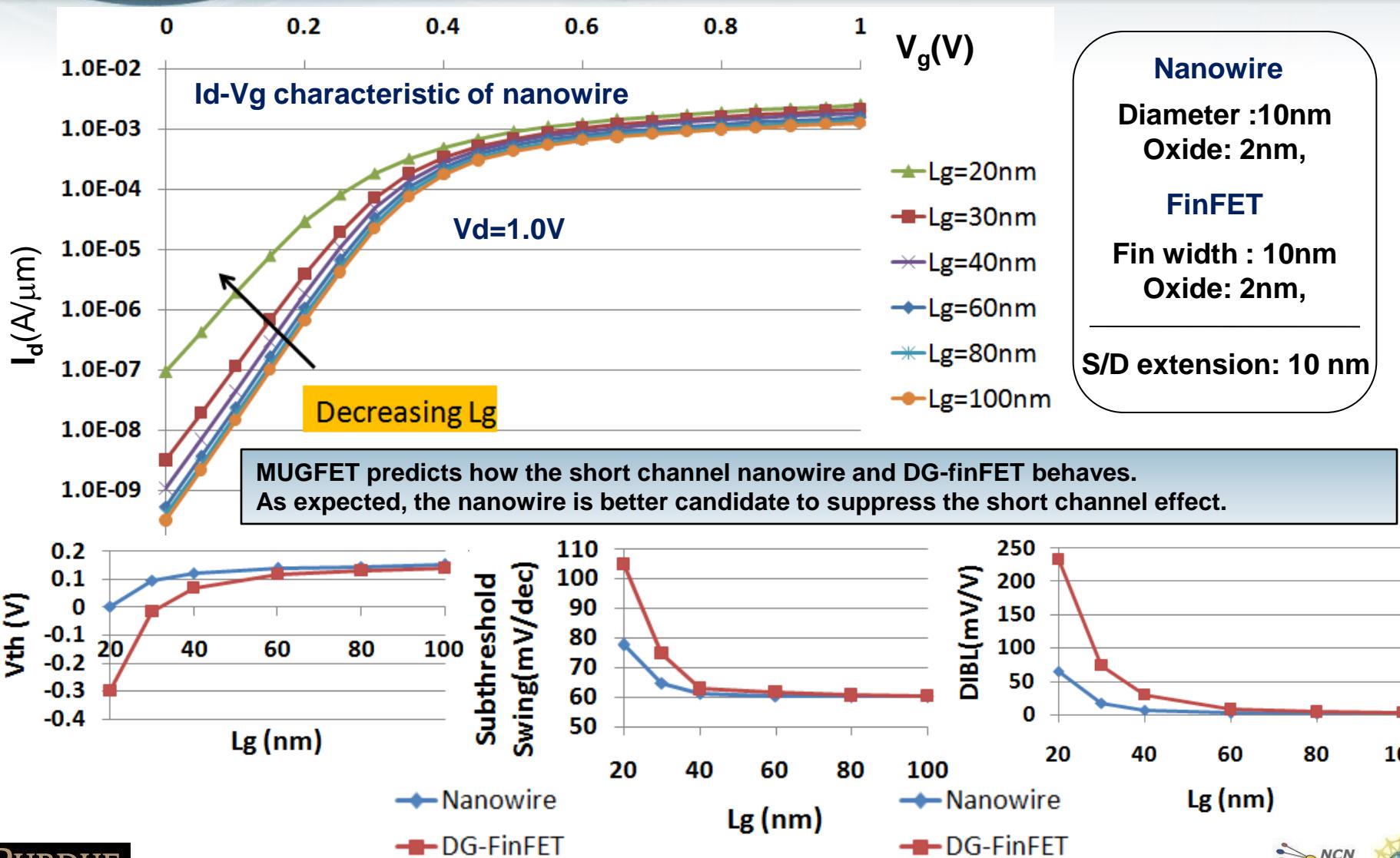
* Experiment - Sung DaeSuk, et al.,
 IEDM 2005, pp 717-720, Dec 2005

** Nanowire - quantum ballistic transport simulation tool
 for nanowire structure - available in nanoHUB.org

Example - Hot Carrier Transport Effect (Velocity Overshoot)



Short Channel Effect - Nanowire/DG-finFET Comparison



Summary

- The drift-diffusion simulator **MuGFET** using PROPHET and PADRE is upgraded to v1.1
- I have included the energy balance equation option to demonstrate the hot carrier effect on transport.
- The input interface has been upgraded for user's convenience.
- So that the Gaussian doping profile will be more realistic, I have upgraded it.

Final Thoughts

Possible Future Work Being Considered:

- » 3D visualization (open DX)
- » Refinement of 3D simulation
- » Process simulation using PROPHET to feed in the result to PADRE
 - realistic doping and geometry
- » AC response in PADRE
- » Quantum correction is already implemented
 - density gradient model in PROPHET
 - balance equation model into PROPHET?
- » Parallelization → new code?
- » Modified drift diffusion model