Introduction to Technology Computer Aided Design (TCAD)

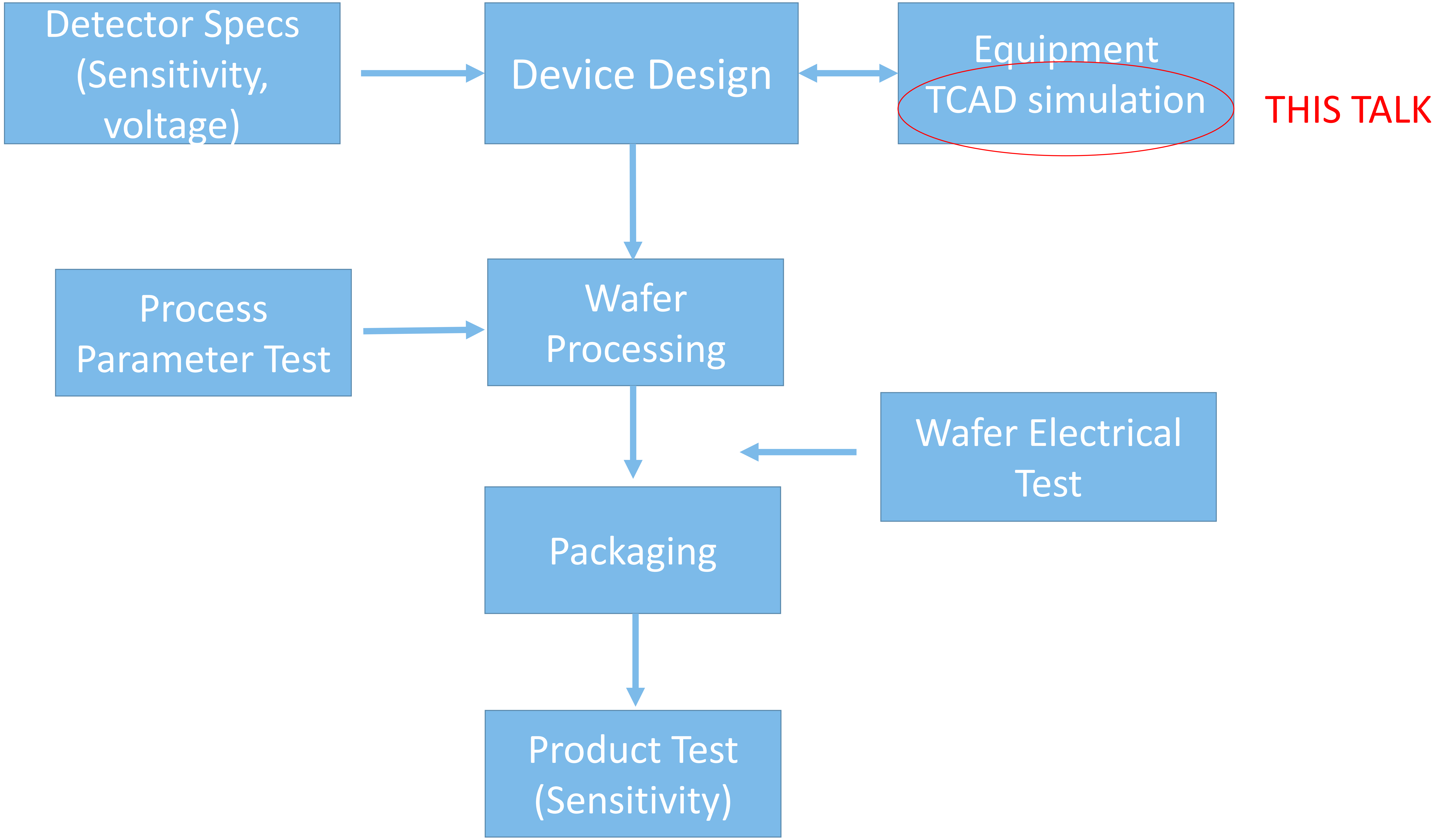
Russell Duane

Outline

- What is Technology Computer Aided Design (TCAD)?
  - Semiconductor Process Simulation
  - Semiconductor Device Simulation

- How does TCAD work?
  - Mesh
  - Models

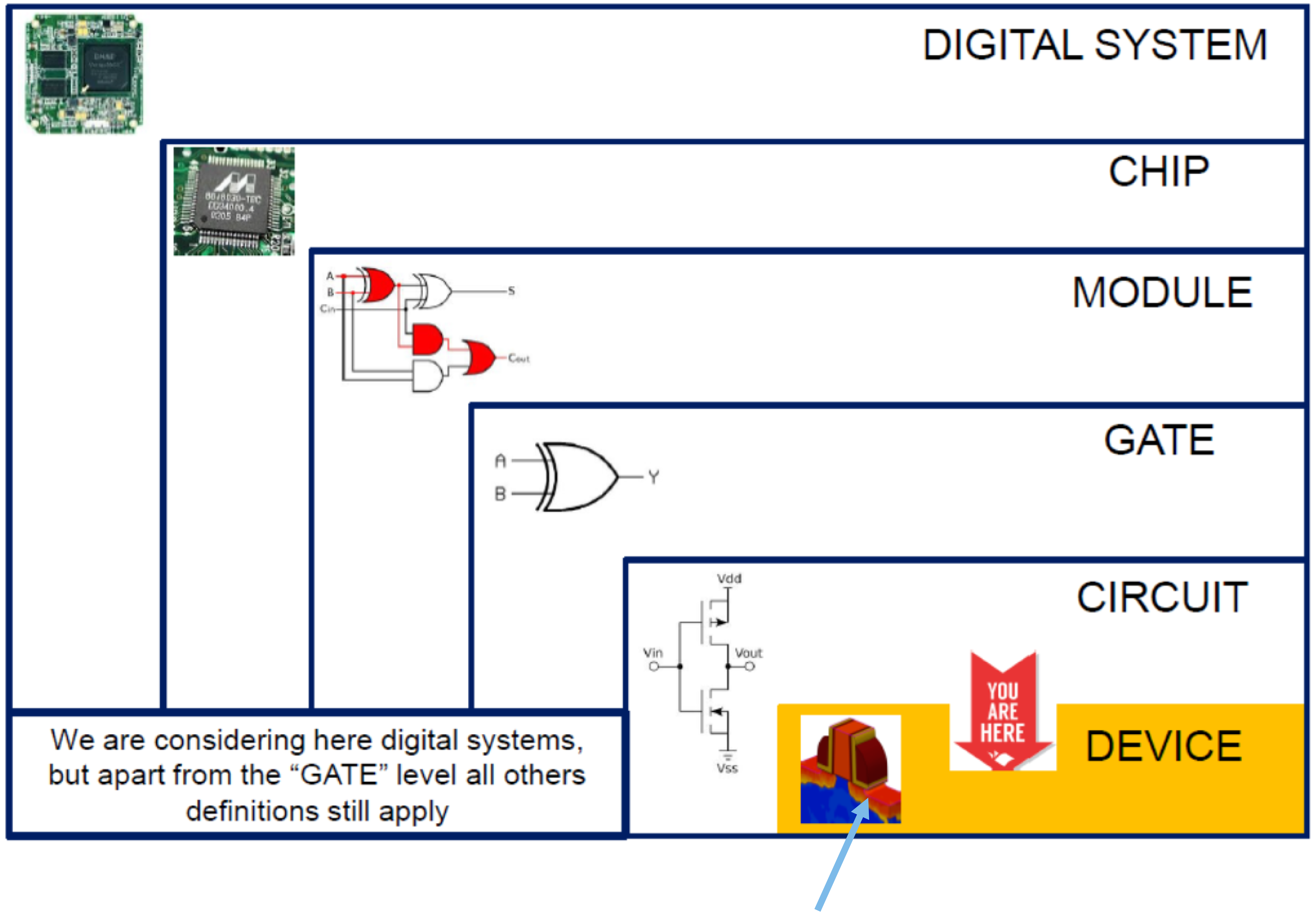
Detector Fabrication



What is Technology Computer Aided Design?

- Number of different TCAD vendors

- SILVACO
- SYNOPSYS
- Coventorware.....



TCAD= Semiconductor Process and Device Simulation

Outline

- What is Technology Computer Aided Design (TCAD)?
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Semiconductor Process Simulation

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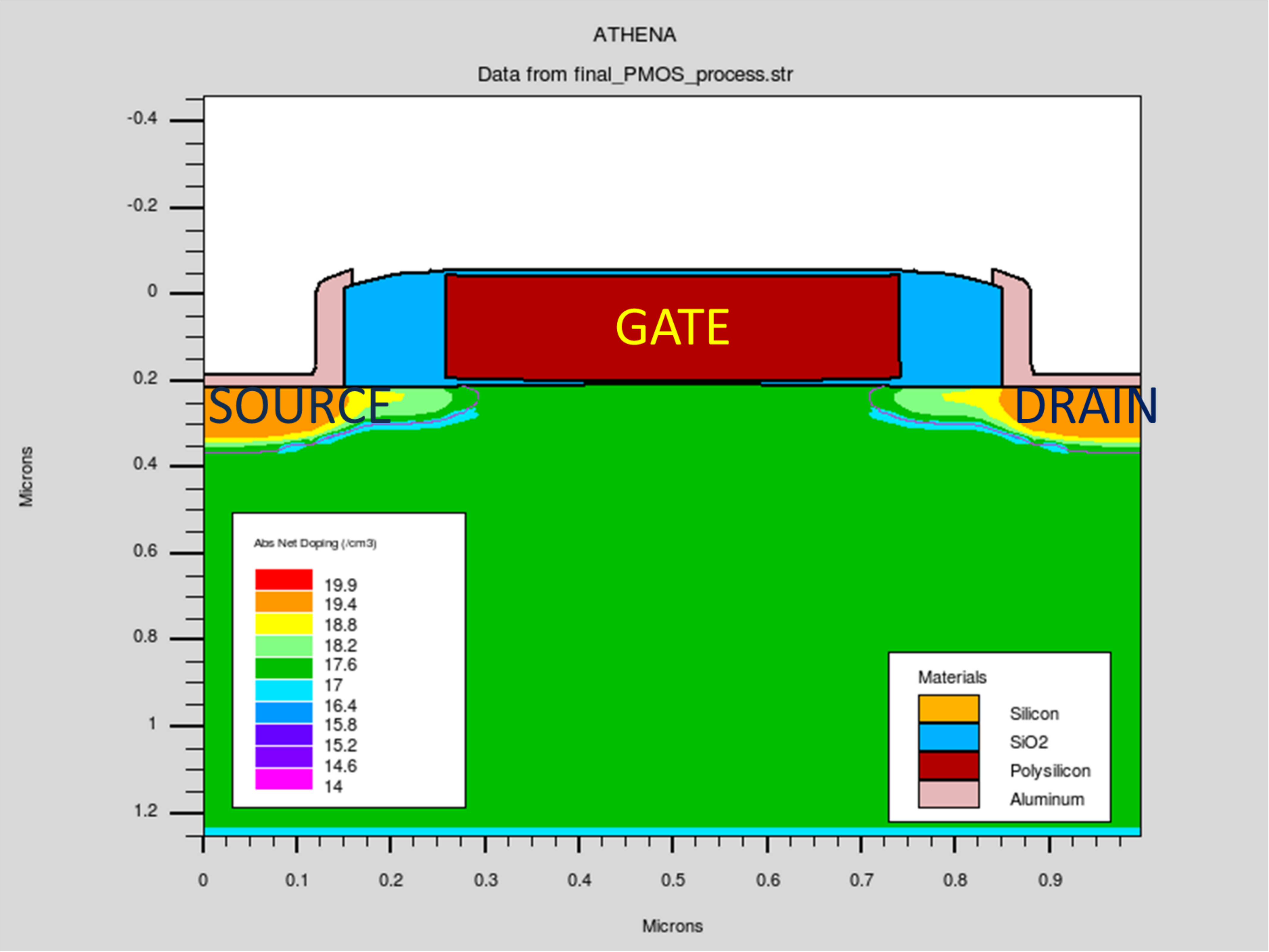
Process Steps

Oxidation Time/Temp
Diffusion Time/Temp
Implant Dose/Energy

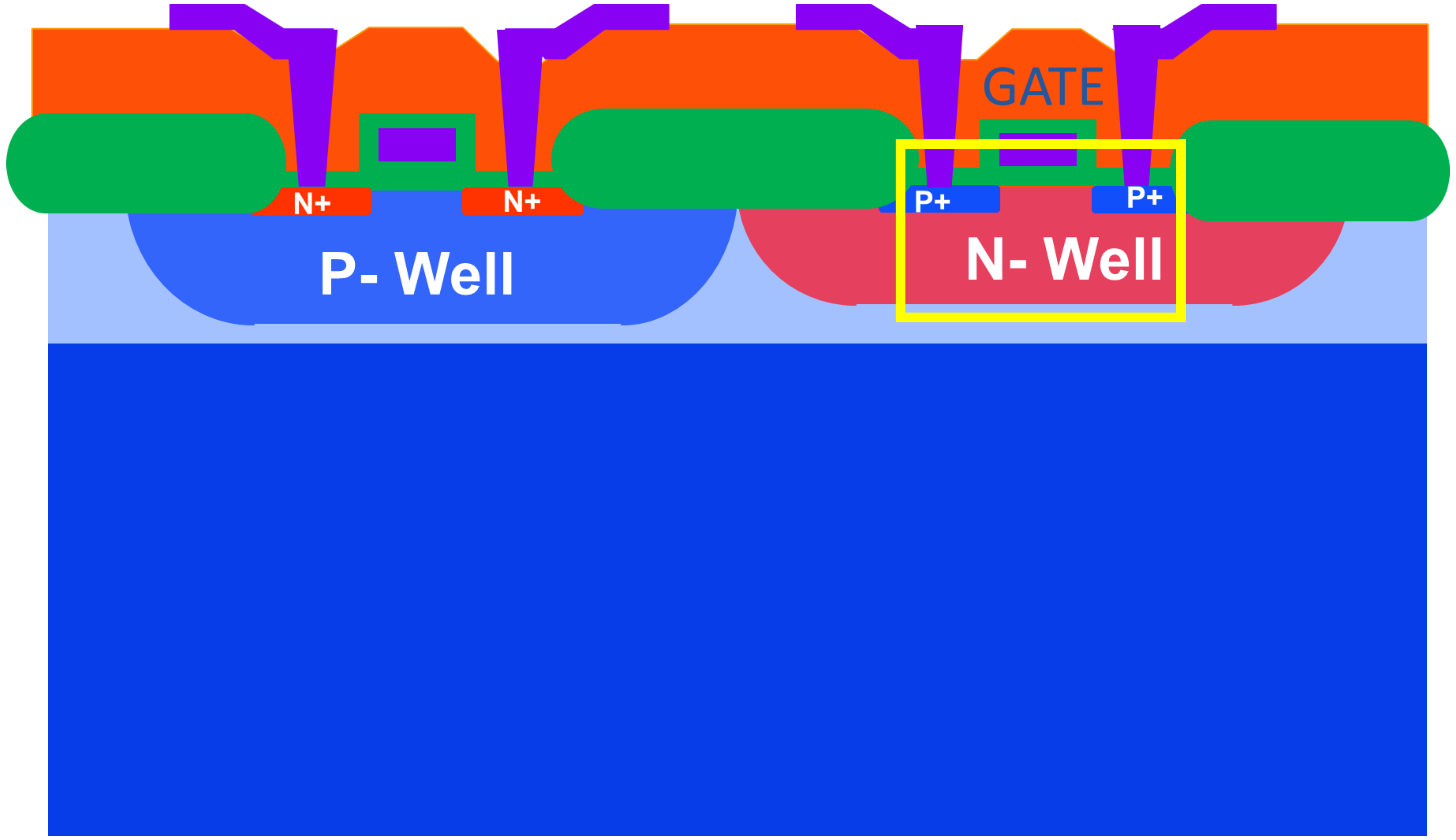
Physics models

Monte Carlo,
Fick's Law …

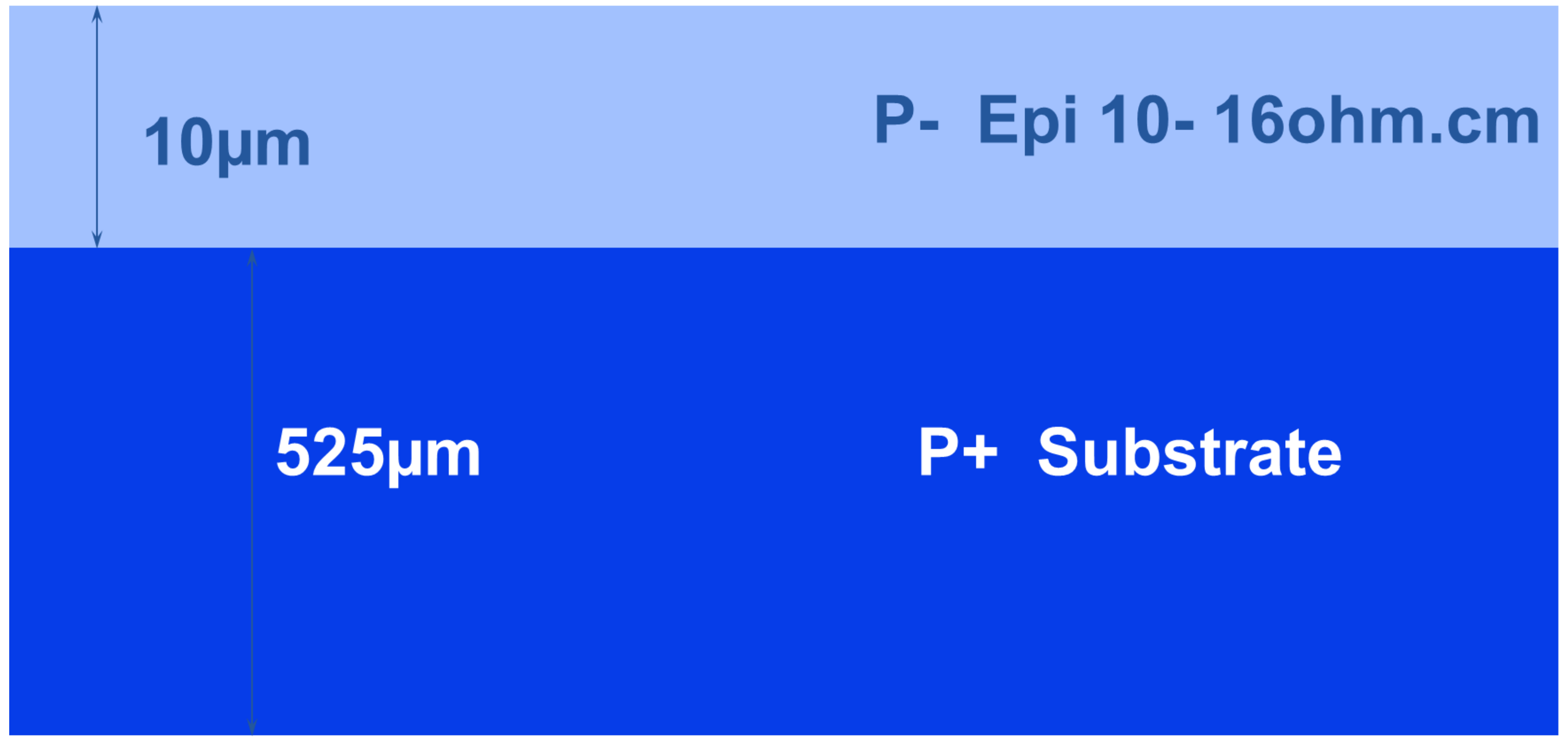


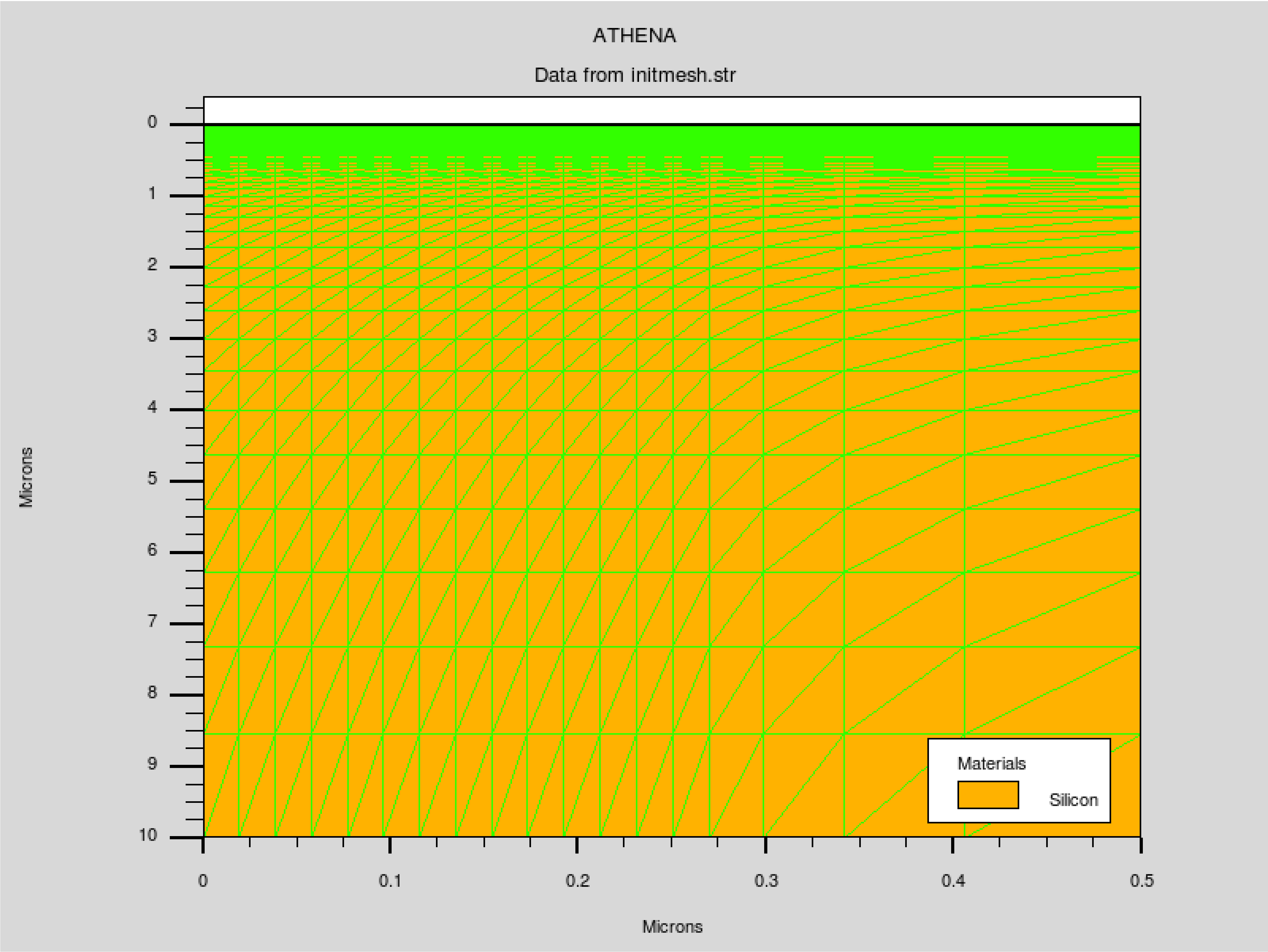
Semiconductor Structure
Dimensions, Materials, Doping levels..

PMOS Transistor

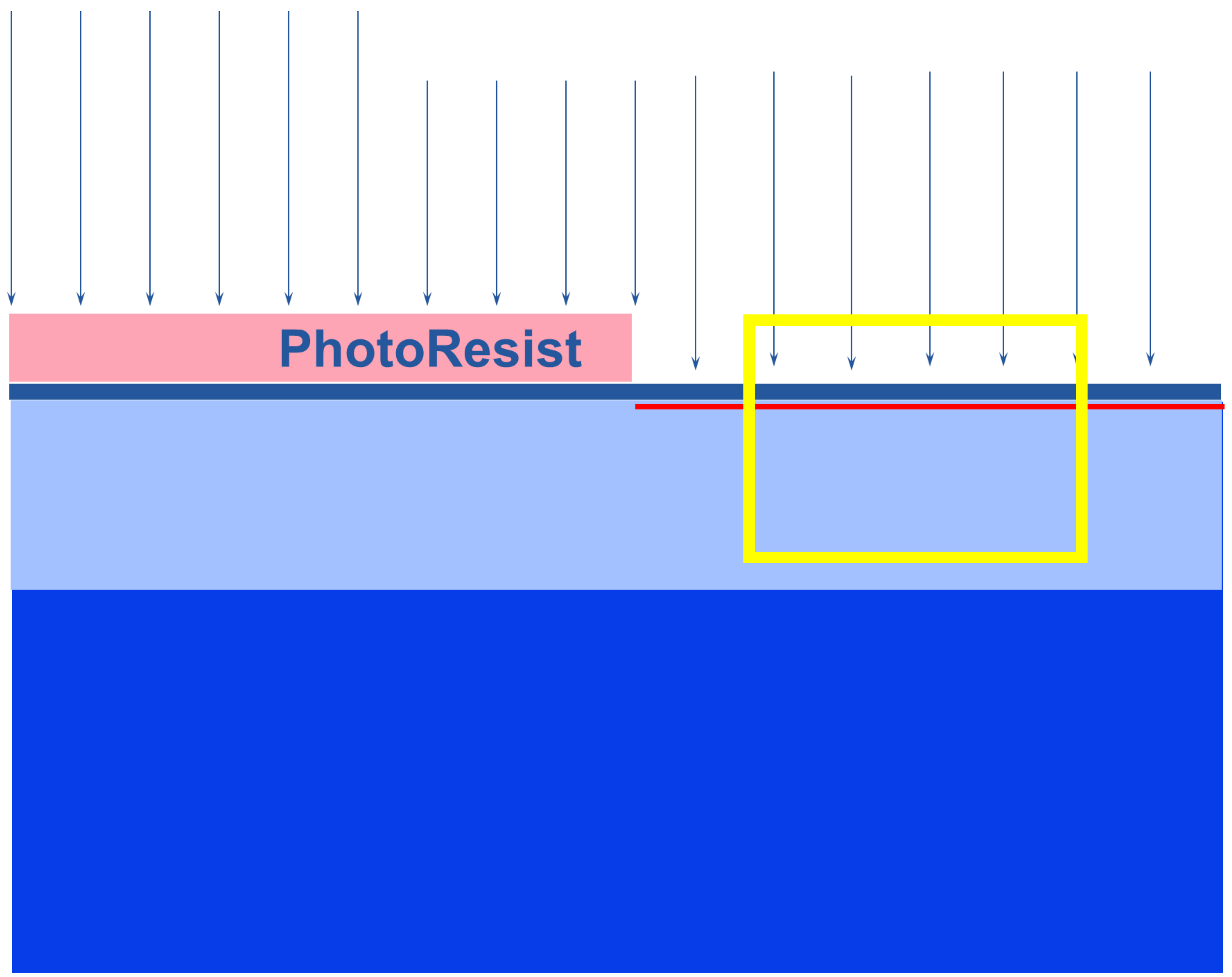


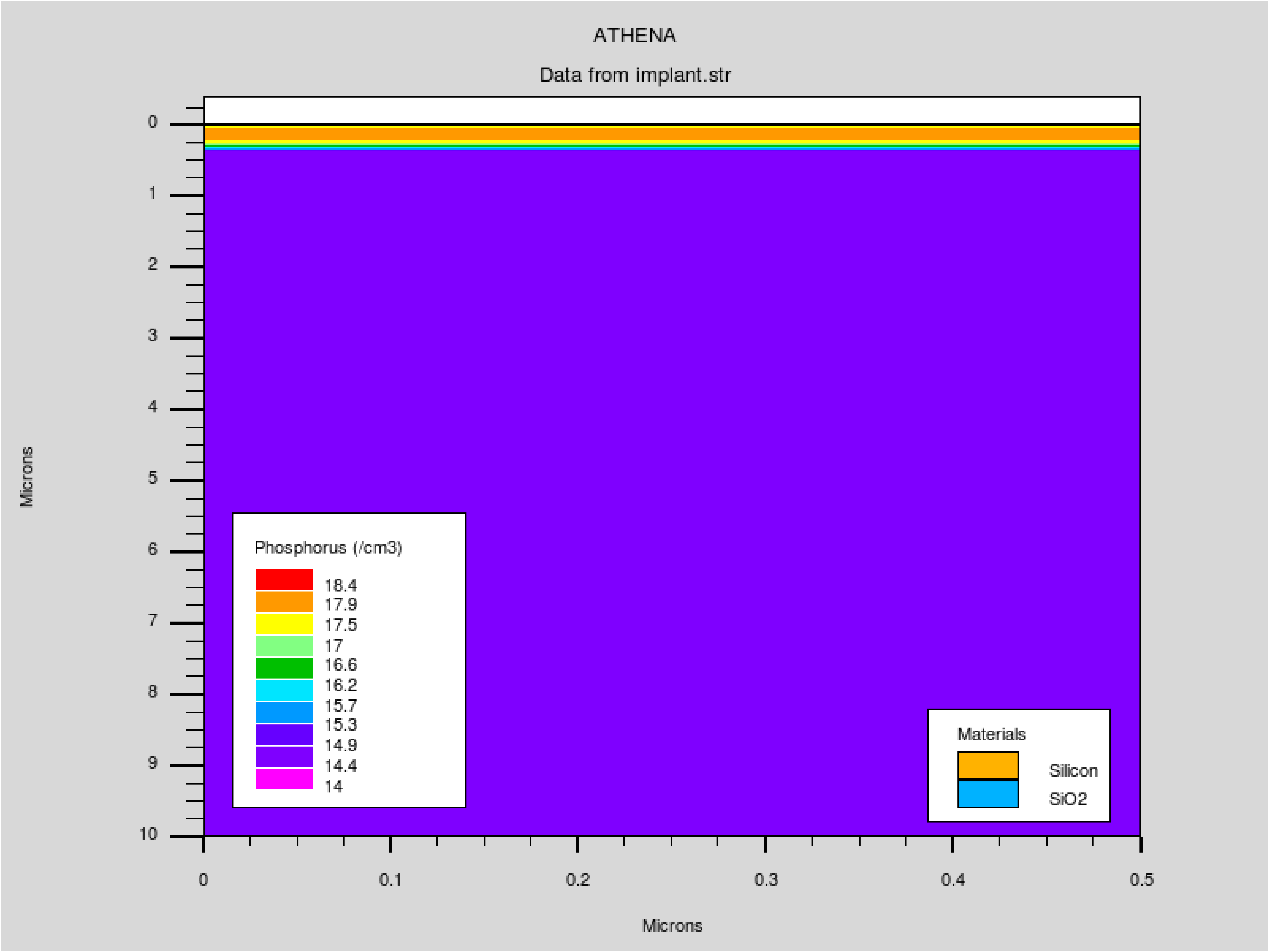
PMOS Major Steps



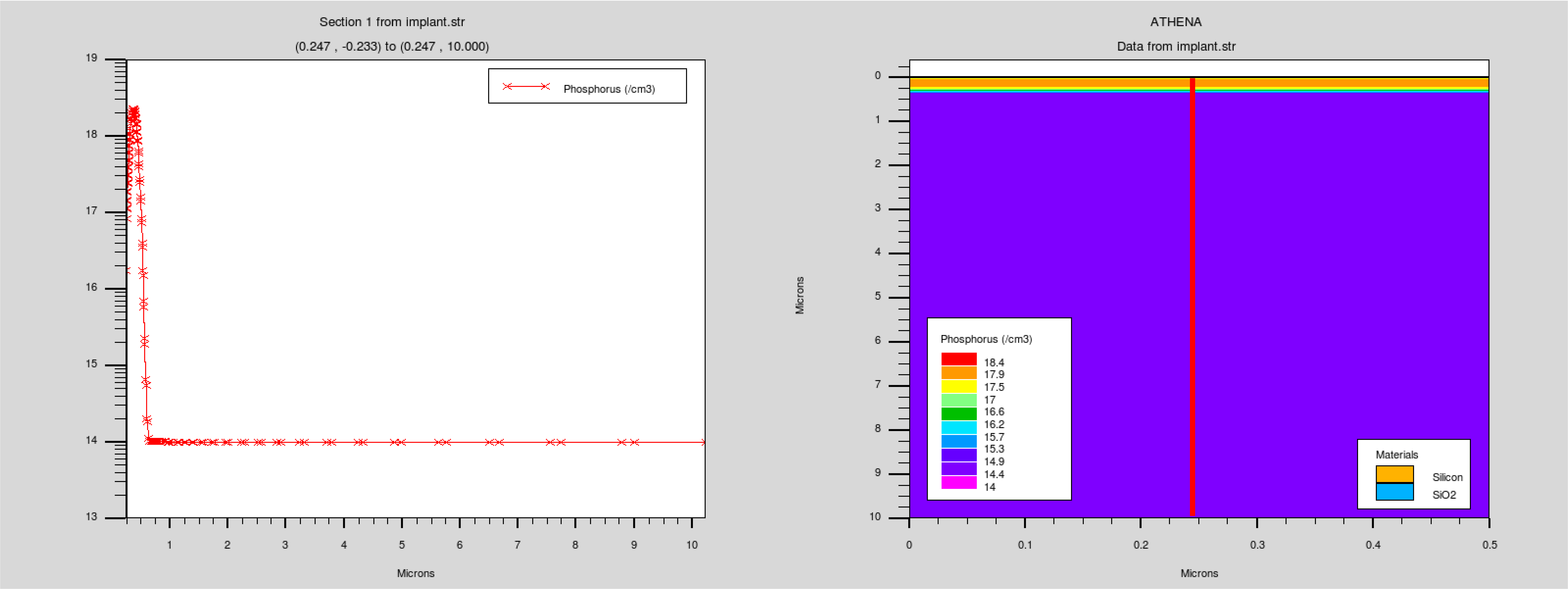


NWELL Phosphorus Implant



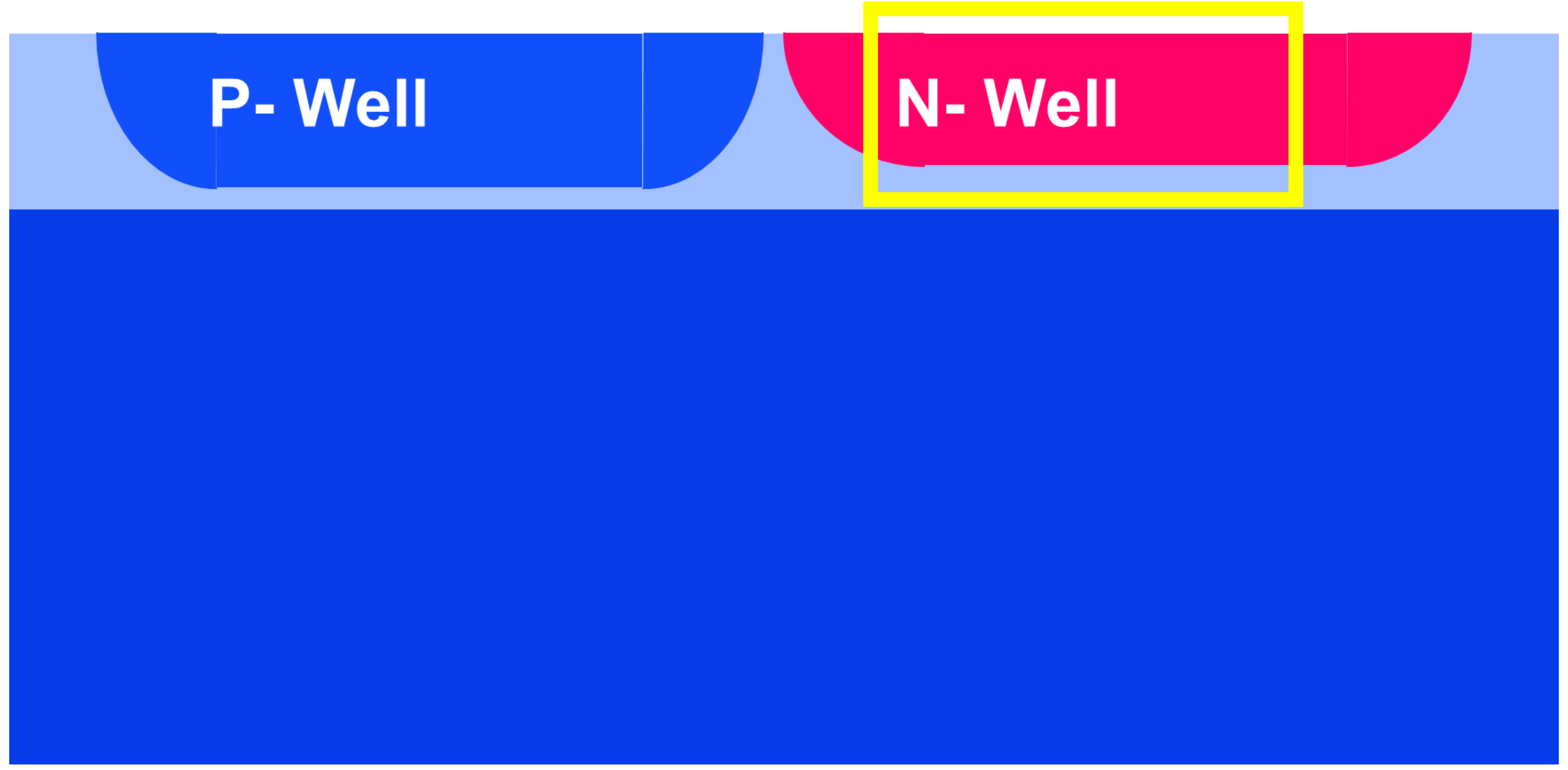


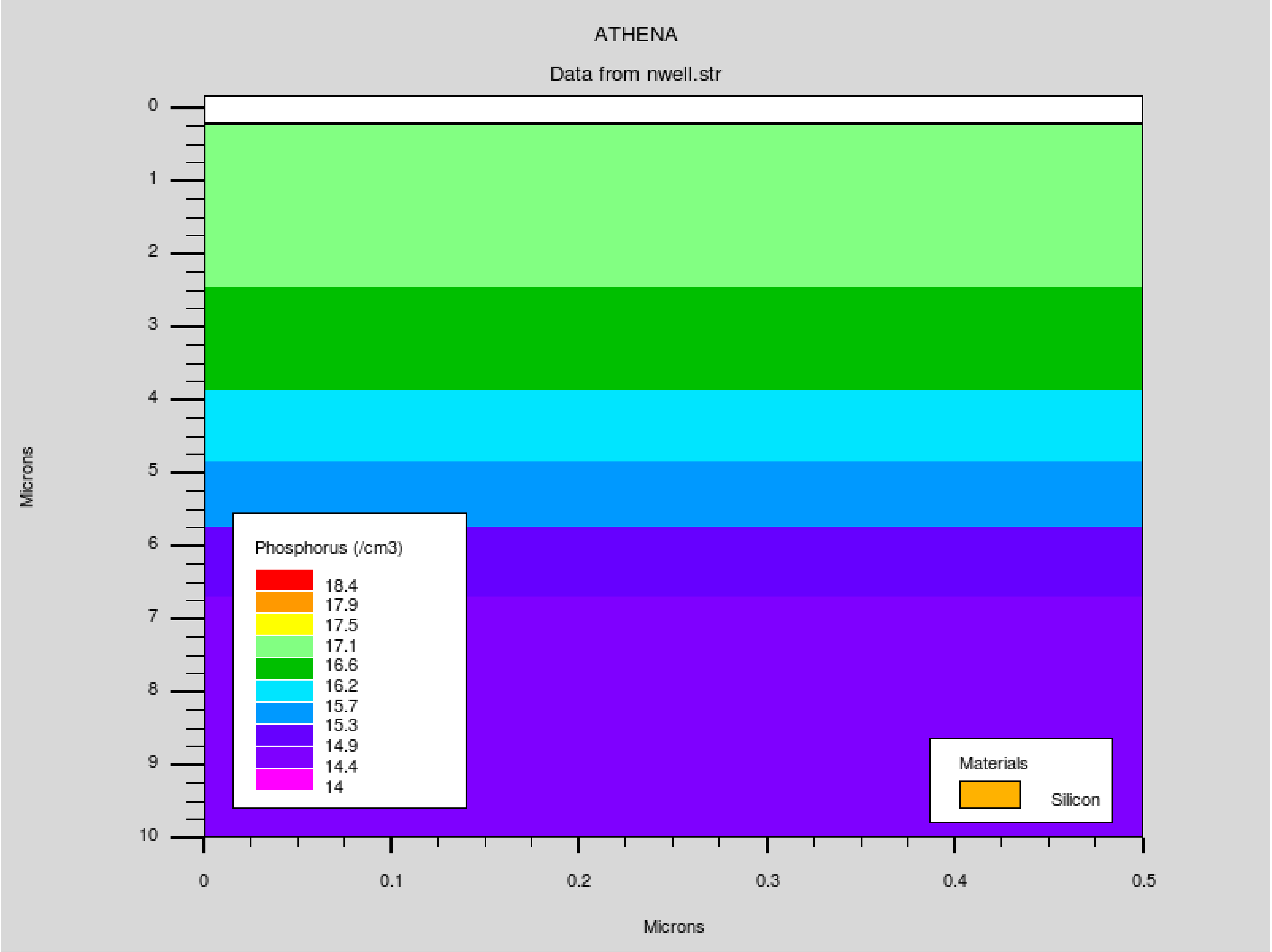
Implanted Phosphorus



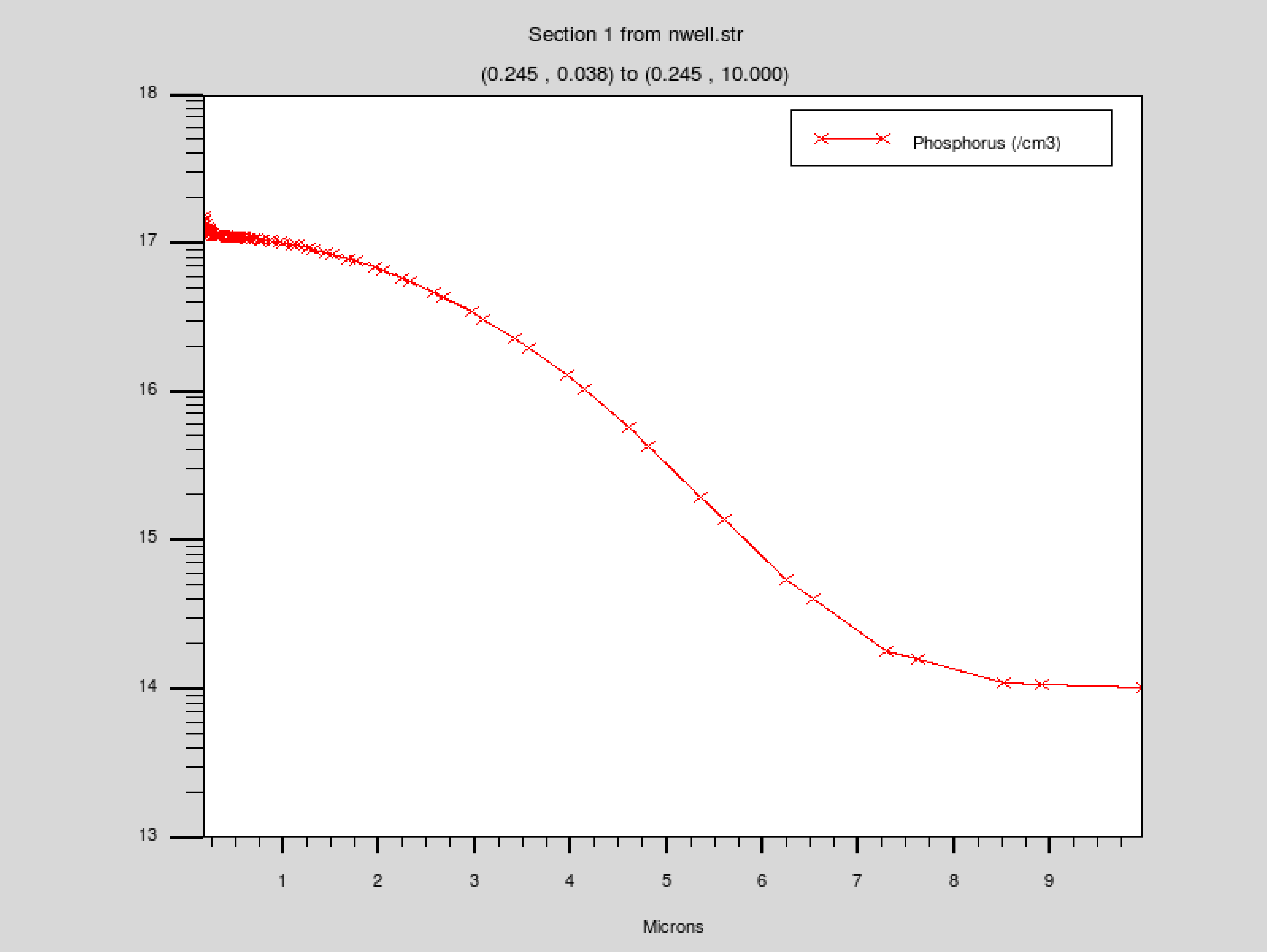
NWELL Dopant Drive-In

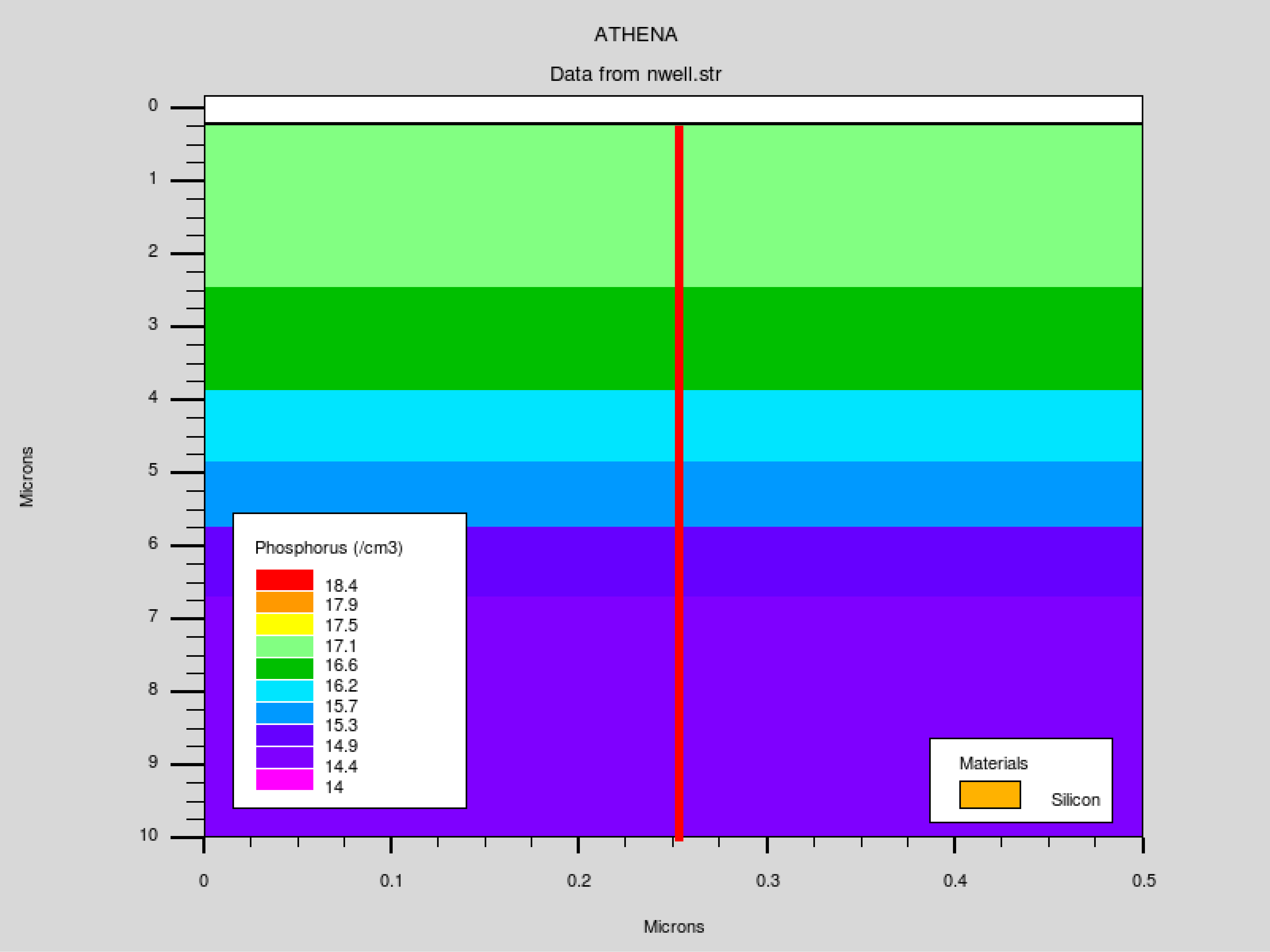
1100C Furnace



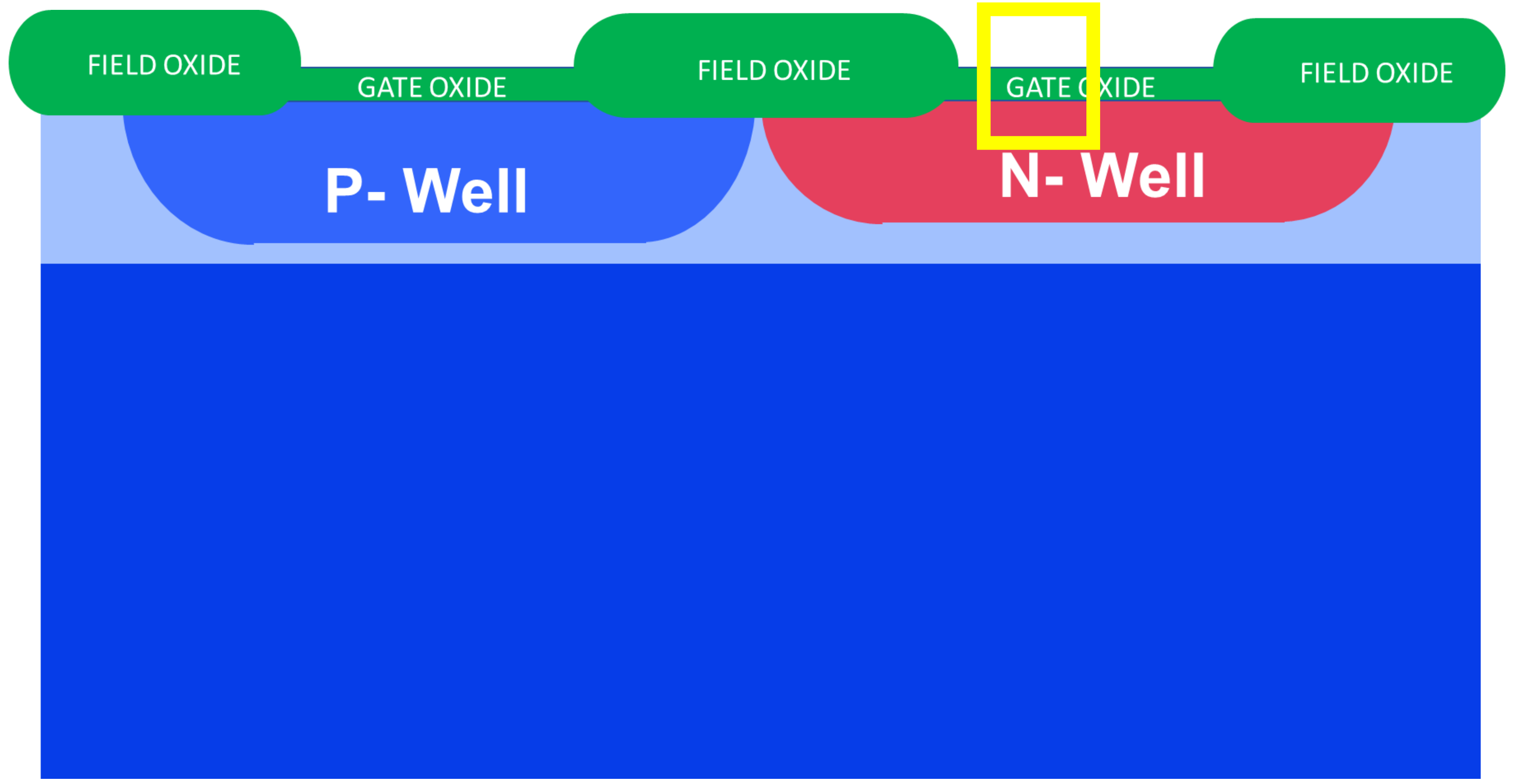


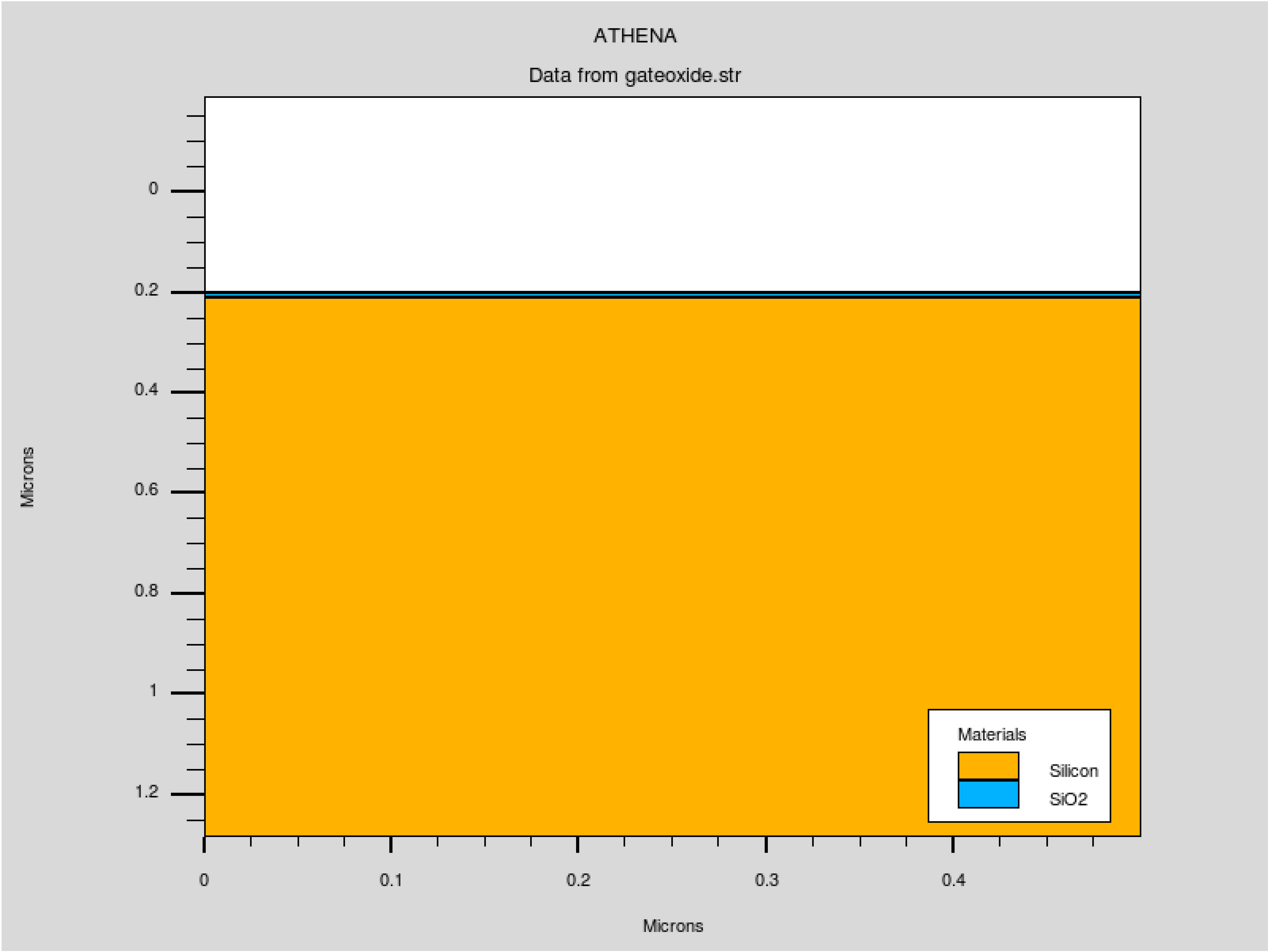
Phosphorus Drive-In



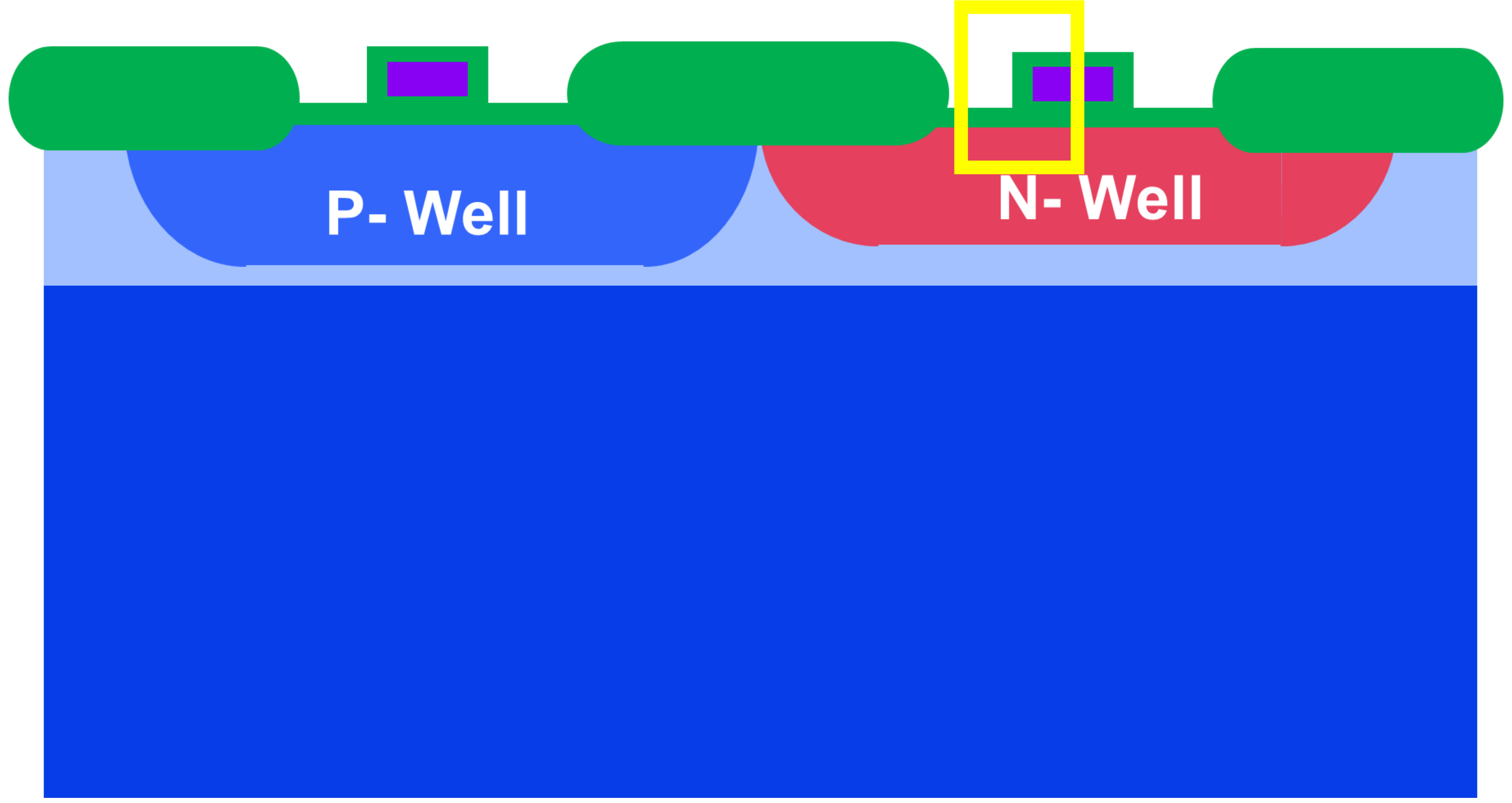


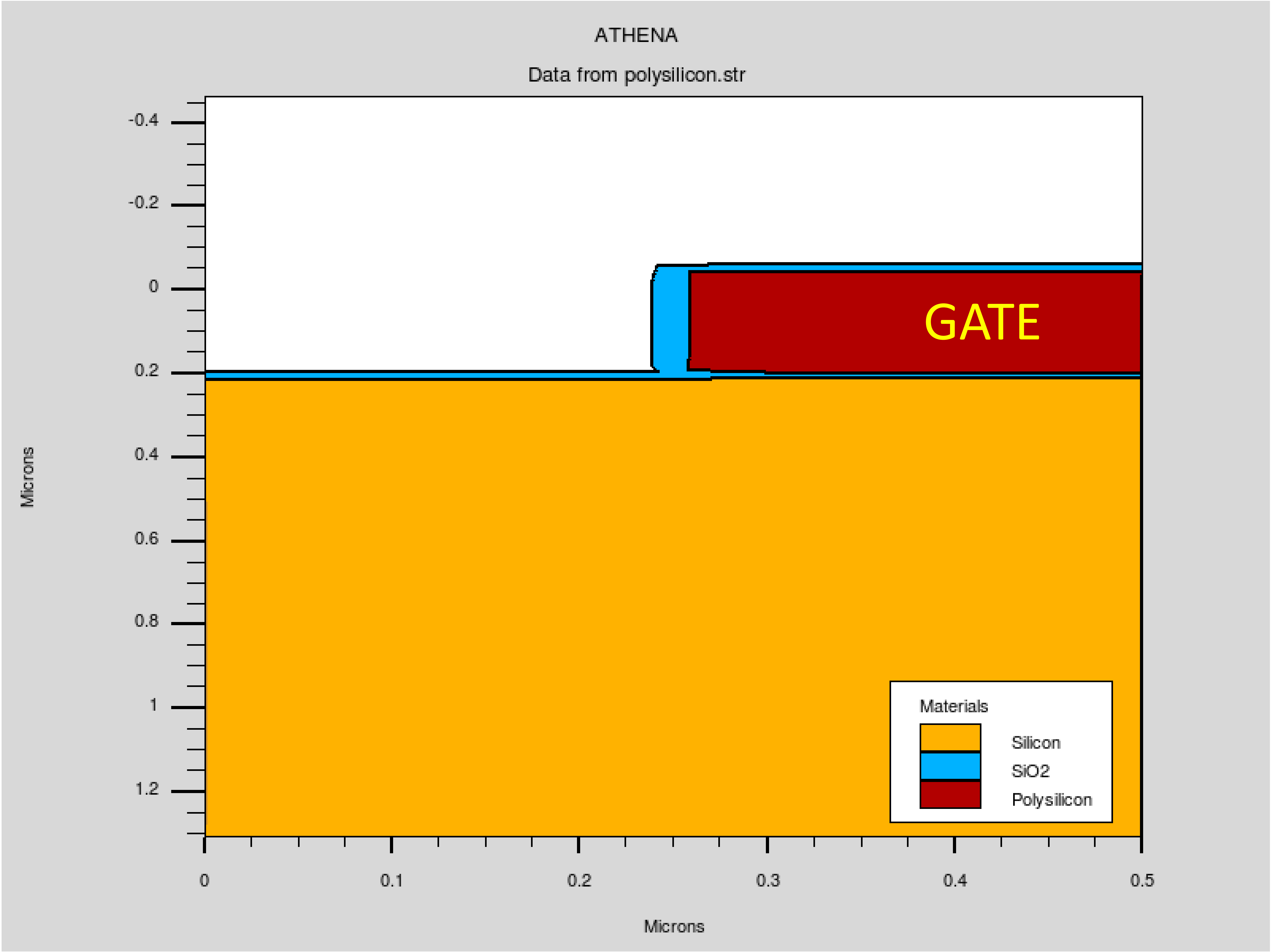
Gate Oxidation



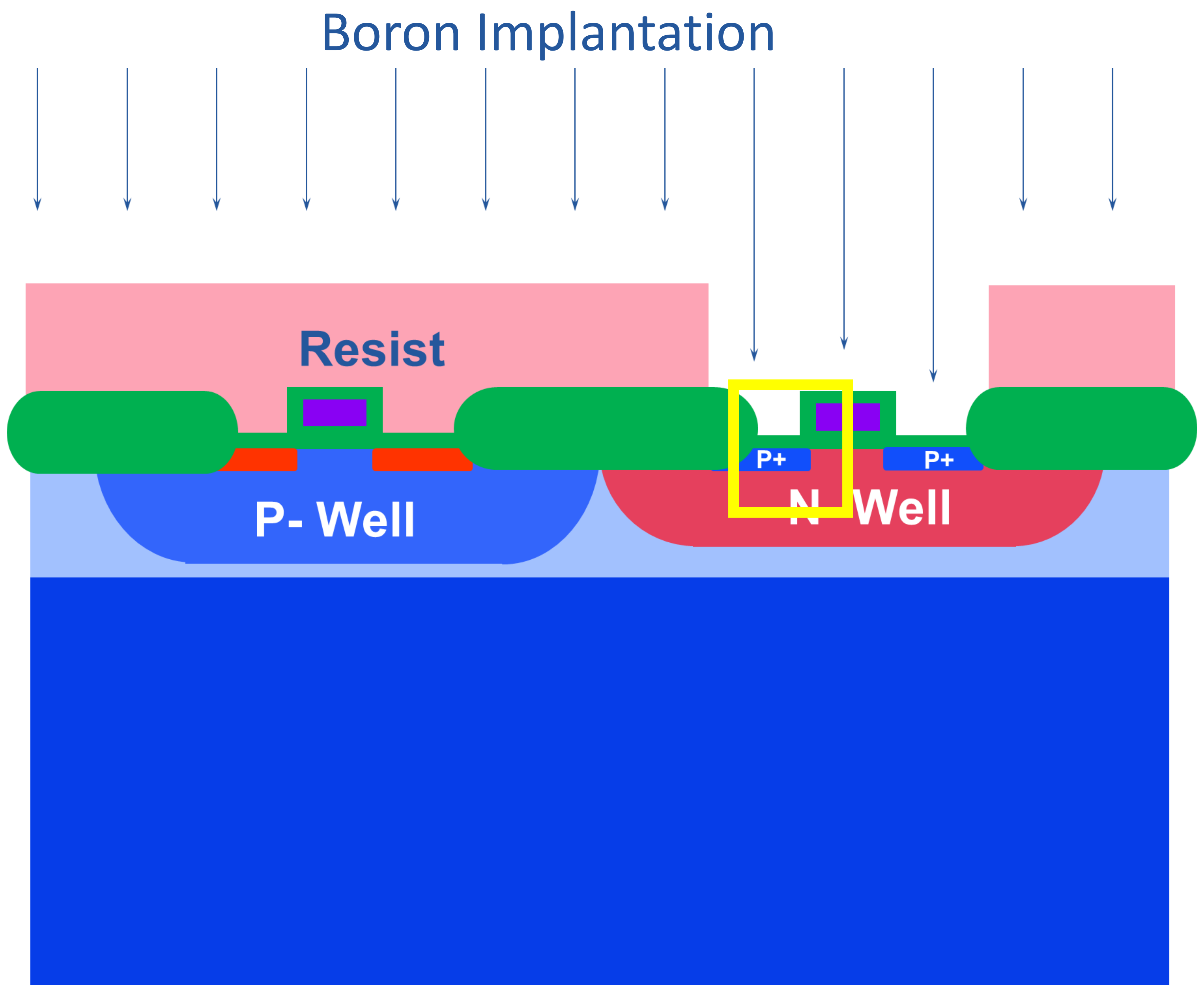


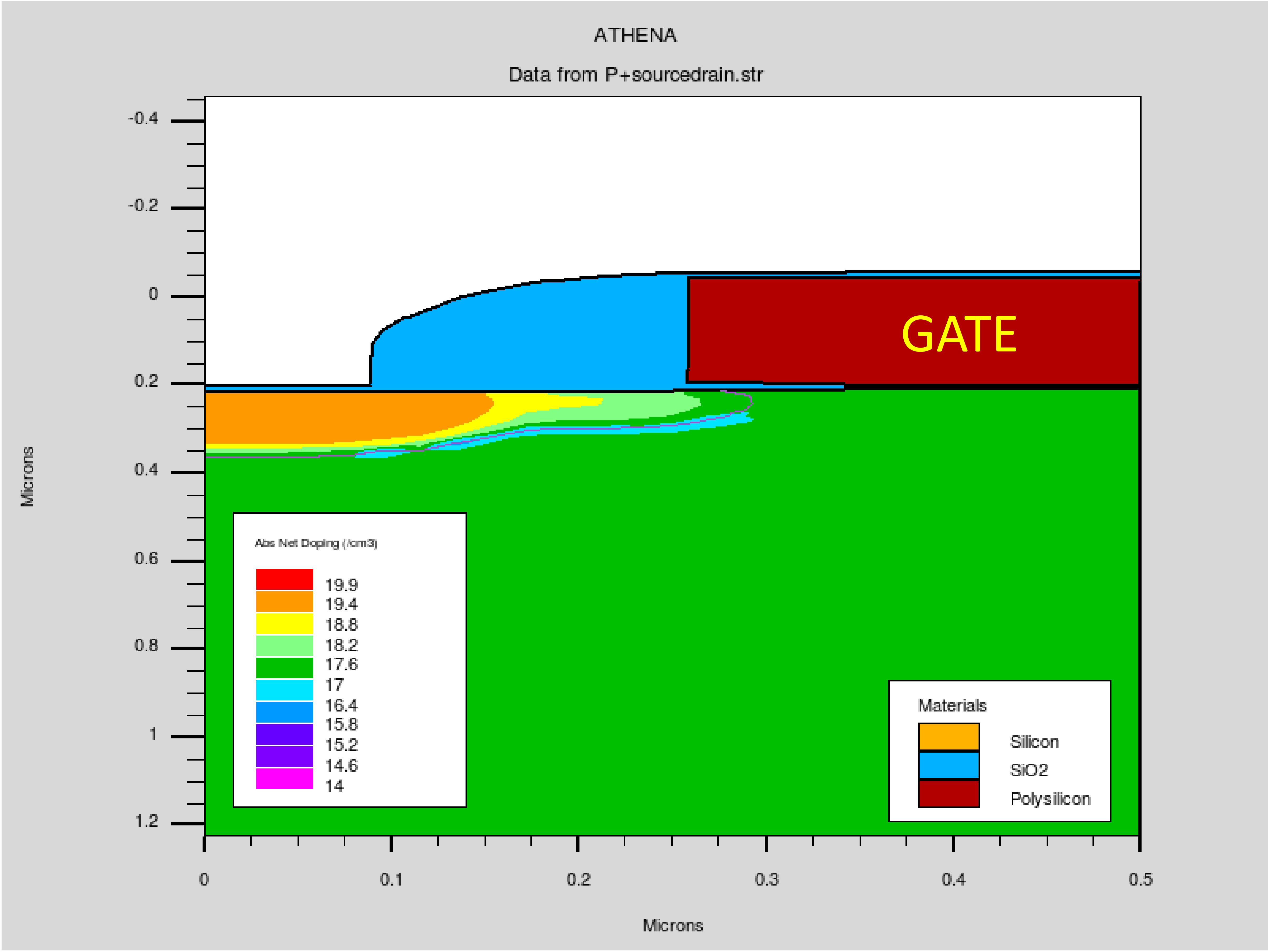
Polysilicon Gate + Reoxidation



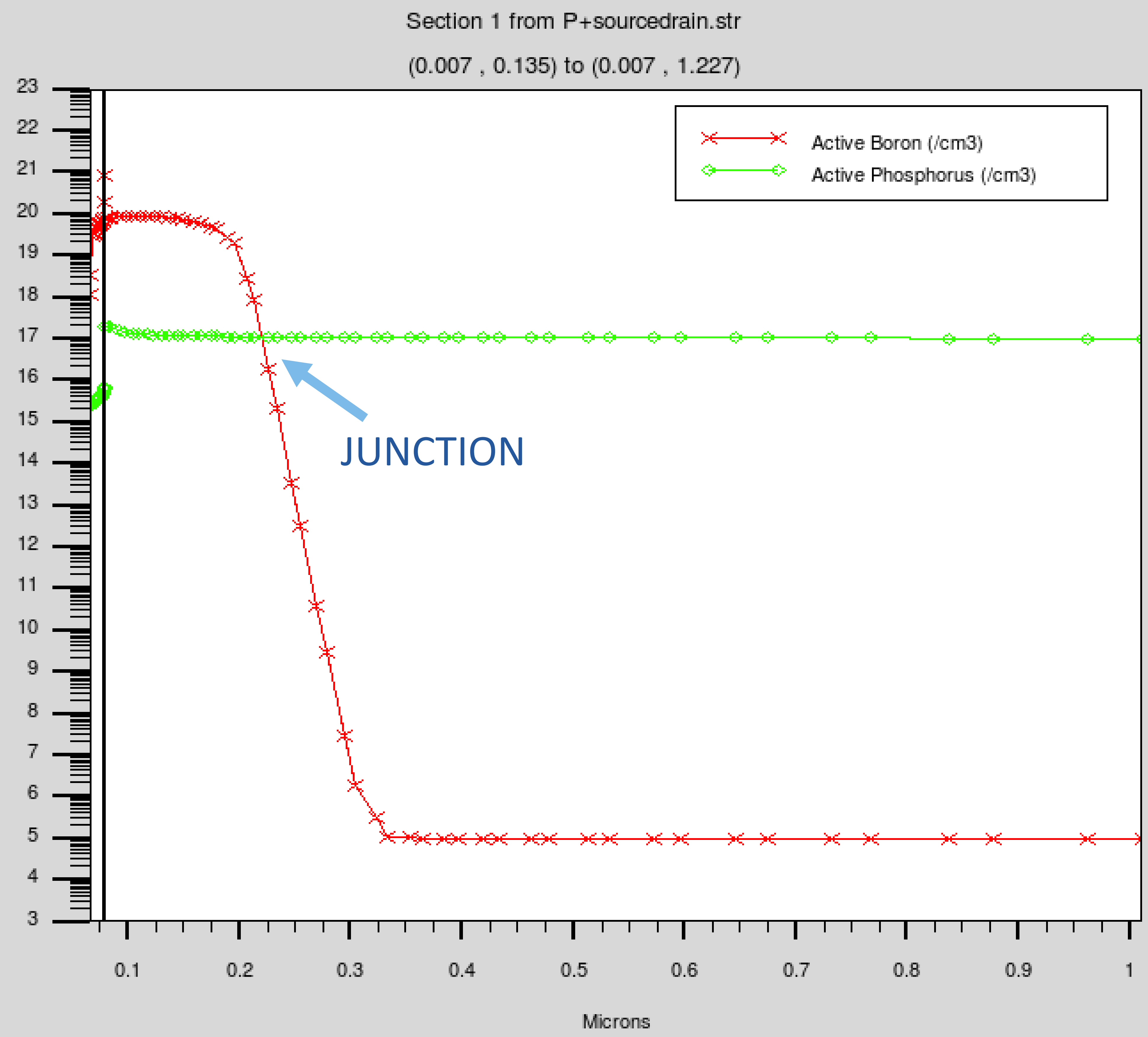


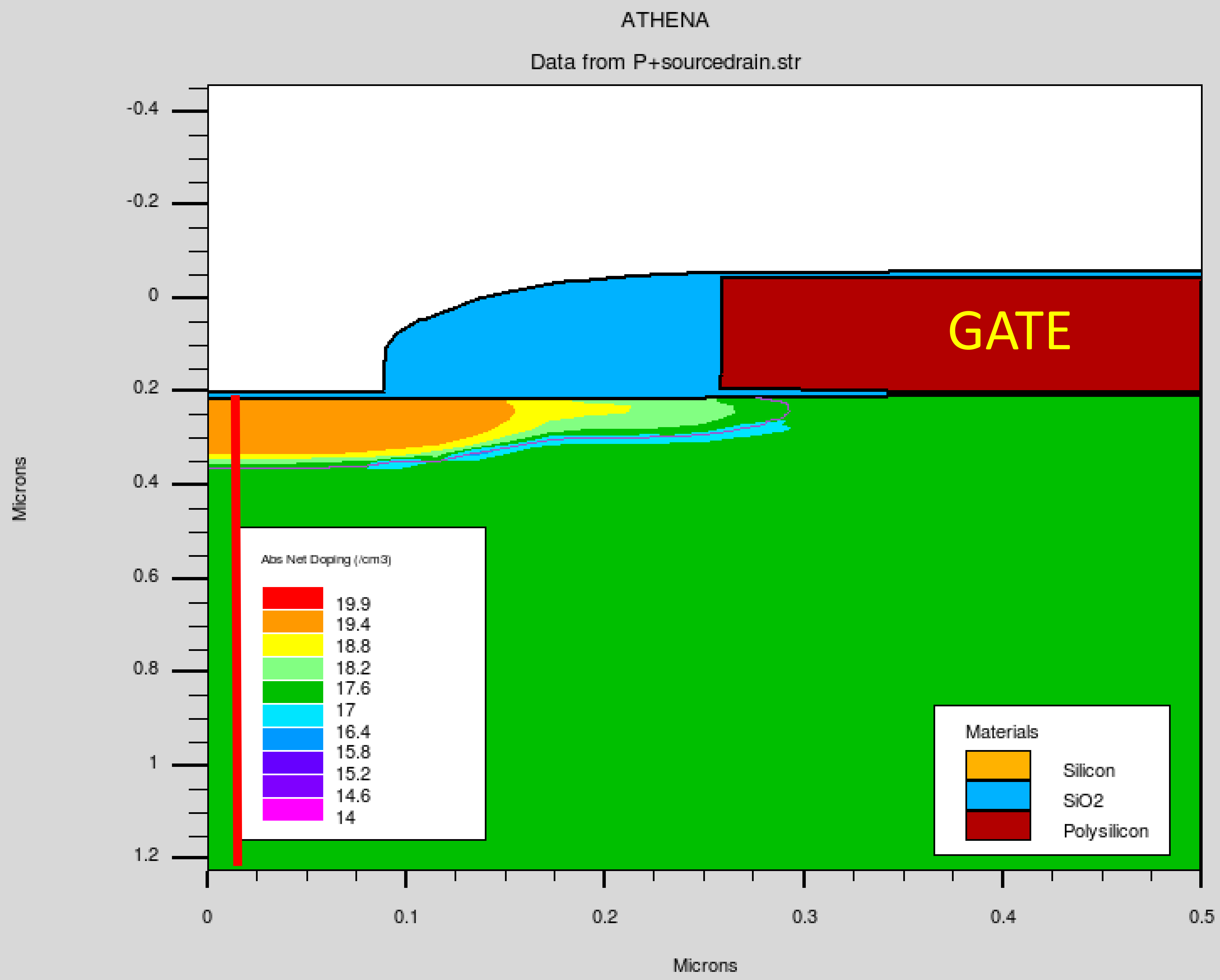
Source/Drain Formation



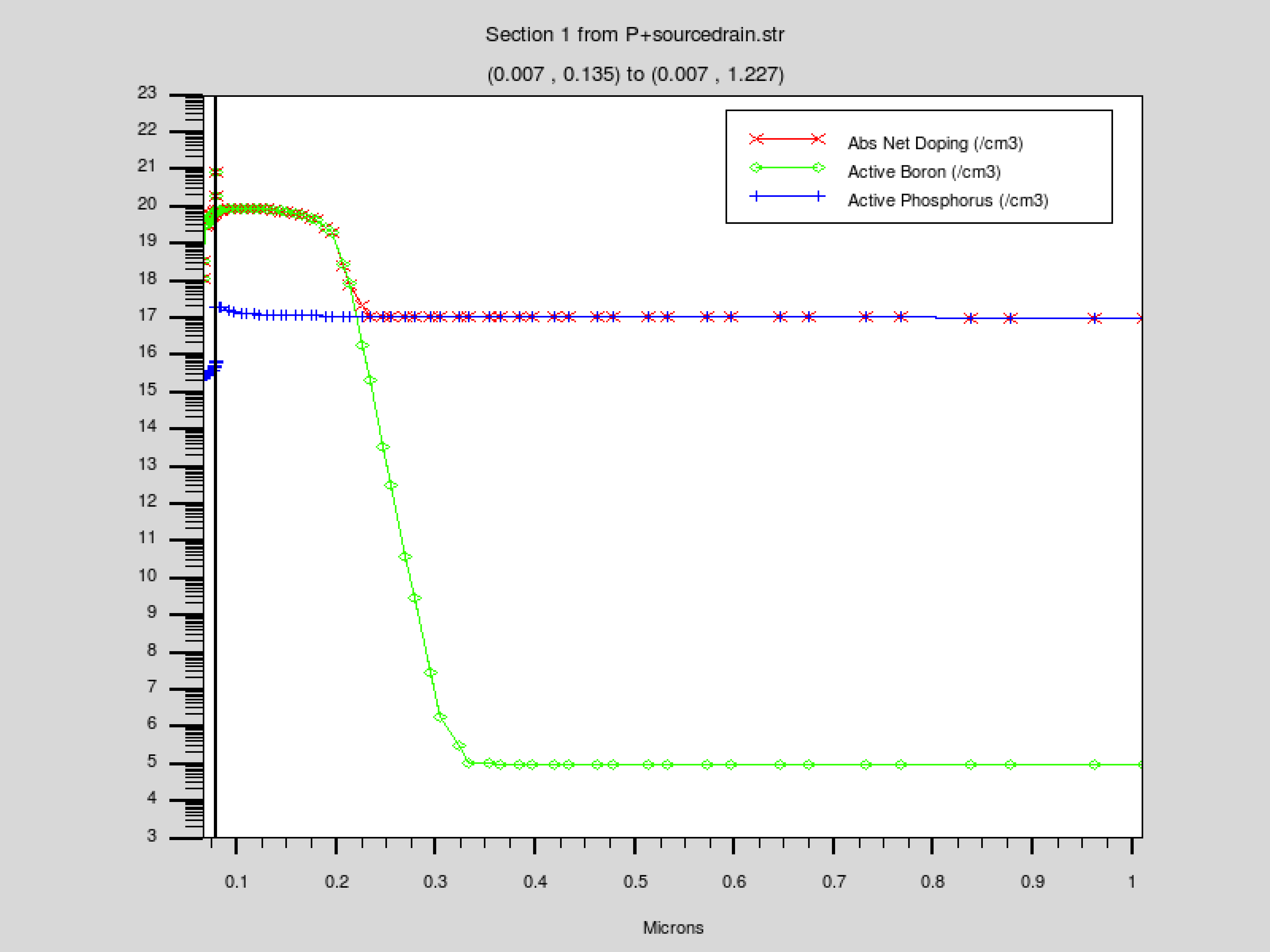


Source/Drain Formation



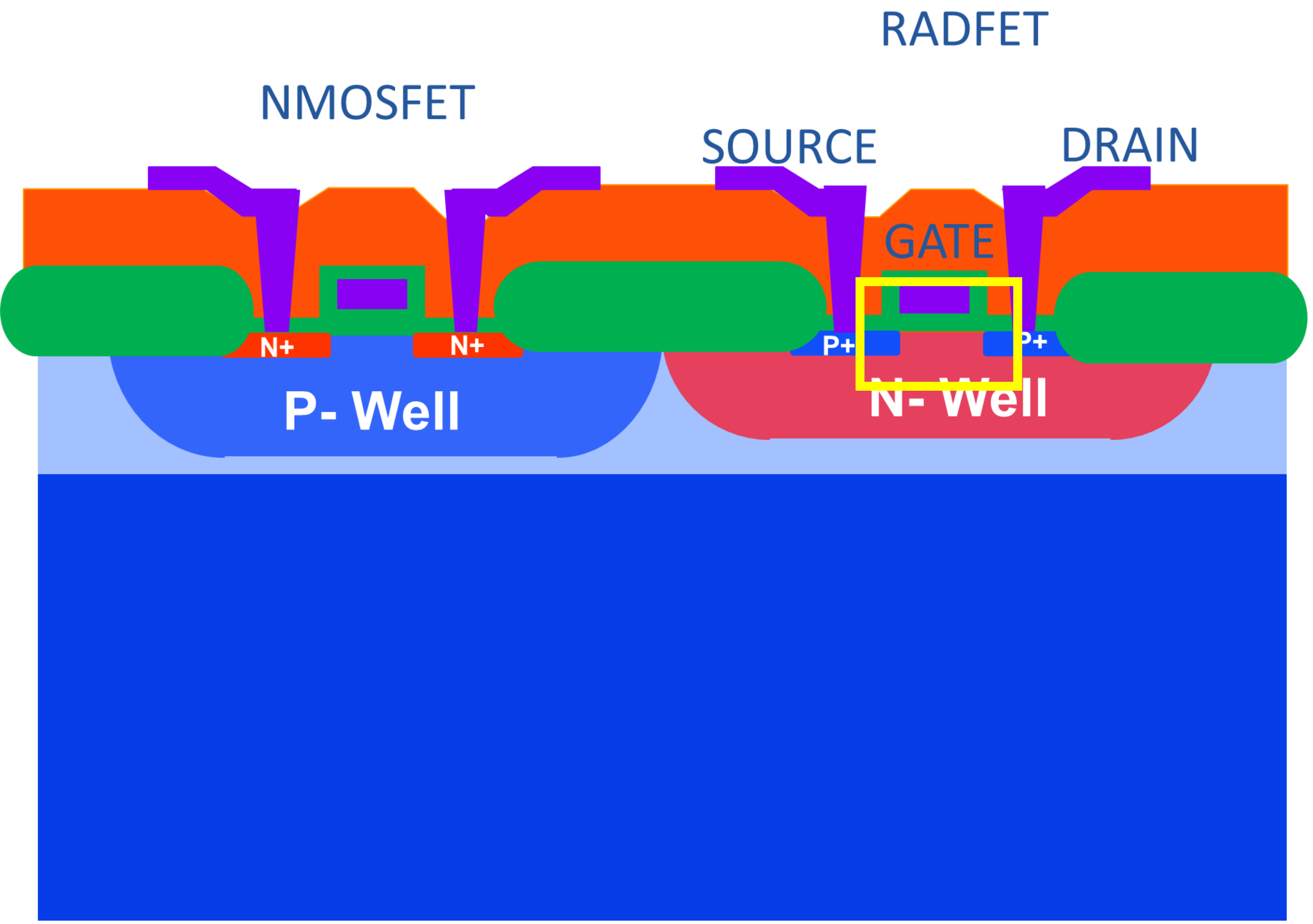


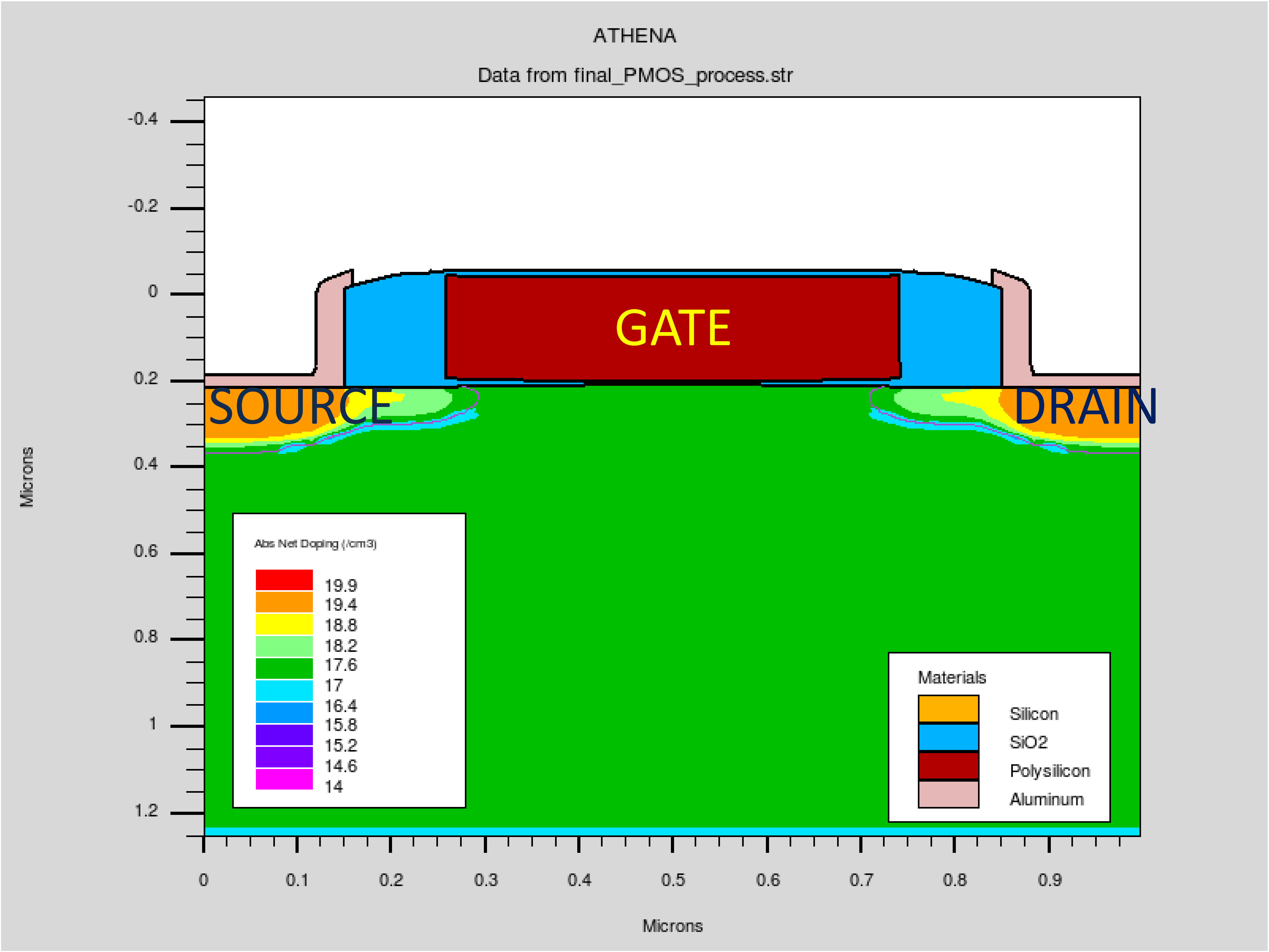
Net Doping



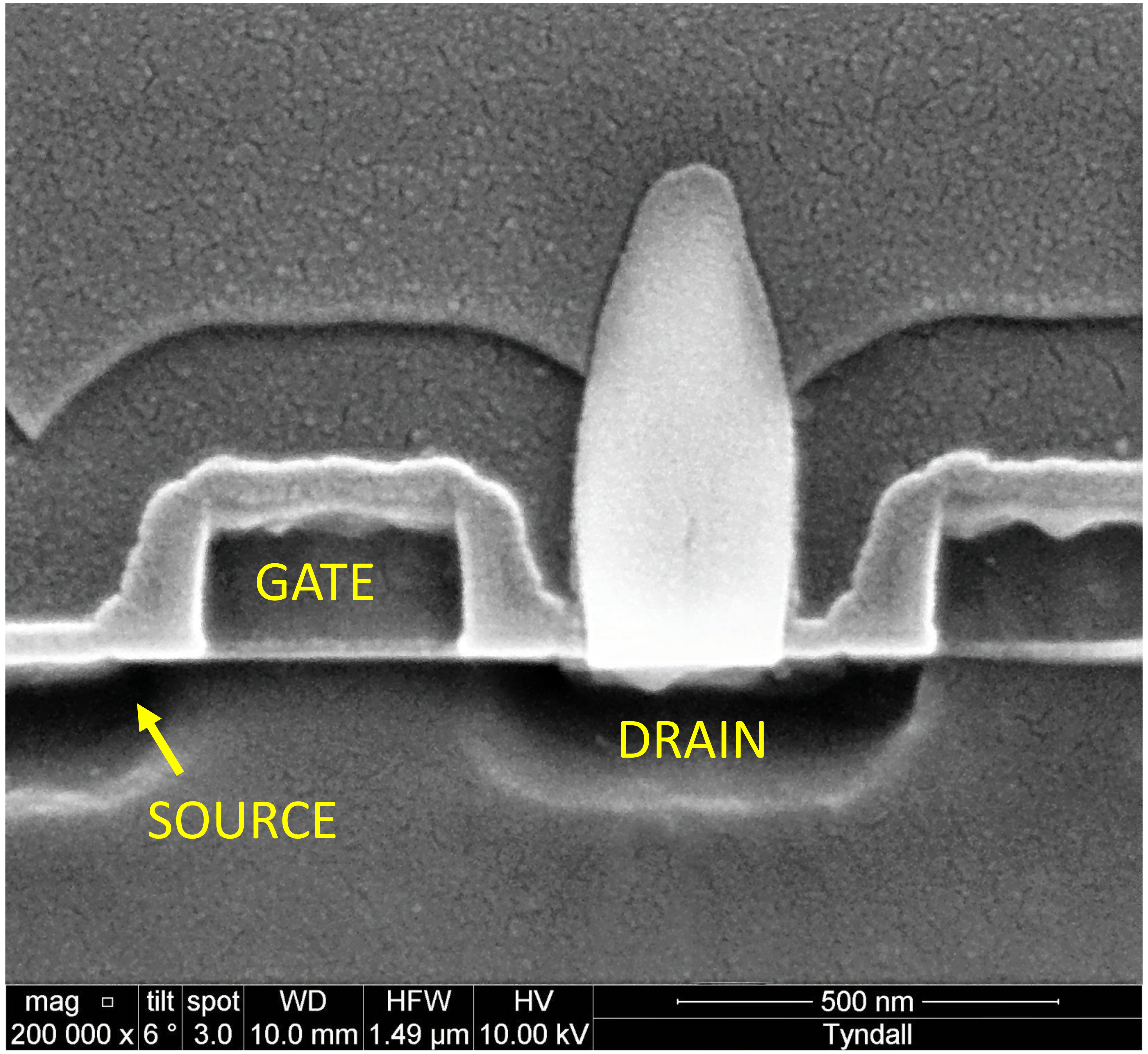
Net Doping = $|N_D - N_A|$

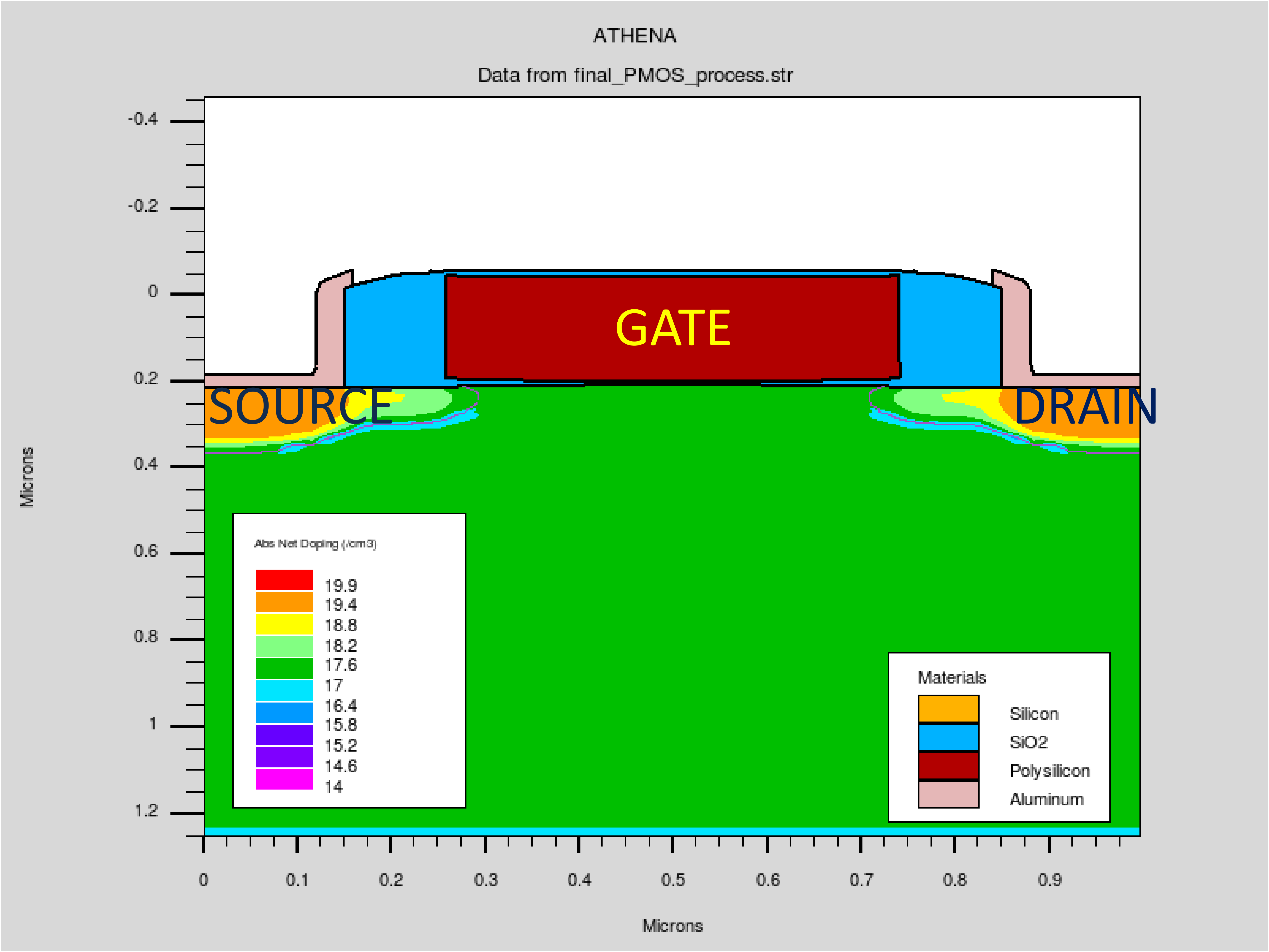
PMOS Transistor





PMOS Transistor





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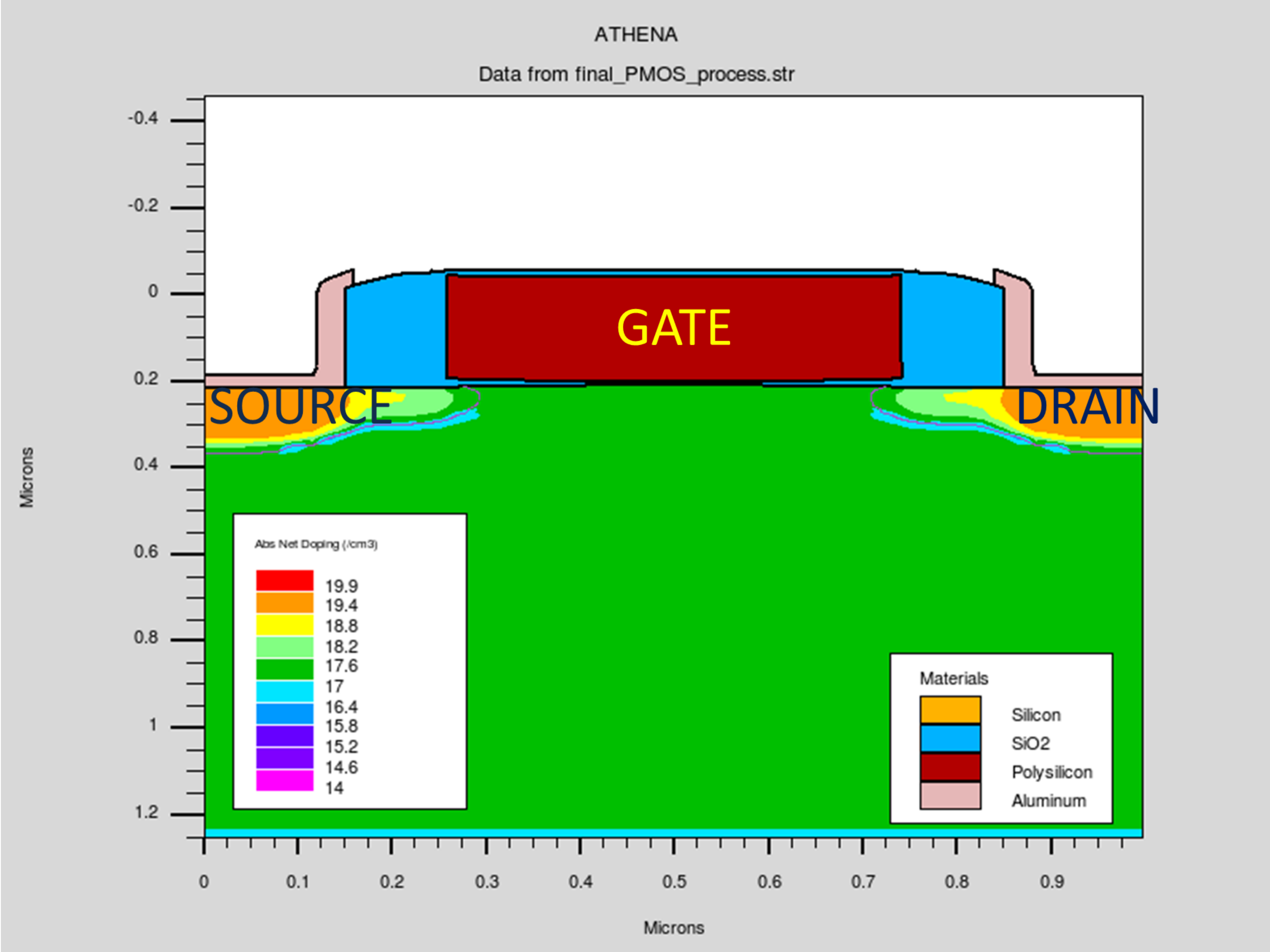
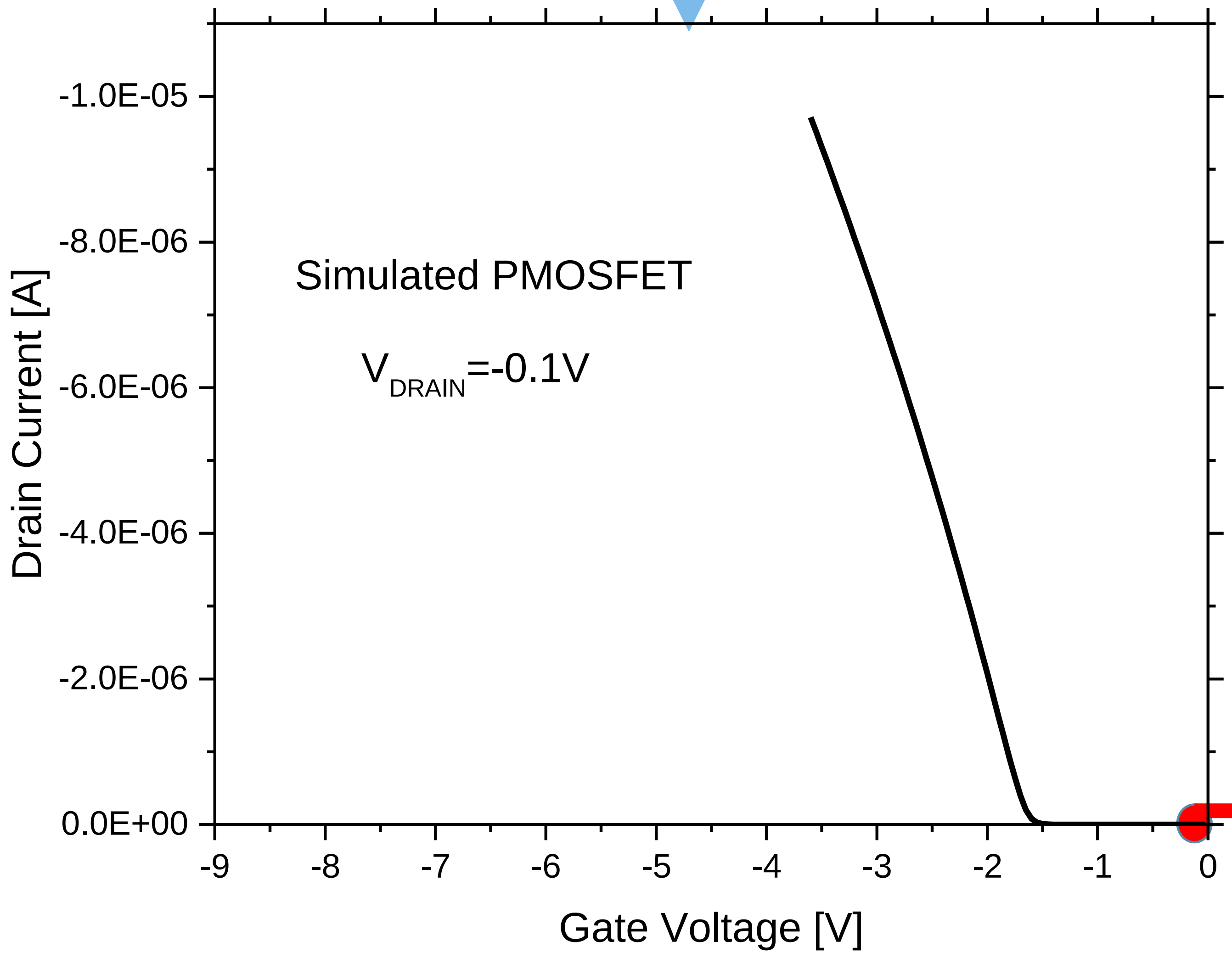
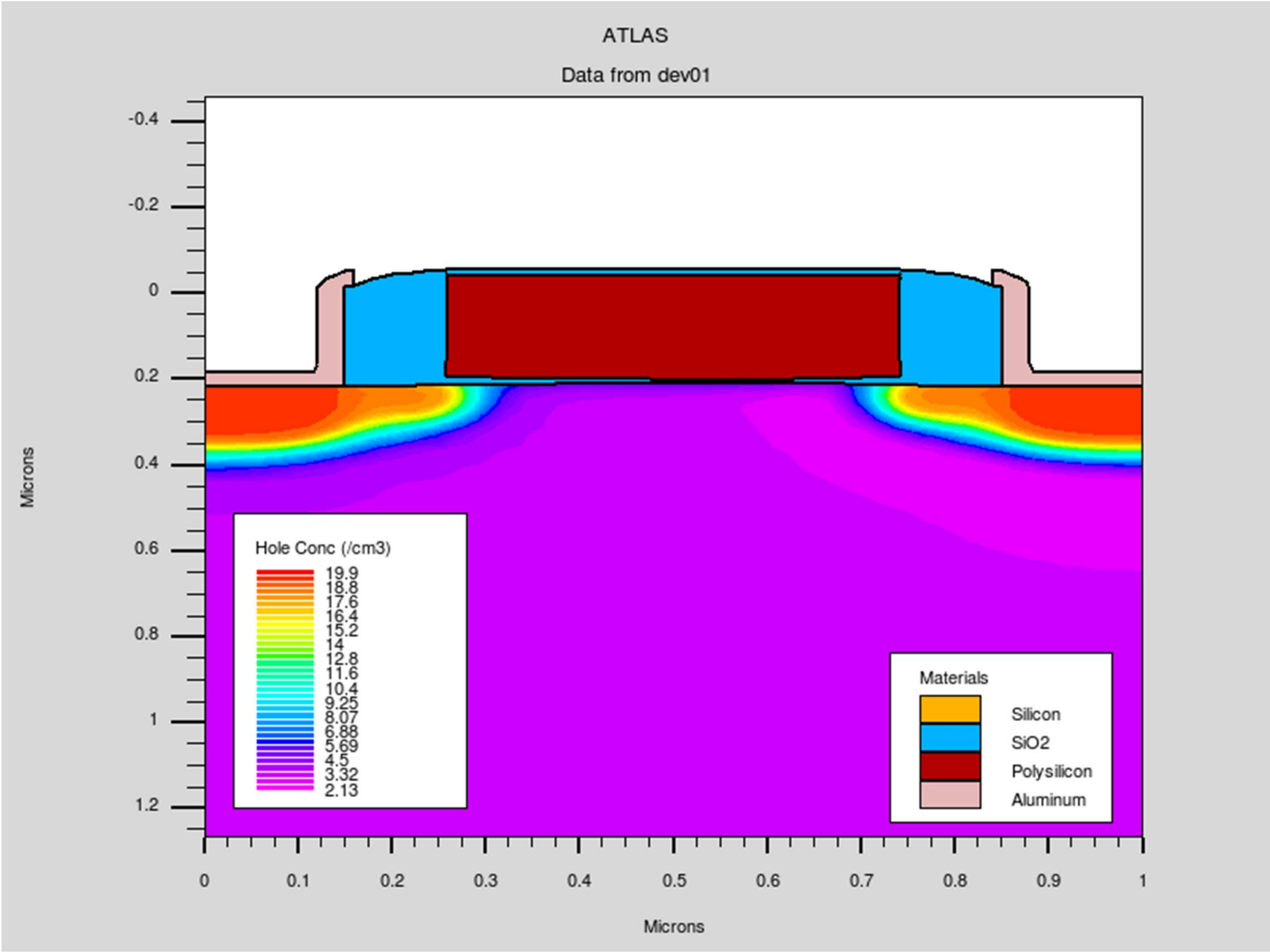
Semiconductor Device Simulation



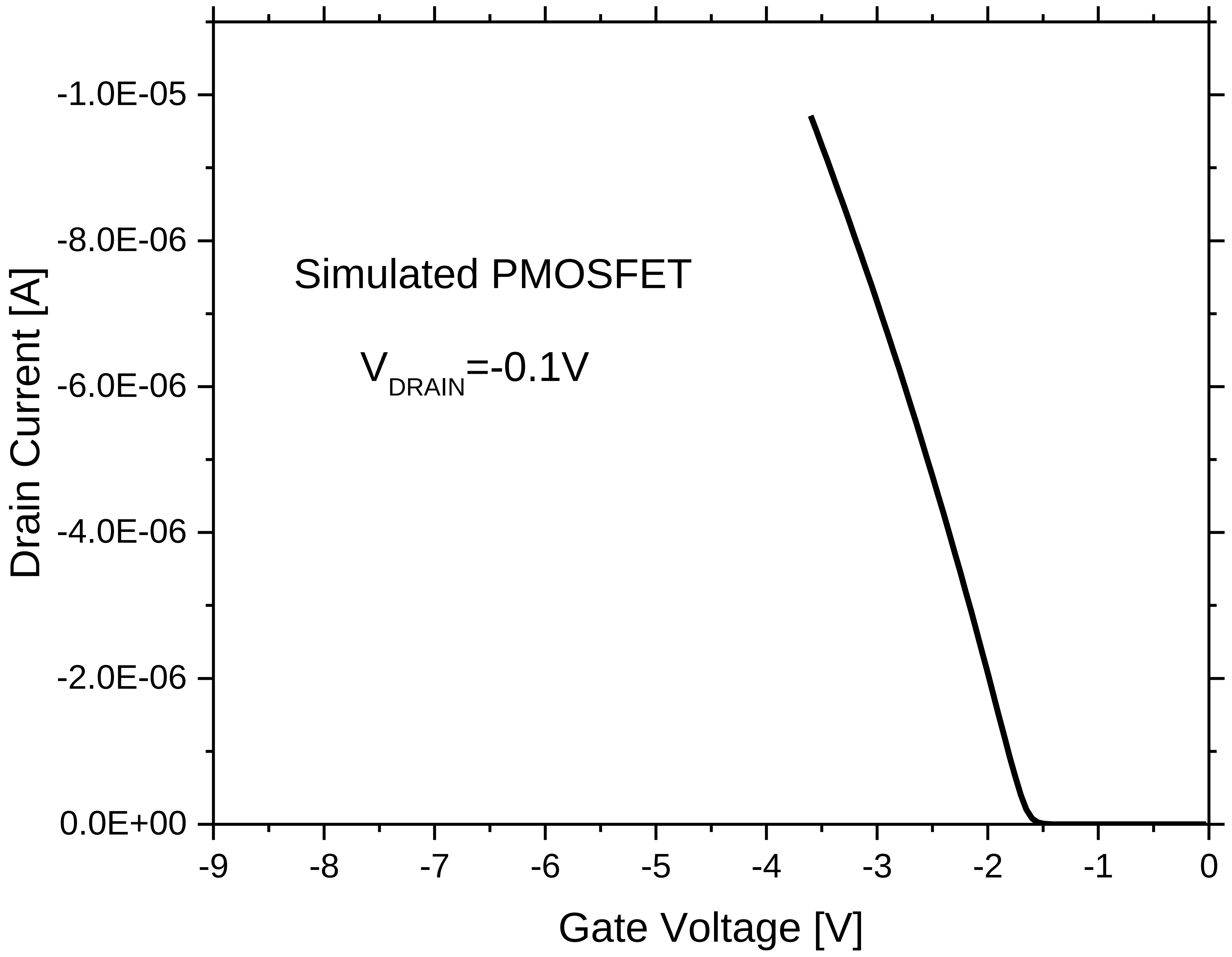
Poisson, Drift Diffusion

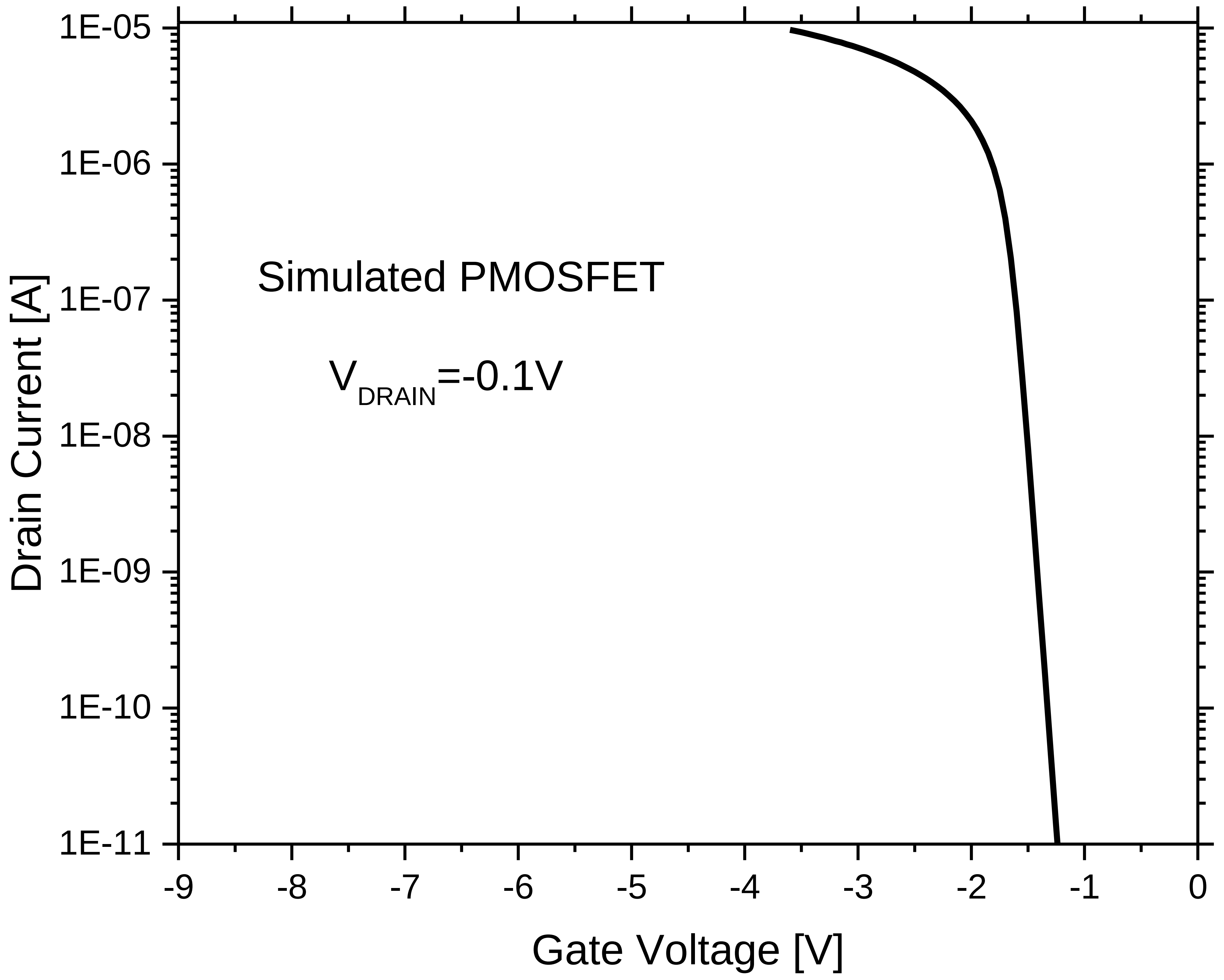
Physics models

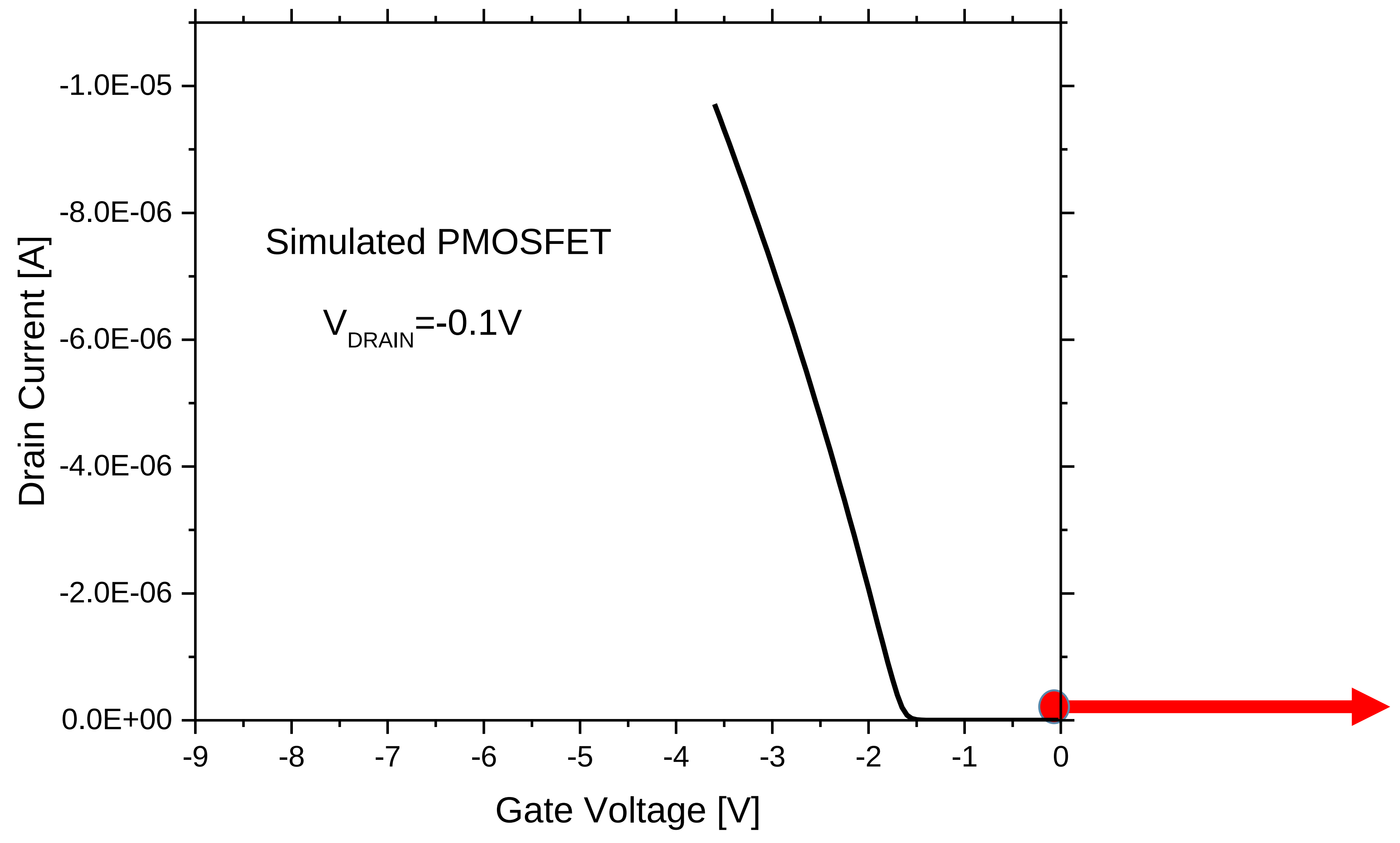




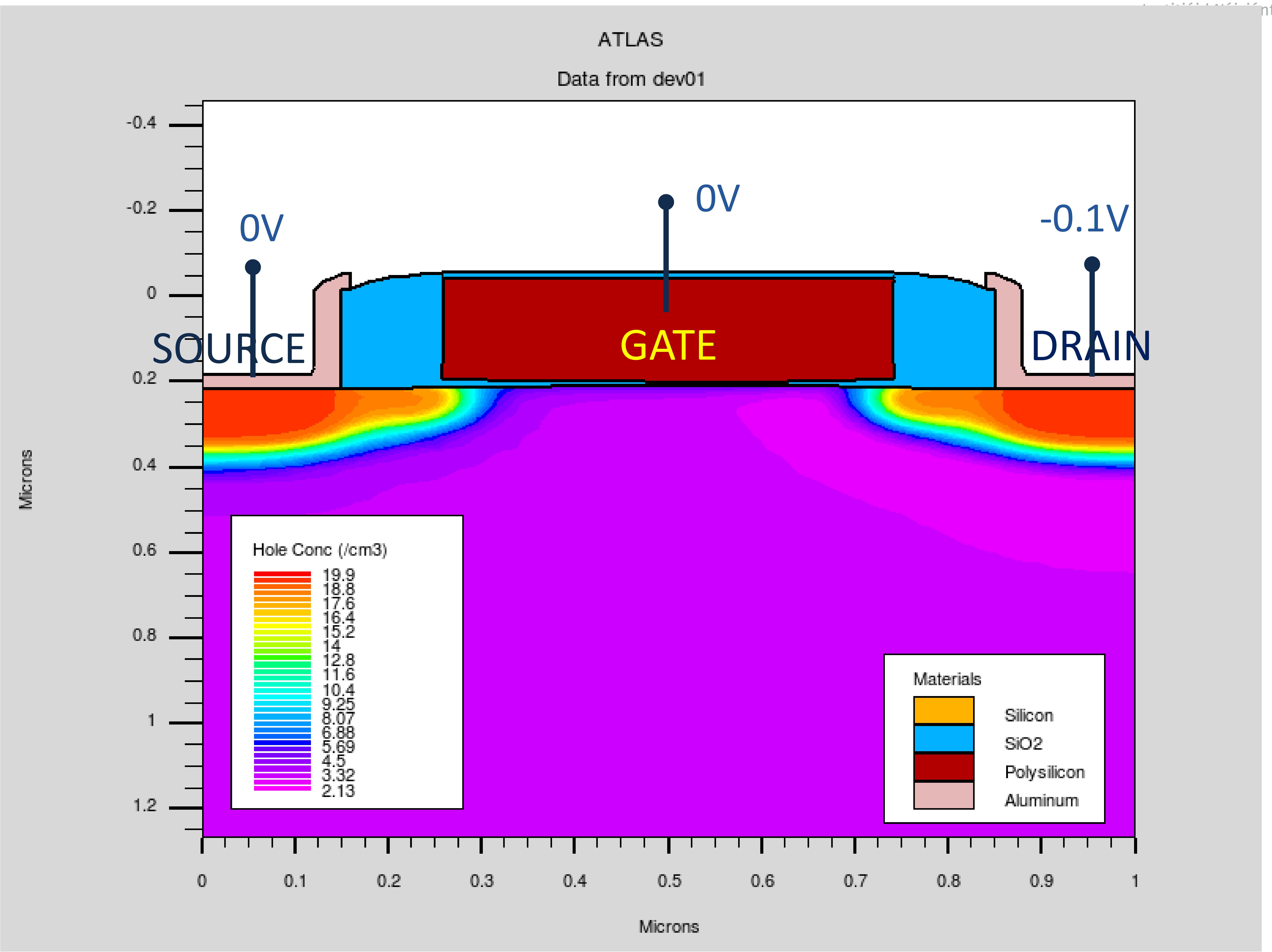
PMOS Device I-V characteristic



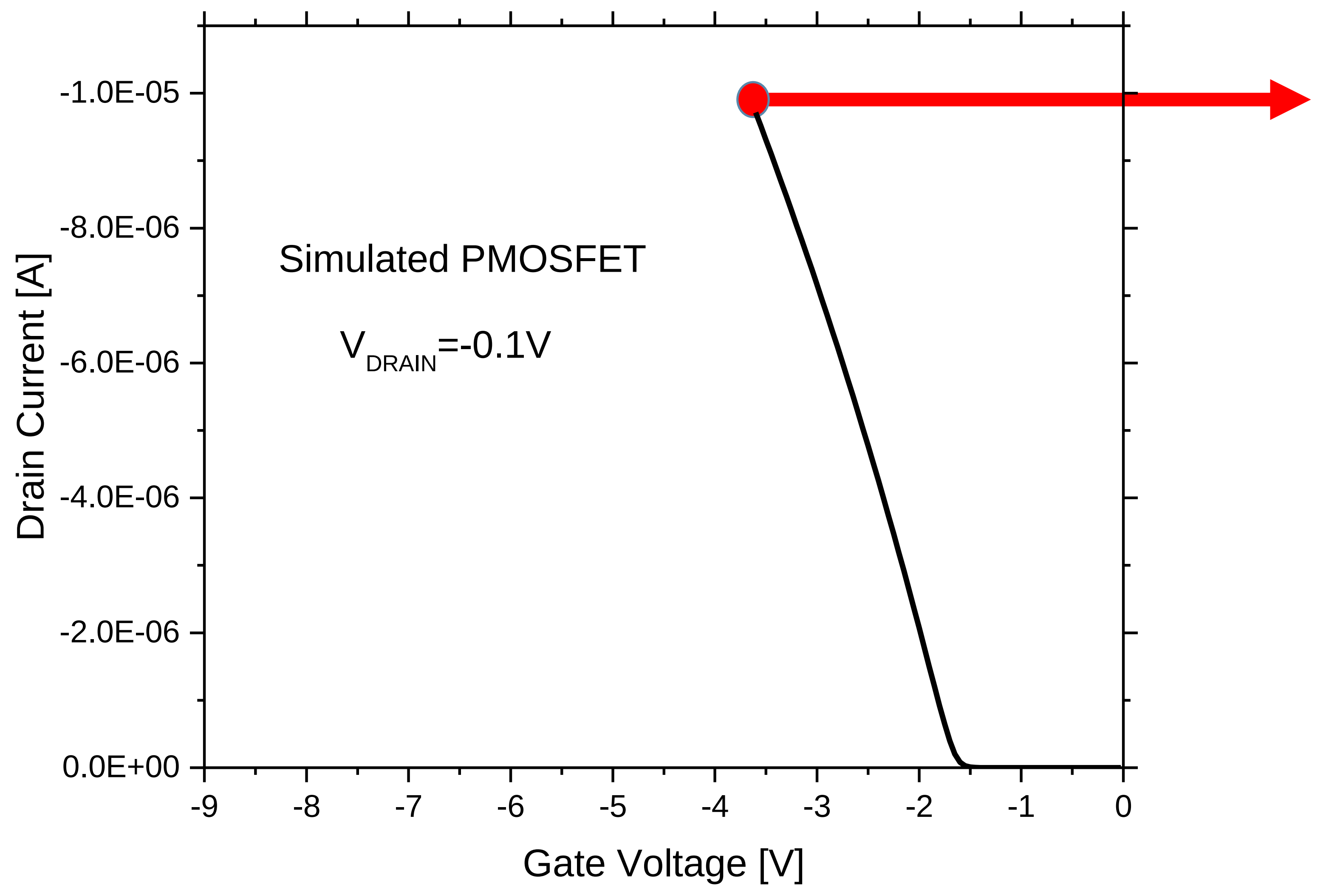




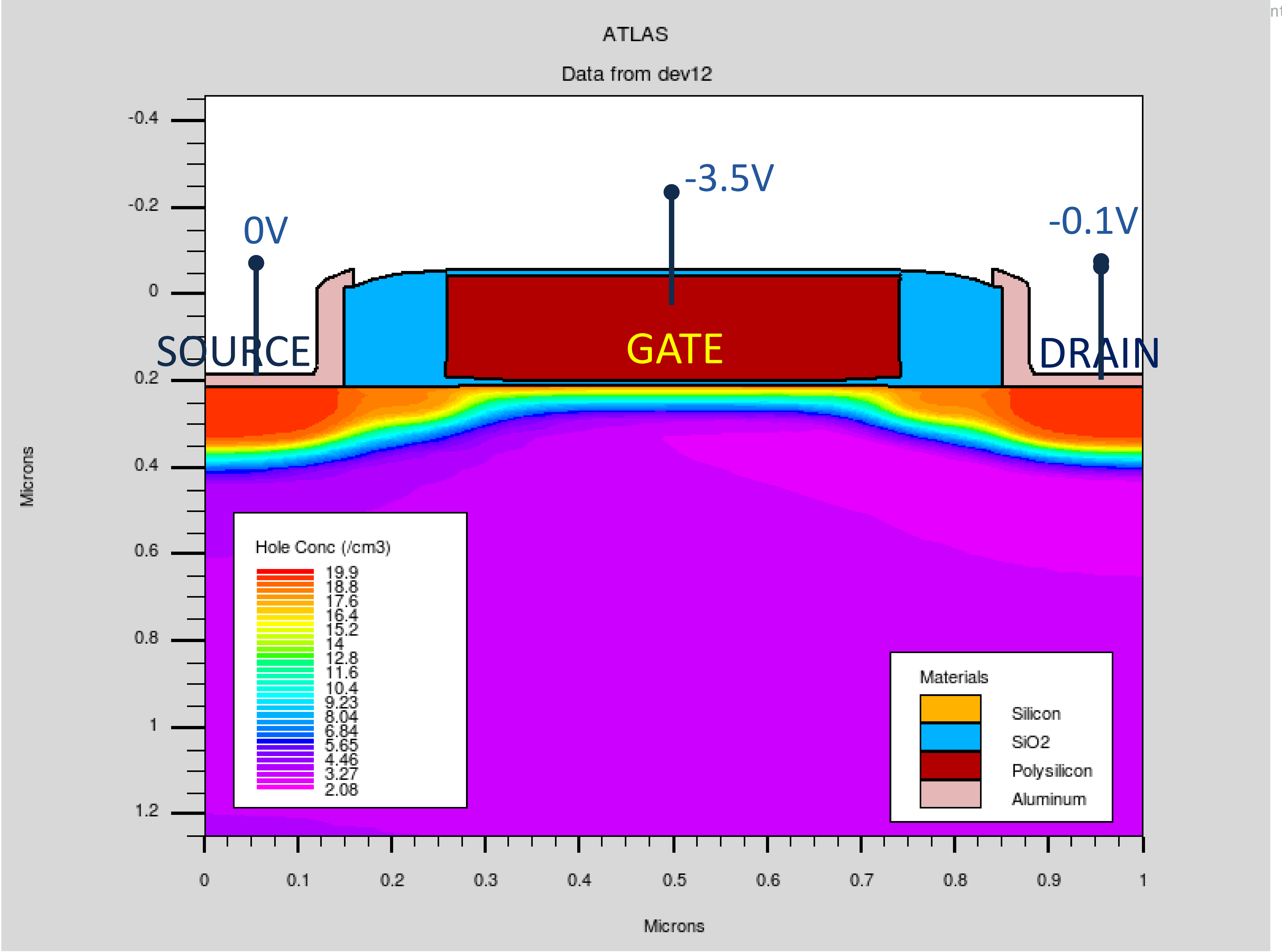
Simulated PMOSFET
V_{DRAIN}=-0.1V
Drain Current [A]
Gate Voltage [V]
-1.0E-05
-8.0E-06
-6.0E-06
-4.0E-06
-2.0E-06
0.0E+00
-9 -8 -7 -6 -5 -4 -3 -2 -1 0



ATLAS
Data from dev01
0V
0V
-0.1V
SOURCE
GATE
DRAIN
Microns
Microns
Hole Conc (/cm3)
19.9
18.8
17.6
16.4
15.2
14
12.8
11.6
10.4
9.25
8.07
6.88
5.69
4.5
3.32
2.13
Materials
Silicon
SiO2
Polysilicon
Aluminum



Simulated PMOSFET
V_{DRAIN}=-0.1V
Drain Current [A]
Gate Voltage [V]
-1.0E-05
-8.0E-06
-6.0E-06
-4.0E-06
-2.0E-06
0.0E+00
-9
-8
-7
-6
-5
-4
-3
-2
-1
0



ATLAS
Data from dev12
-3.5V
0V
-0.1V
SOURCE
GATE
DRAIN
Microns
Hole Conc (/cm3)
19.9
18.8
17.6
16.4
15.2
14
12.8
11.6
10.4
9.23
8.04
6.84
5.65
4.46
3.27
2.08
Materials
Silicon
SiO2
Polysilicon
Aluminum
Microns

Outline

- What is Technology Computer Aided Design (TCAD)?

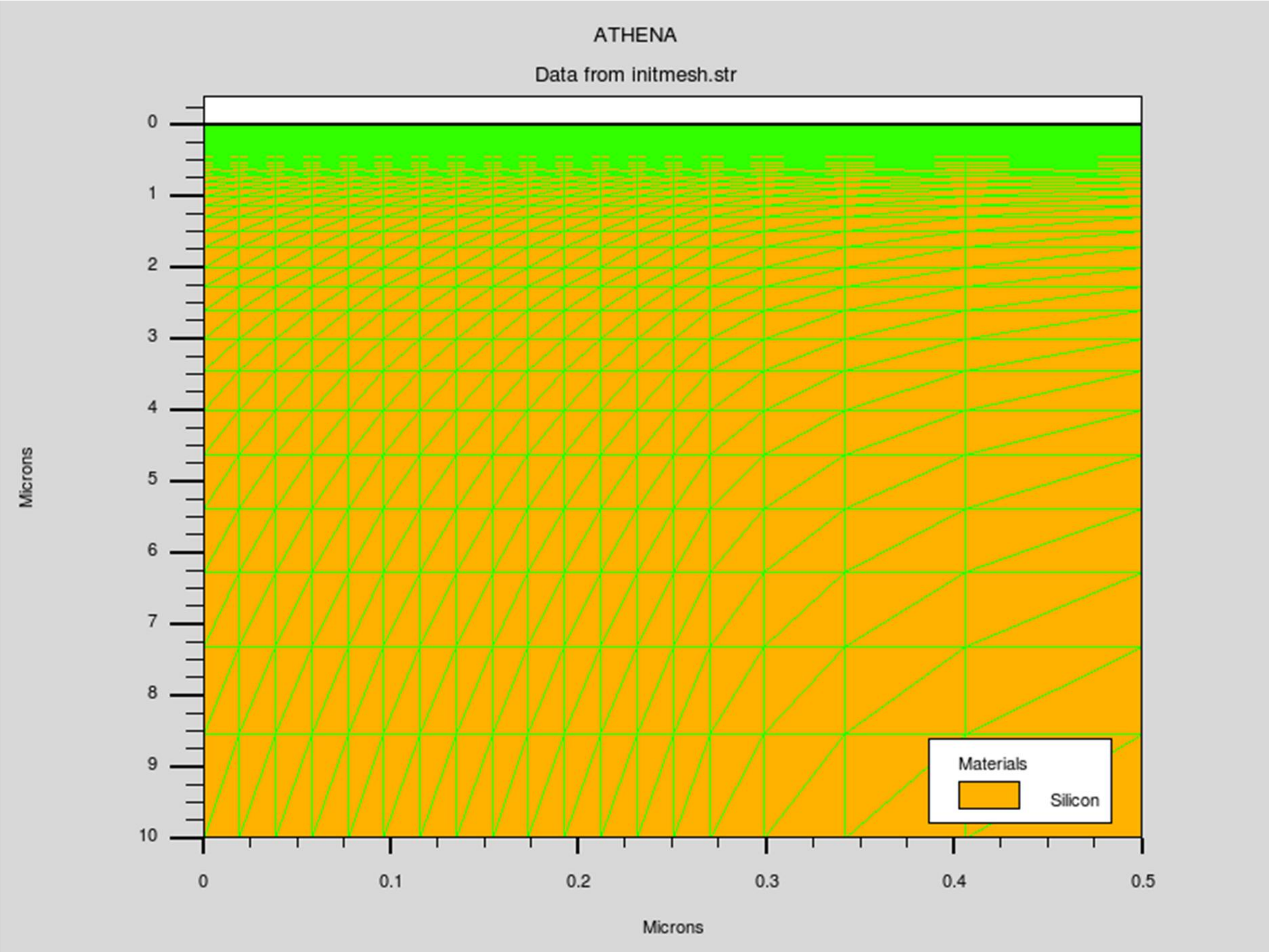
- How does TCAD work?
    - Mesh
    - Models

How does TCAD work?

- Semiconductor Structure defined by specific regions (e.g. doped Silicon, Aluminium contacts, gate oxide)

- Regions are broken down into smaller triangular (Finite) Elements which define nodes on which physics equations are solved numerically

- Array of Finite Elements called a mesh or grid



Mesh specification

- User specifies mesh for both process and device simulators
- Number of nodes N_P in the mesh directly influences simulation accuracy and time
- Number of arithmetic operations necessary to run simulation $\propto (N_P)^\alpha$

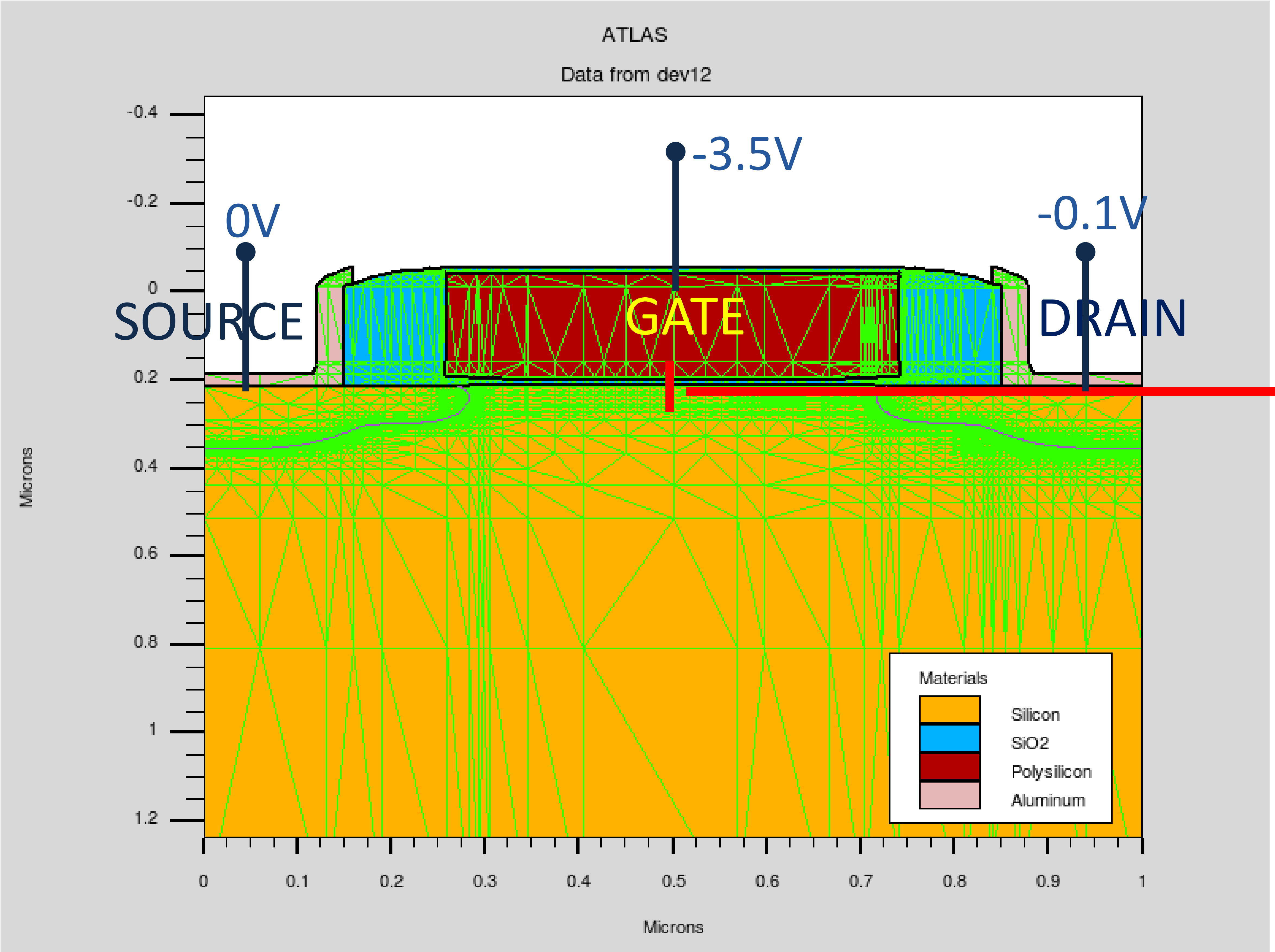
  where $\alpha = 1.5$ to 2.0 [*]

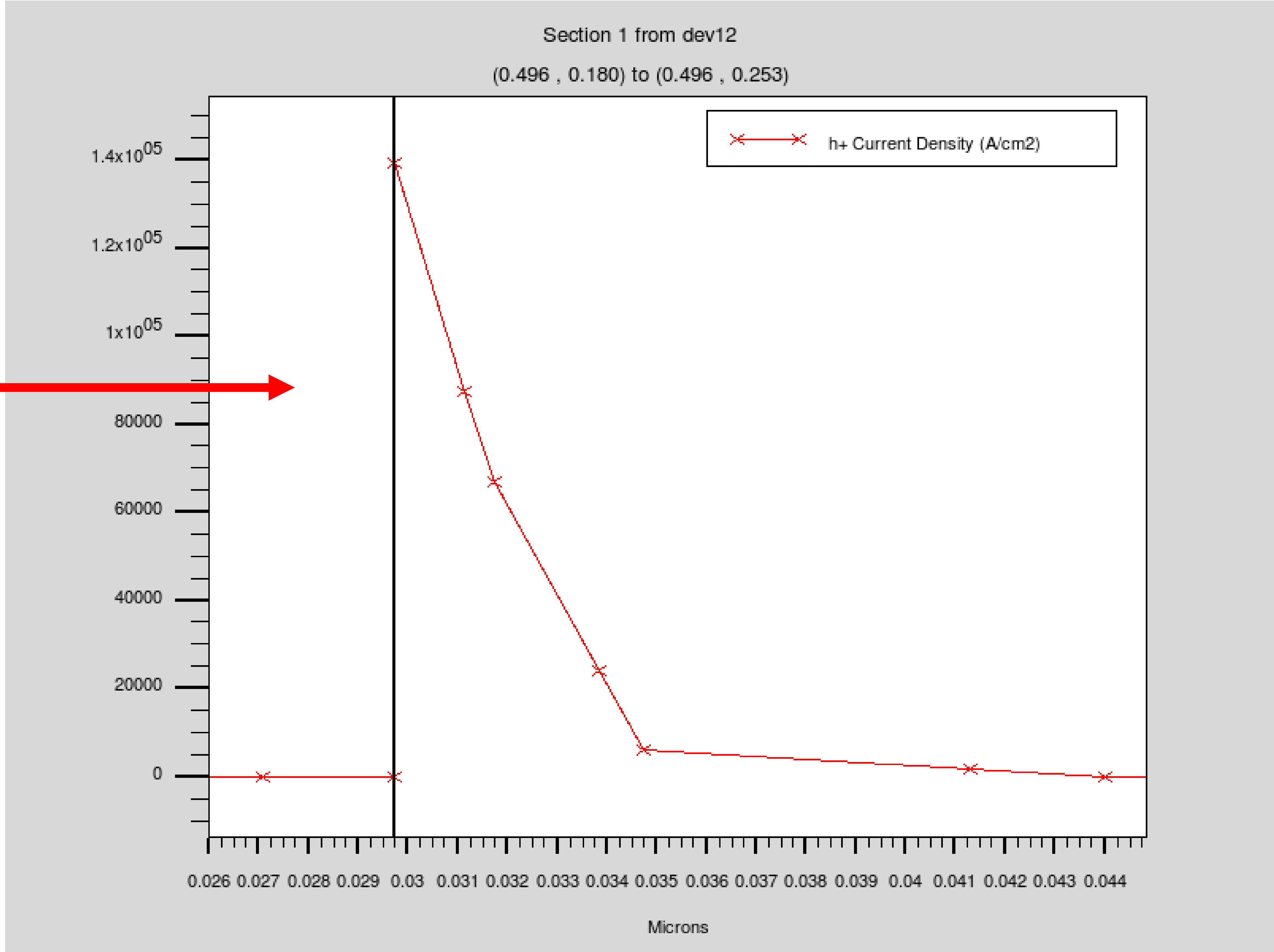
➢ Do not want any unnecessary nodes in mesh as increases computation time

➢ Require sufficient mesh in areas where dependent variables change to ensure accuracy

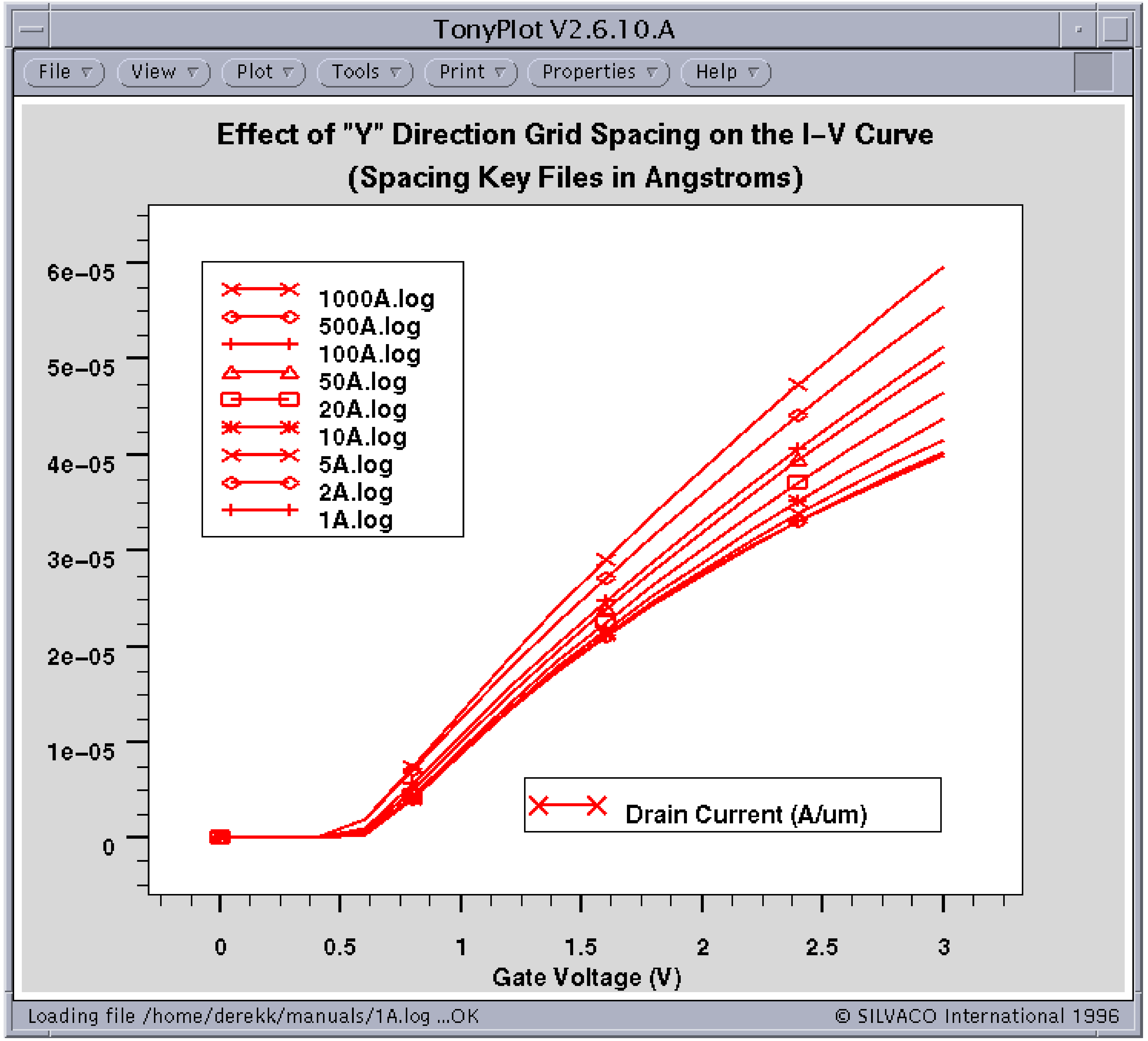
[*] SILVACO Athena Manual

Device Mesh Example – MOSFET mesh





Device Mesh Example – MOSFET mesh



Outline

- What is Technology Computer Aided Design (TCAD)?

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Models

- Always cross check simulations with experiments

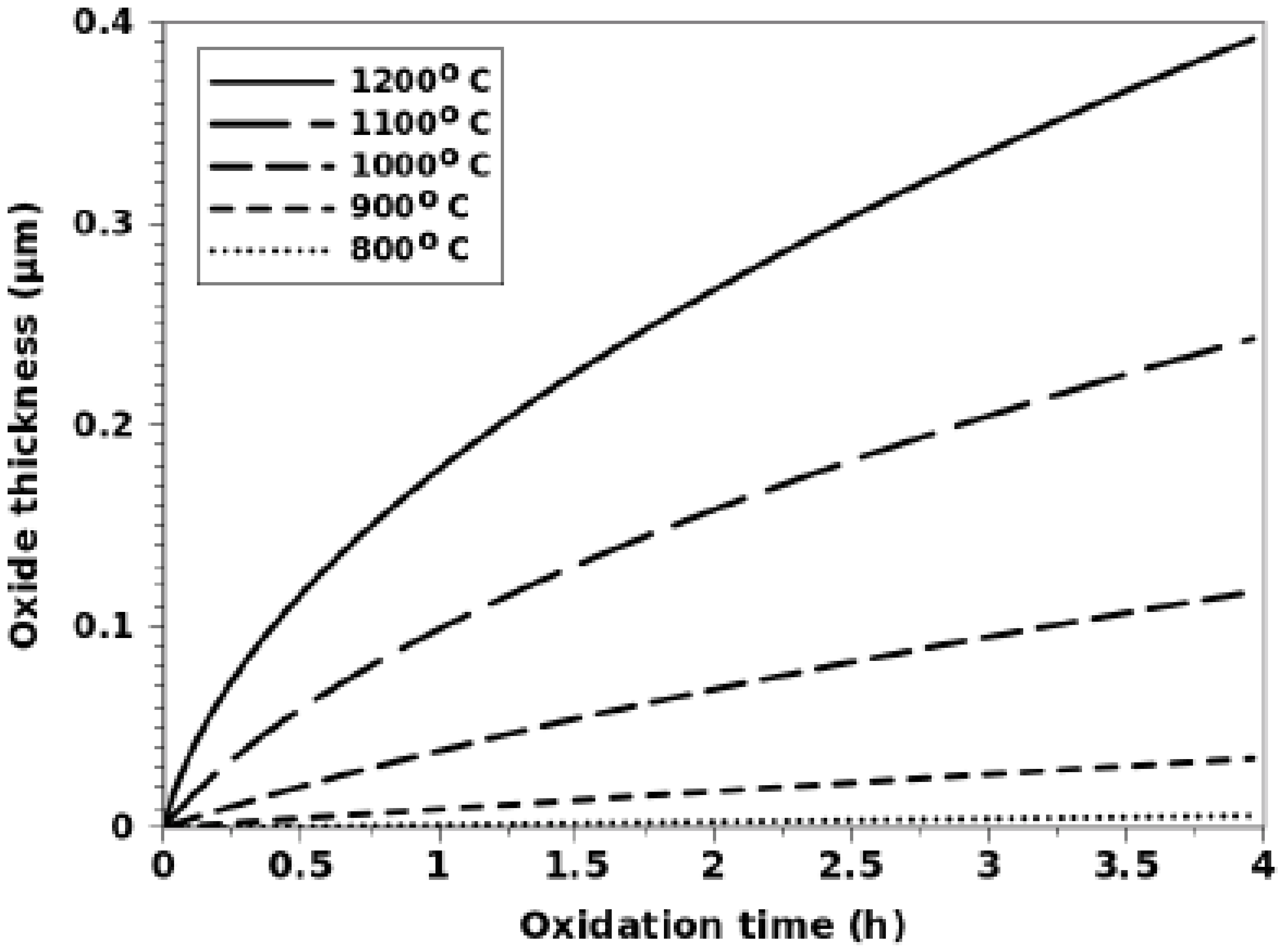
1. 1D Oxidation
2. Diffusion/Segregation of Dopants
3. Device Simulation

Gate Oxide Growth

Deal and Grove proposed a physics based linear-parabolic model to describe oxide growth on silicon

$$\frac{dx_o}{dt} = \frac{B}{A + 2xo}$$

where x_o is the oxide thickness and A and B are experimentally measured coefficients dependent on temperature, ambient, silicon orientation

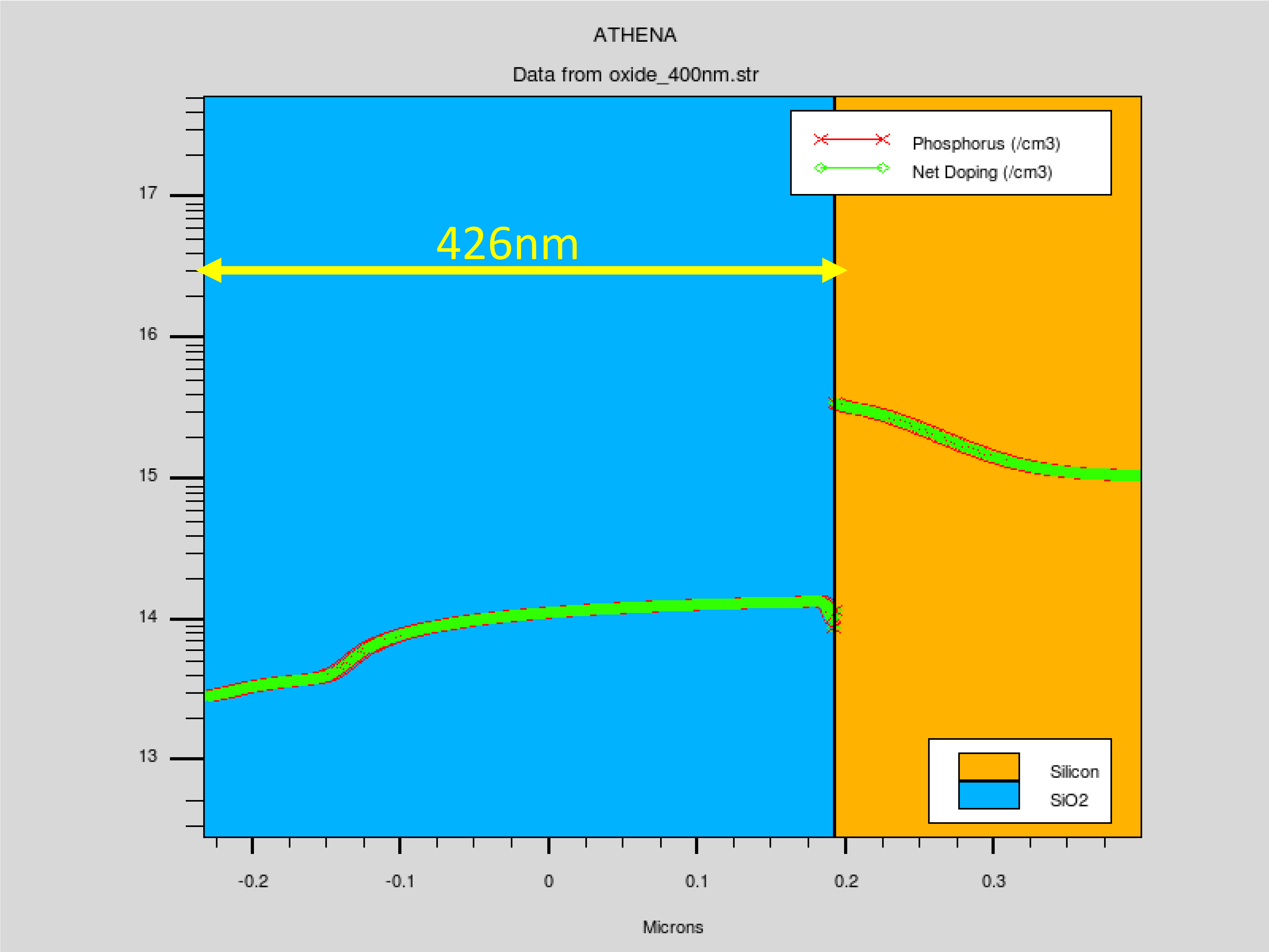


"Topography Simulation of Novel Processing Techniques", Ph.D. Thesis, by Lado Filipovic, 2012

Deal Grove Model – Tyndall

Design [nm]	Simulated [nm]
28	26
100	96
400	426
1000	1020

Tyndall Gate Oxides



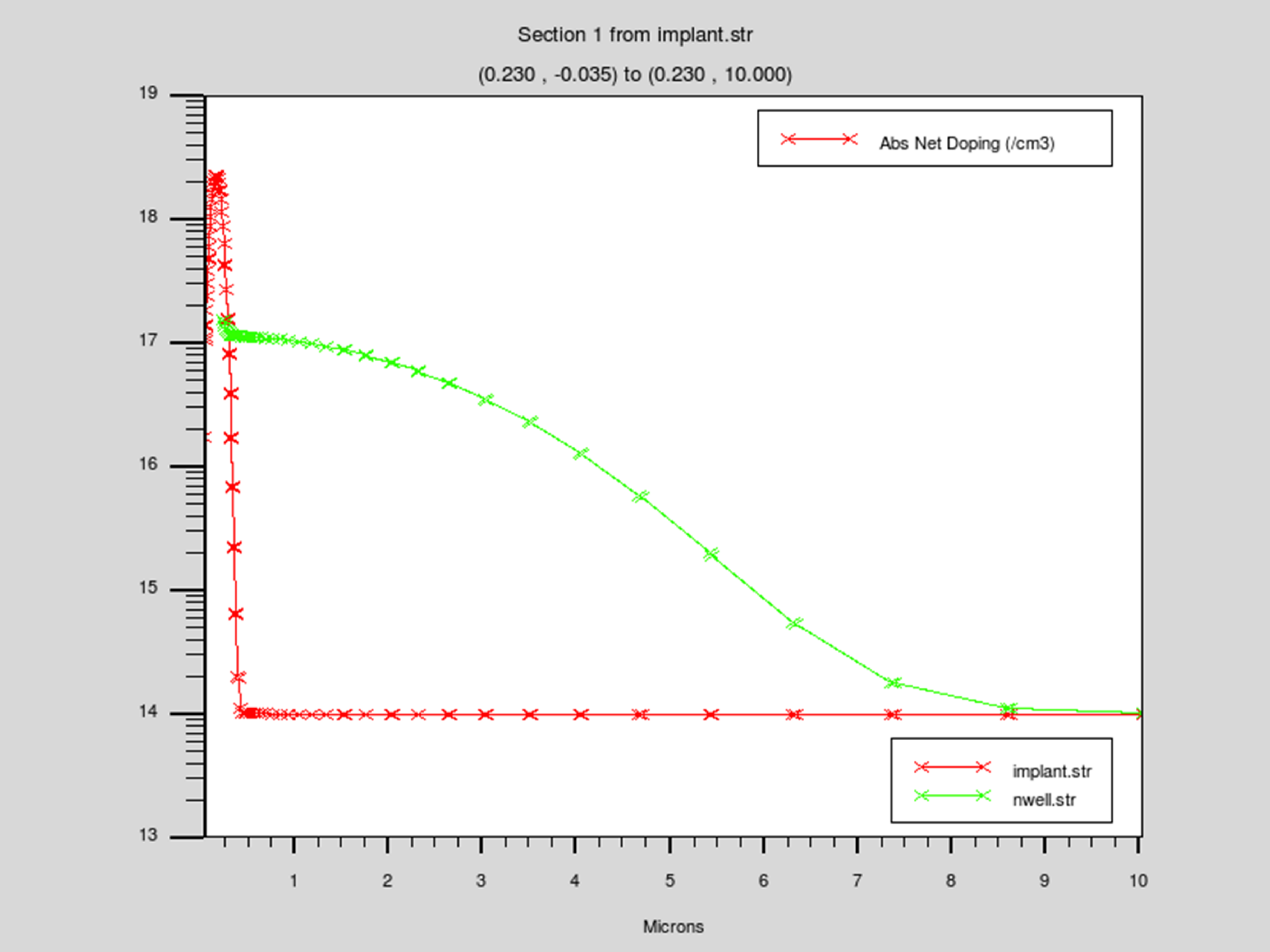
Gerlach, Gerald, and Karl Maser "A self-consistent model for thermal oxidation of silicon at low oxide thickness." *Advances in Condensed Matter Physics*, 2016

Dopant Diffusion Models

$$\frac{\partial C_A}{\partial t} = D_A \frac{\partial^2 C_A}{\partial x^2}$$

Where C_A is the dopant concentration and D_A is the Diffusion Coefficient

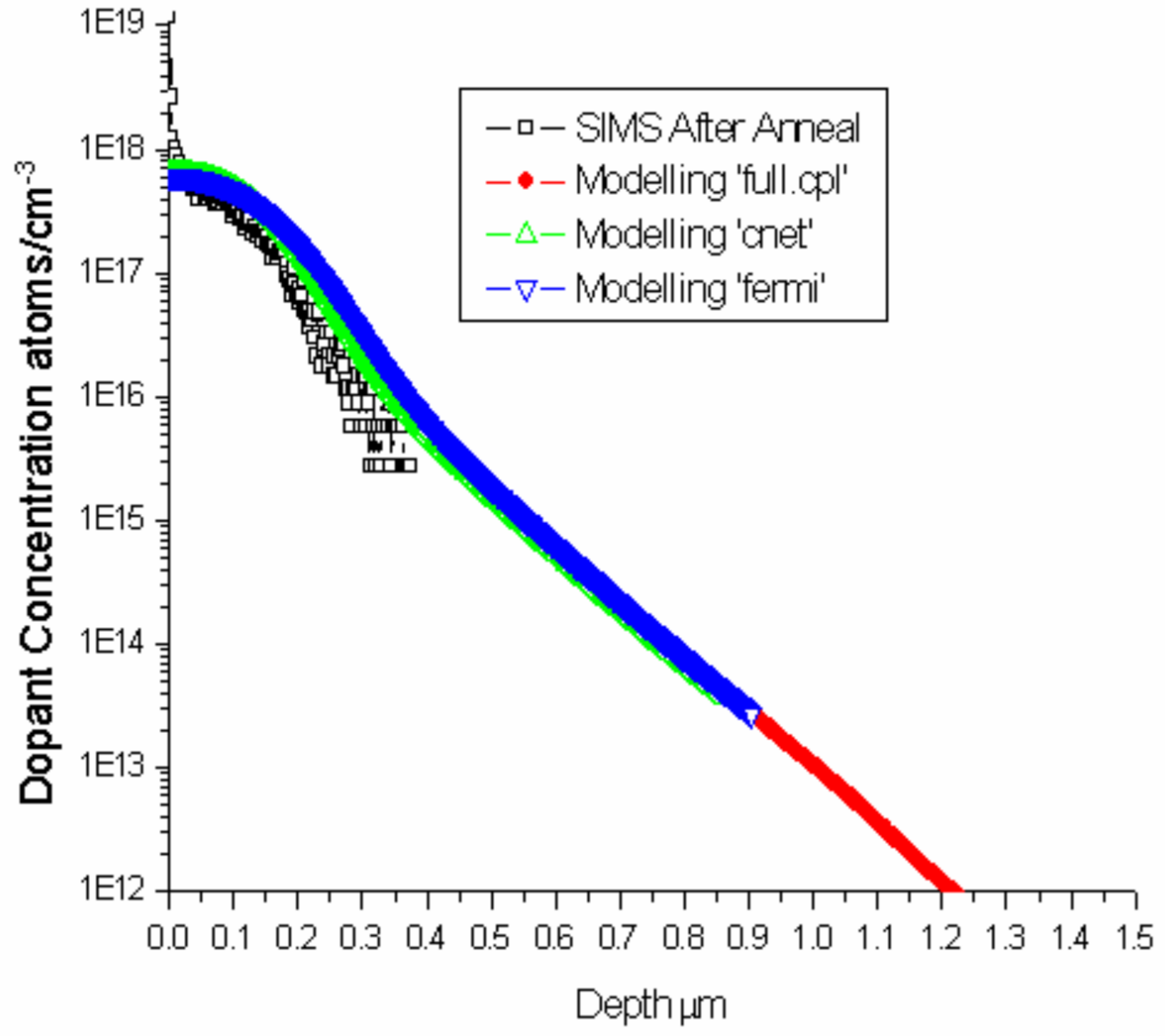
- Dopants are introduced into silicon through implantation or solid source diffusion
- Diffusion Coefficient (D_A) depends on defect distributions in the semiconductor
  - Implantation, Oxidation introduce defects
- Segregation of dopants into other materials at interfaces
  - e.g. gate oxide



Dopant Diffusion Models

- Simulations need to be carefully cross-checked against experiments prior to performing any optimisation studies

- Good agreement in the literature does not necessarily mean models will be accurate for your simulations



"Development of Fine Geometry SOI Technology," Rathnait Long, Masters Thesis, University College Cork.

Device Simulation Models

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1. Poisson's Equation (Gauss Law)

$$-\nabla \bullet (\varepsilon \nabla \psi) = \rho$$

where ε is the dielectric permittivity and ψ is the electric potential

and the charge density is defined $\rho = q(p - n + C)$

where q is the electronic charge; C is the electrically active net impurity concentration and p and n are the mobile hole and electron concs

2.. Current Continuity Equation (Charge conservation principle)

$$-\frac{1}{q}\nabla \cdot J_n - G_n + R_n + \frac{\partial n}{\partial t} = 0$$

$$\frac{1}{q}\nabla \cdot J_p - G_p + R_p + \frac{\partial p}{\partial t} = 0$$

where G and R are the generation and recombination rates and J_n and J_p are the electron and hole currents respectively

$$J_n = q\mu_n nE + qD_n \nabla n$$

$$J_p = q\mu_p pE - qD_p \nabla p$$

where $\mu_{n,p}$ and $D_{n,p}$ are the mobility and diffusion coefficients for electrons and holes and are experimentally determined

Mobility Model

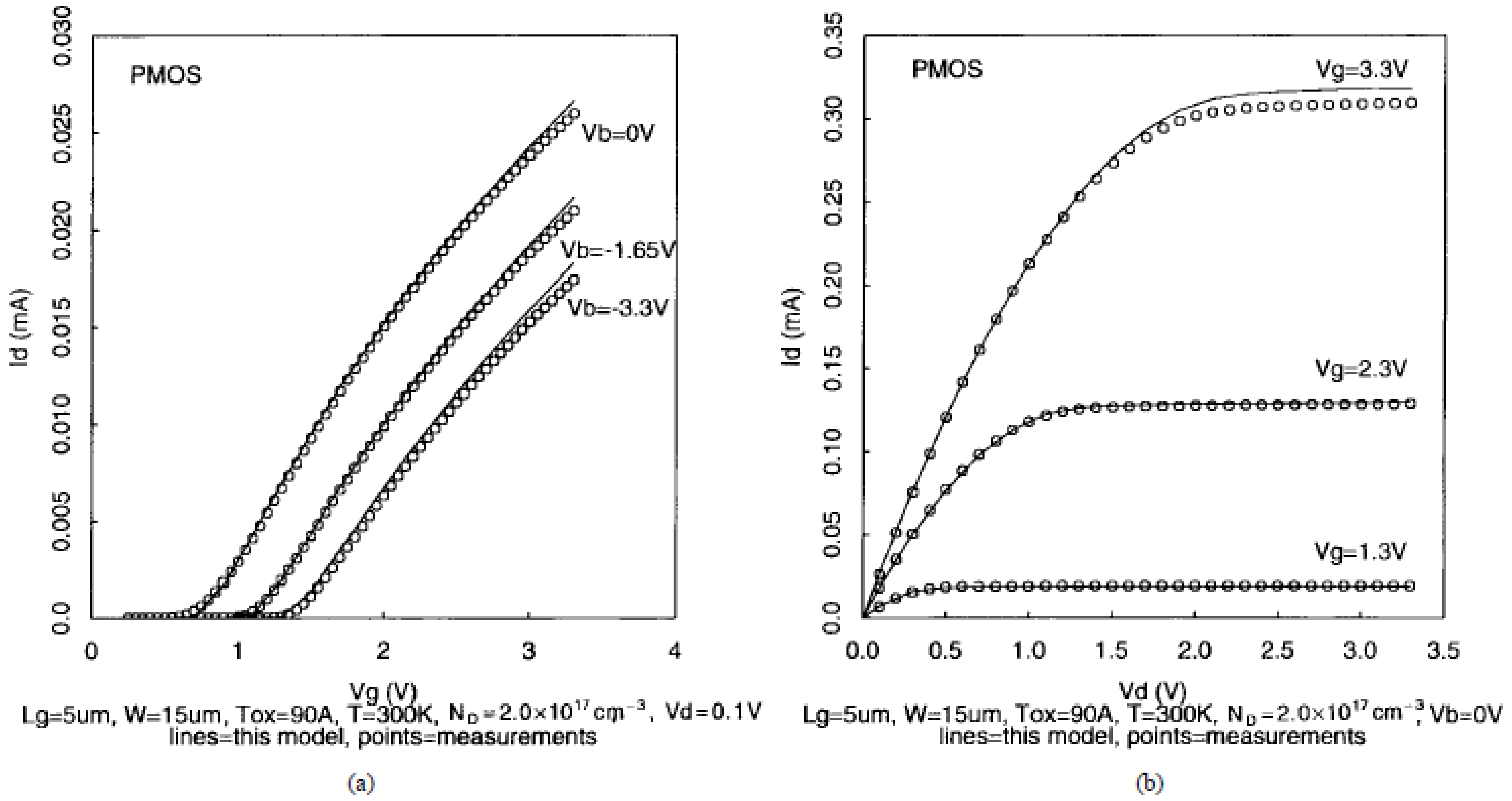
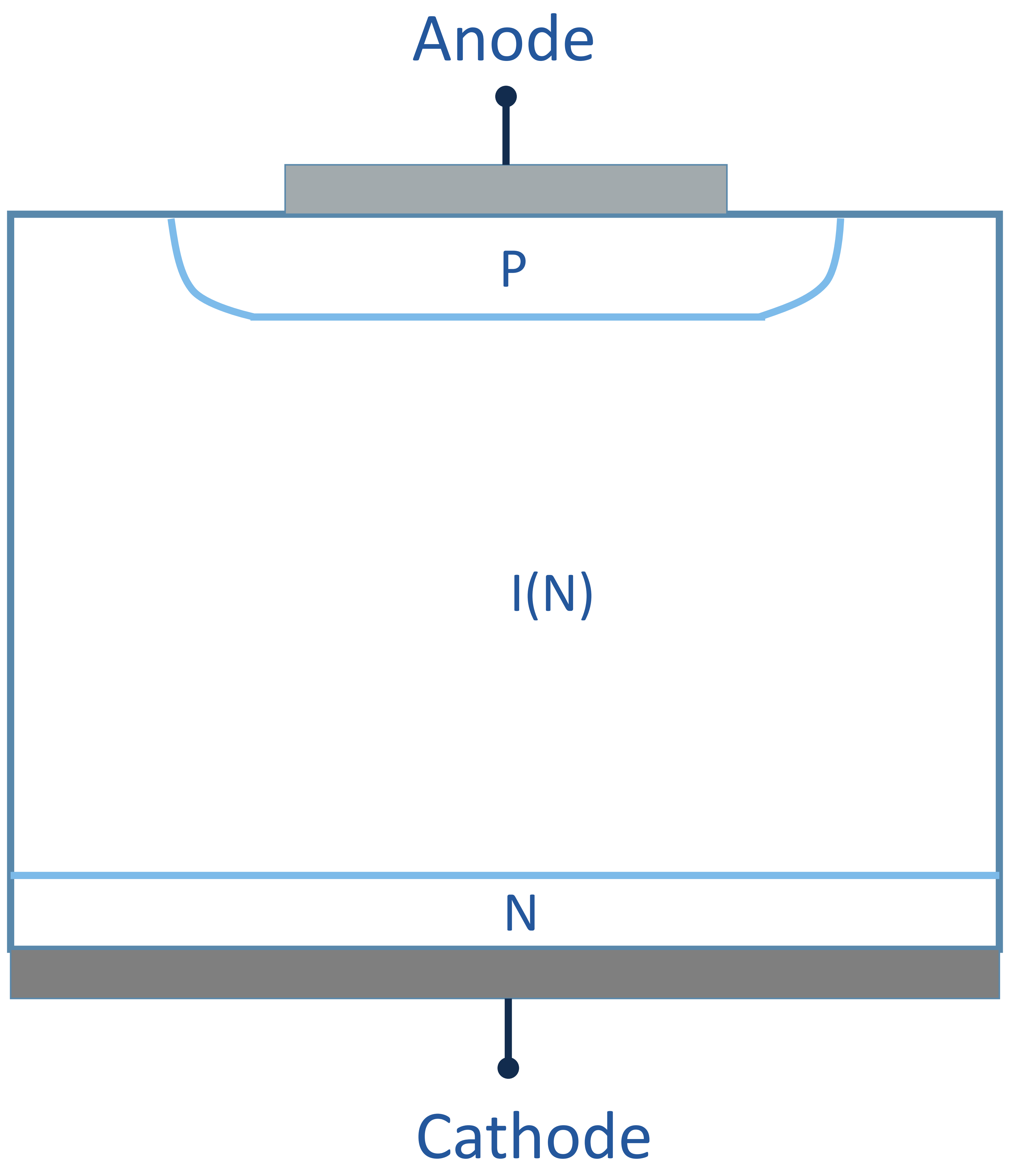


Fig. 10. (a) Threshold characteristics with $V_{bs} = 0, 1.65$, and 3.3 V, and (b) output characteristics with $V_{gs} = -1.3, -2.3$, and -3.3 V for a 5-μm long PMOS device with a 90 Å gate oxide. Points are measurements, lines are simulation.

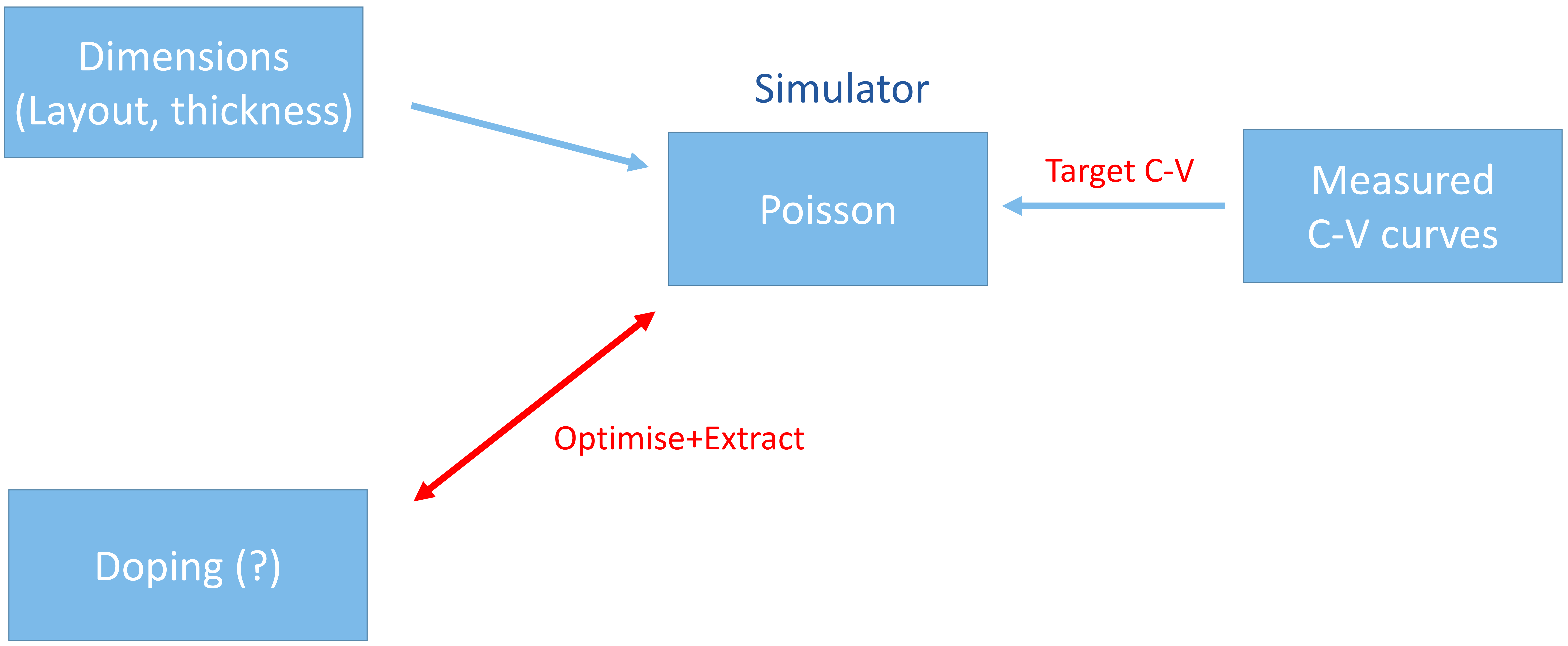
*** M. N. Darwish, J. L. Lentz, M. R. Pinto, P. M. Zeitzoff, T. J. Krutsick and Hong Ha Vuong, "An improved electron and hole mobility model for general purpose device simulation," in *IEEE Transactions on Electron Devices*, vol. 44, no. 9, pp. 1529-1538, Sept. 1997.**

PIN Diode Project

- PIN Diode Radiation Sensor
- Complicated Anode Metal Design
- Very low N-type substrate doping
    - Substrate Doping could not be measured

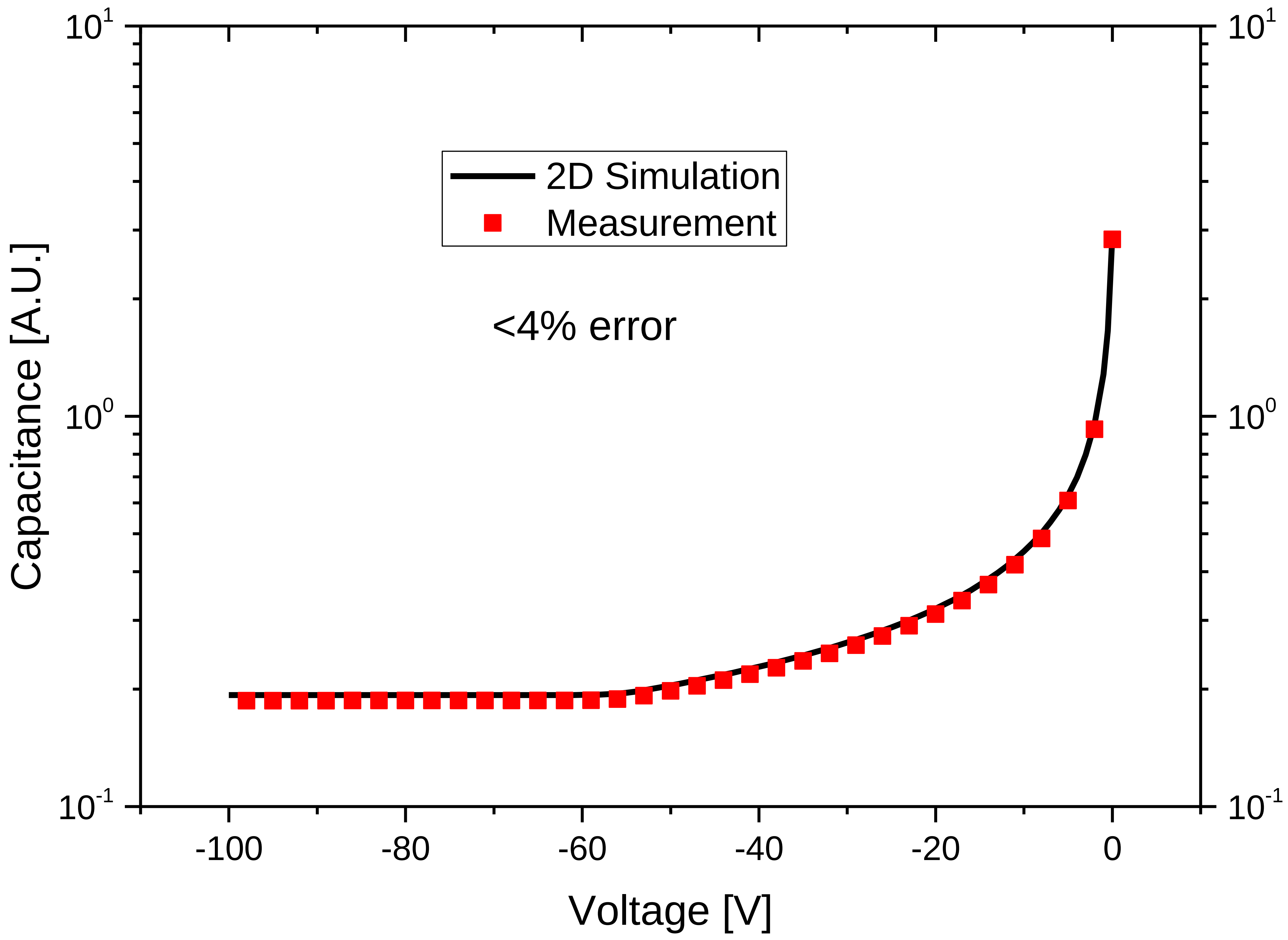


Inverse Modelling Approach



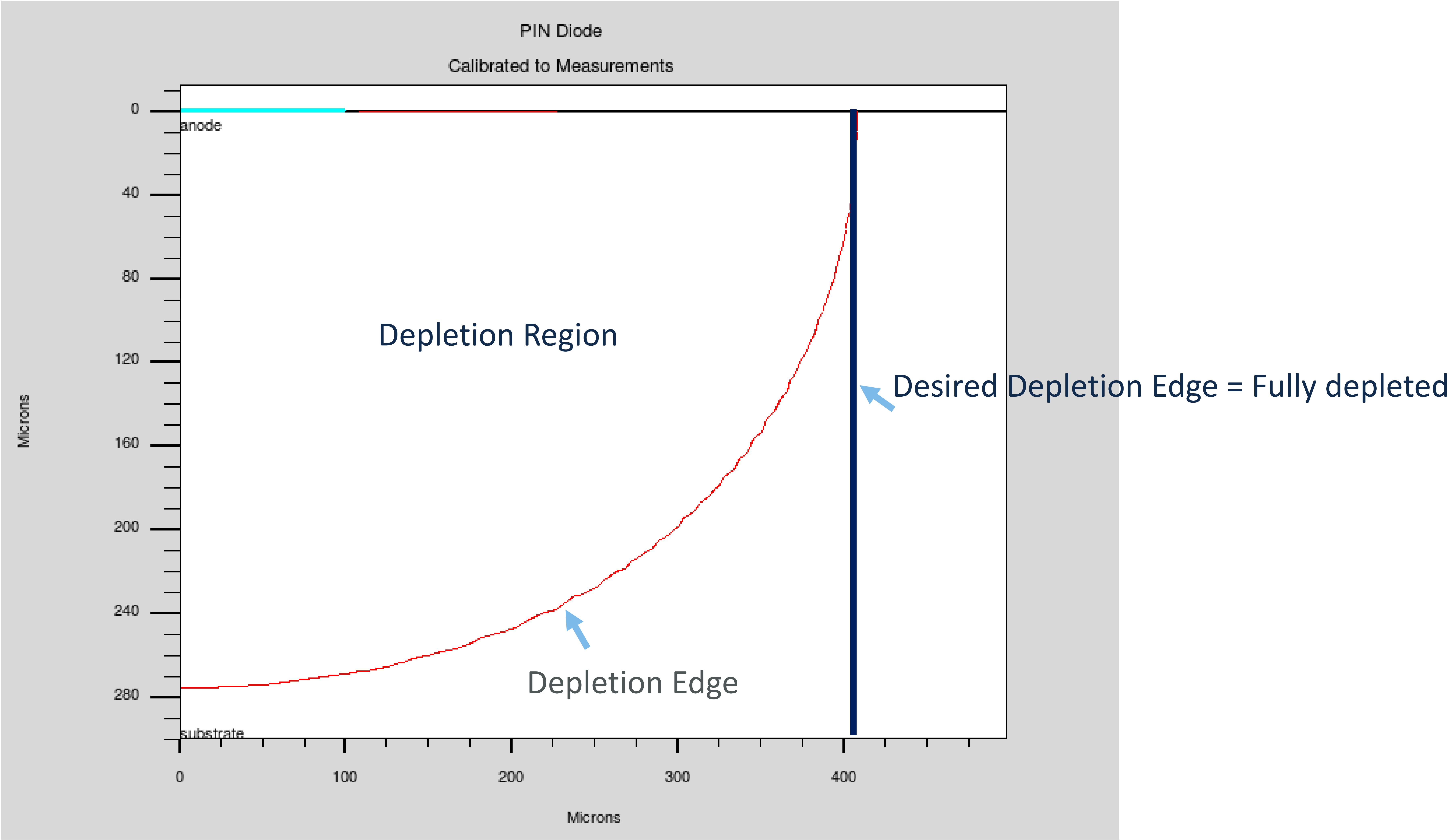
Chapter 2 of "Semiconductor Material and Device Analysis" by D.K. Schroder, 3rd Edition.

PIN Diode – Inverse modelling



- Uniform Substrate dopant extracted

PIN Diode - Depletion Region Shape



TCAD Summary

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- Useful Tool
  - Provide insight, understanding
  - Reduce matrix of experiments e.g. gate oxide optimisation
  - Inverse Model physical parameters such as doping
  - Not a replacement for measurements

- User needs to take care of
  - Mesh Definition
    - Simulation accuracy and computation time
  - Model Knowledge
    - Simulations always need to be cross-checked against measurements

Questions?

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