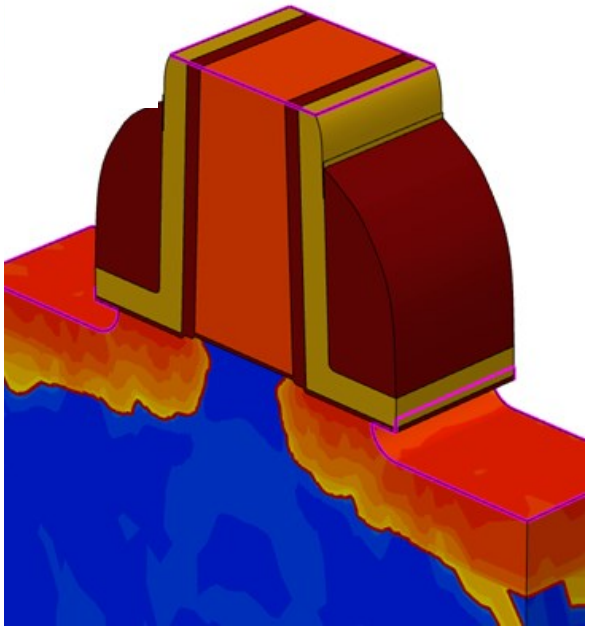
Technology Computer Aided Design (TCAD) Laboratory

Lecture 4, the ideal diode (pn-junction)



[Source: Synopsys]

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Outline

- Review of basic properties of the diode
- Sentaurus Workbench setup (SWB)
- Implementation of Input files
  - Sentaurus Structure Editor (SDE) command file
  - Sentaurus Device (SDevice)
    - command file
    - parameter file
- Run the simulation
- Post-processing of results

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The diode: structure and applications

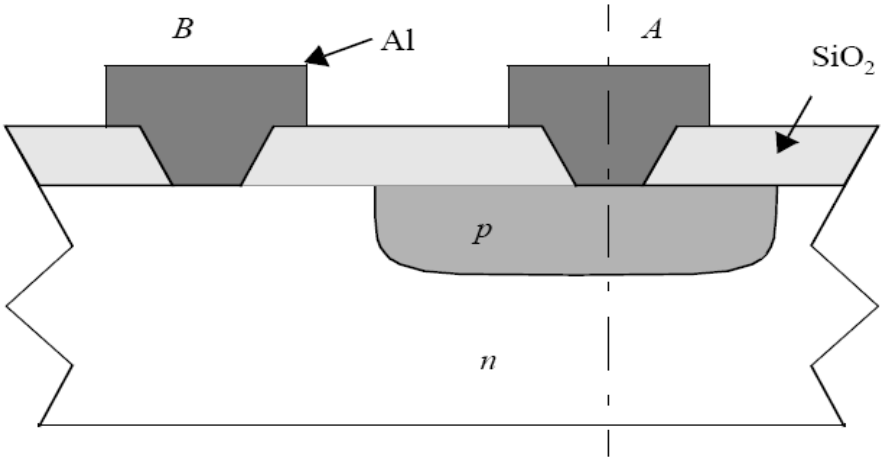
Structure:
Simplest possible semiconductor device is made by a so-called pn-junction.

It consist of two regions of homogeneous semiconductor, one doped with acceptors (*p-type*) and the other one doped with donors (*n-type*).

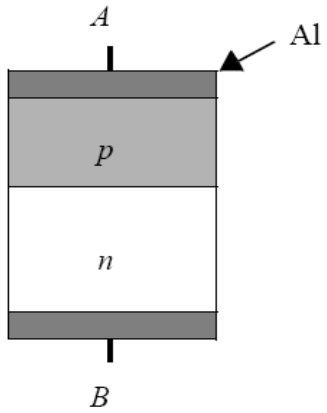
If the transition region between the two semiconductor types is assumed to be thin the junction is said to be *abrupt* or *step*

Applications:

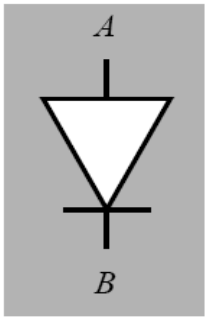
Logic: rarely integrated in the schematic of digital systems but omnipresent, as the Metal-Oxide-Semiconductor Field-Effect-Transistor (MOSFET) contains several reverse-biased diodes. Also, used as a device to protect IC input from ElectroStatic Discharges (ESD).
Optoelectronic devices: solar cells, lasers, LED.



(a) Cross-section of *pn*-junction in an IC process



(b) One-dimensional representation



(c) Diode symbol

The diode: physics at equilibrium

- Because of the concentration gradient experienced by electrons and holes in the structure (*p* -region rich of holes and depleted of electrons, *n*-region rich of electrons and depleted of holes), when the junction is formed, electrons tend to pass from the *n*- to the *p*-region, and holes do the opposite.
- As a result of diffusion, some dopants near the junction are depleted of free charge (i.e. they become ionized), giving origin to the so-called “space-charge-region”.
- These fixed ion charges create an electrostatic potential which tends to hamper a further diffusion of carriers (they give rise to the so-called “built-in” potential) by superimposing to the diffusion current a drift component.
- At equilibrium drift and diffusion microscopically counterbalance each other and no current flows in the device.

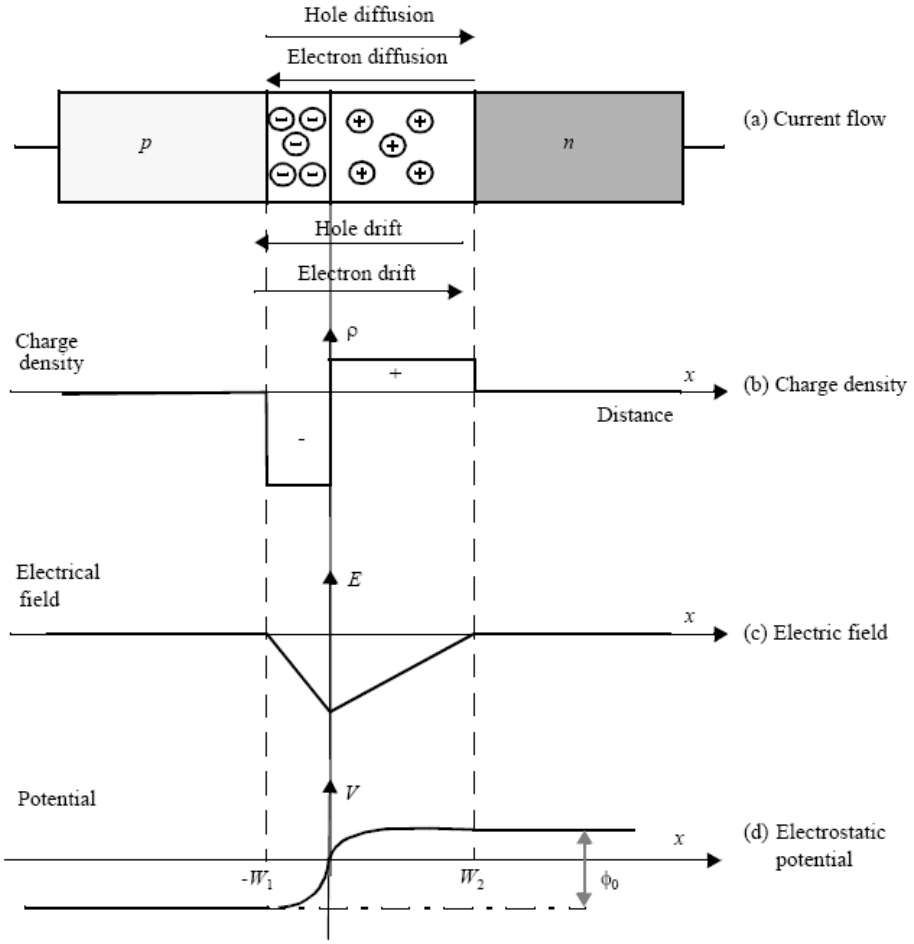


Figure 3.2 The abrupt *pn*-junction under equilibrium bias.

in this example, *p*-doping is higher than *n*-doping, giving rise to a thinner depletion region at the *p*-side

The diode: built-in potential

- If N_A is the concentration of acceptors at the *p*-side, and N_D is the concentration of donors art the *n*-side, it can be shown that, **if the semiconductors are non-degenerate**, the built-in potential φ_0 is given by the formula (1), where the thermal voltage $\varphi_T = kT/q$ = 26mV at room temperature, and where n_i is the semiconductor intrinsic carrier density, which is a material property (depends on density of states and on band-gap)

- Therefore, **the higher the product of the *p* and *n* doping, the higher φ_0**

- The built-in potential is "built-in" since it is an intrinsic property of the junction. It represents the energy barrier that majority carriers (electron in *n*-region, holes in *p*-region) have to overcome in order to obtain a net current flow by diffusion

$$\varphi_0 = \varphi_T \ln\left(\frac{N_A N_D}{{n_i}^2}\right) \quad (1)$$

Example (Silicon)

If $N_A = 10^{16} cm^{-3}$, and $N_D = 10^{16} cm^{-3}$, $n_i \cong 1.5x10^{10}\ cm^{-3}$,

φ_0 = 697 mV

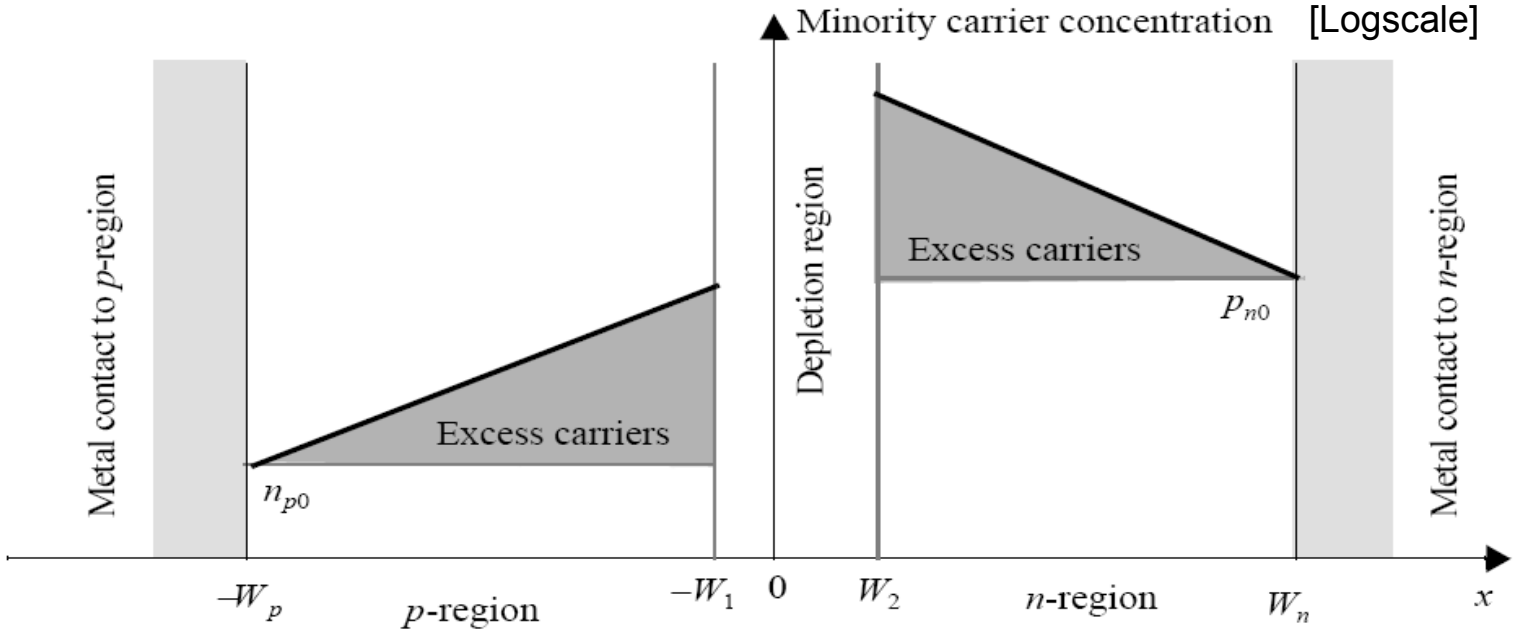
- By modulating the built-in voltage using an external battery it is possible to modulate the behavior of the device. In particular:

- The application of a positive voltage at the *p*-region (or, equivalently, a negative voltage at the *n*-region) lowers the potential barriers, and current can flow by diffusion through the space-charge region. In this regime, current increases exponentially with voltage and the diode is said to be forward biased.

- The application of a negative voltage at the *p*-region (or, equivalently, a positive voltage at the *n*-region) further increases the potential barrier, current can flow only by drift of minority carriers, it is very weak and almost independent by voltage. In this regime, the diode is said to be reverse biased.

The diode in forward bias

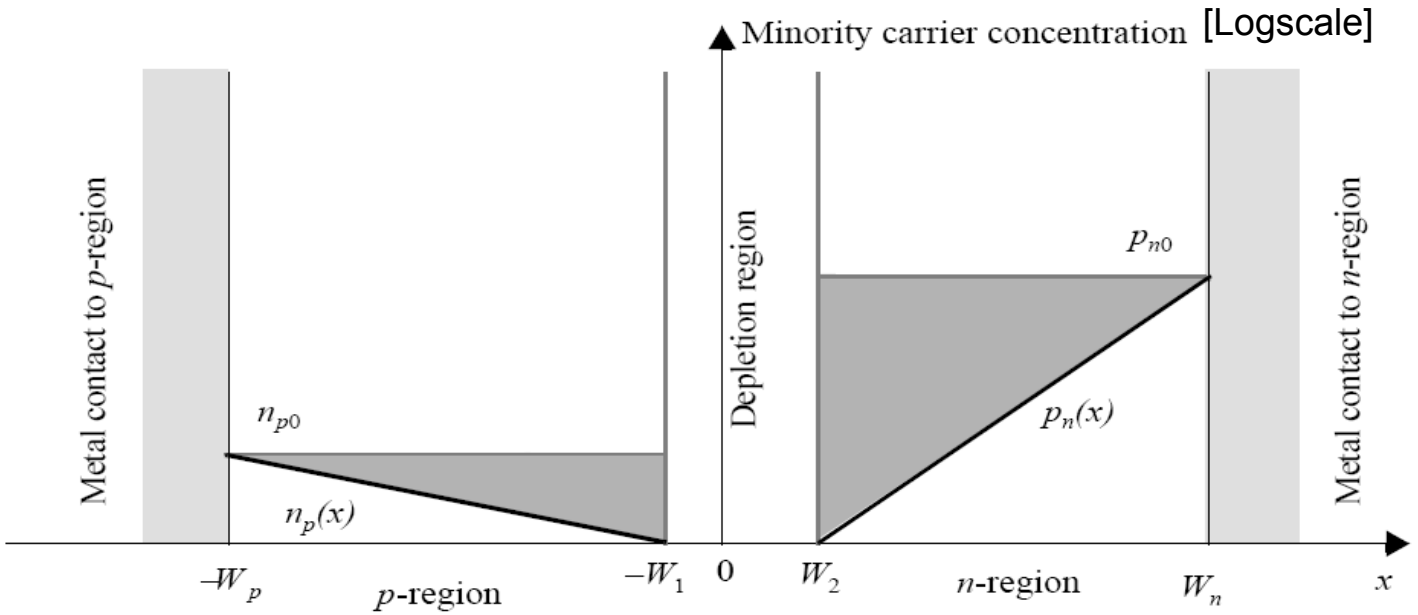
- In forward bias, electrons from the *n*-region can flow toward the *p*-region, and holes from the *p*-region can flow toward the *n*-region, causing an **excess (compared to the equilibrium condition, n_{p0}, p_{n0}) of electrons in the *p*-region and of holes in the *n*-region**. **This excess of carriers is named "minority carrier excess".** It can be shown that the minority carrier concentration is exponentially decreasing from the junction line. The minority carrier profile it is approximated with a linear behavior if there is no generation-recombination (i.e. no traps or very short diode)
- These excess carriers give rise to a large current which exponentially increases with voltage. In forward bias the diode is conducting, ideally as a short circuit.



in this example, *p*-doping is higher than *n*-doping, thus the amount of available holes is higher than the amount of available electrons

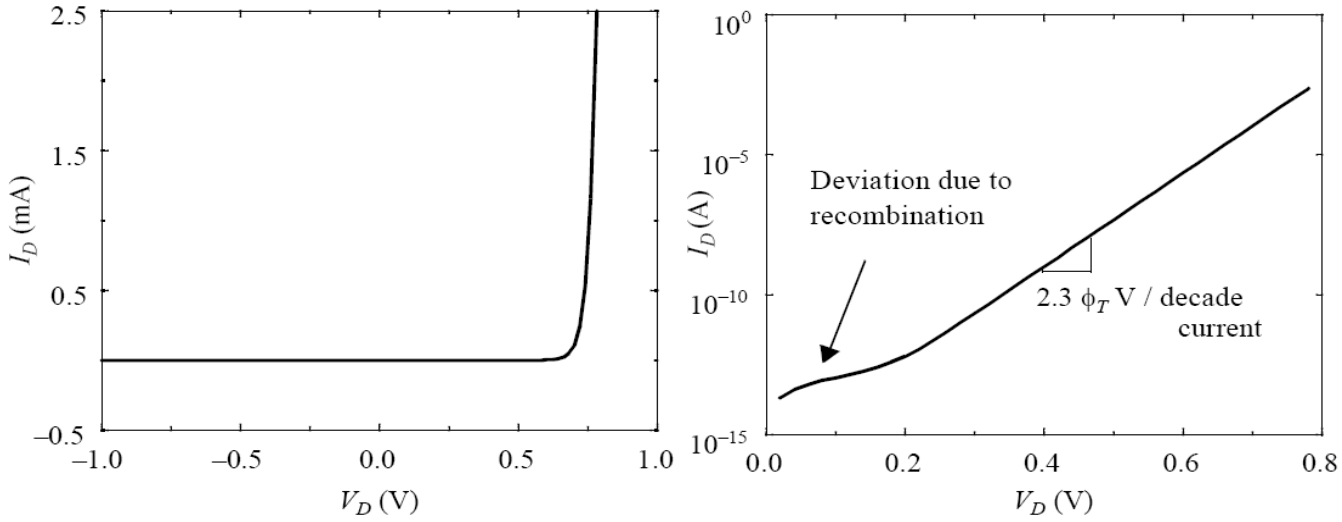
The diode in reverse bias

- In reverse bias, minority carriers leave the space charge region because of the reverse field. The space-charge region width is increased, and there is a diminution of minority carriers compared to the equilibrium condition. The minority carrier profile is again exponential, but it is often approximated by a linear behavior if there is no generation-recombination (i.e. no traps or very short diode)
- The concentration of moving carriers in the space-charge region is very low, therefore in reverse bias the diode is practically a non-conducting device, ideally an open circuit.



The diode: electrical behavior and compact model

- the diode acts as a one-way conductor with an exponential behavior
- in direct bias, the current increases of a factor of 10 for every extra 60 mV
- at small voltages, a deviation of the slope of the exponential behavior can be observed: it is due to generation-recombination phenomena occurring in the space-charge region



(a) On a linear scale

(b) On a logarithmic scale (forward bias only)

- The compact model for the diode IV characteristics is given in Eq.(2):

$$I_D = I_S[e^{V_D/(\eta\varphi_T)} - 1] \quad (2)$$

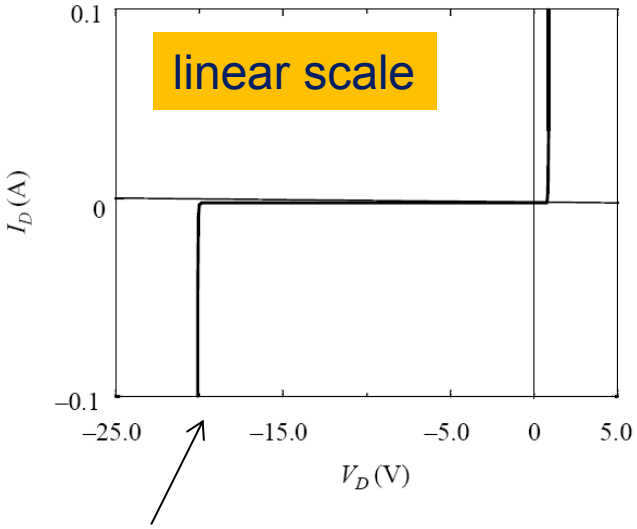
where I_D is the current flowing through the diode, V_D is the applied bias, and I_S is called the *reverse saturation current* (since if $V_D < 0, ID \cong -IS$~10^{-17} A for a silicon device with an area of 1 μm^2). It depends on many physical parameters like doping and diffusion lengths. Finally, η is called the ideality factor, it is a number between 1 and 2; the more the generation-recombination phenomena are important, the more its values approaches 2.

Secondary effects

1. Voltage drop over the neutral region → series resistance. Only significant al large currents (> 1mA)
2. When the reverse bias exceeds a certain level called *breakdown voltage*, the current is no more constant but shows a dramatically increase. This behavior is due to the *avalanche breakdown* or to the *Zener breakdown* phenomena.

Avalanche Breakdown.
In reverse bias, the built-in barrier is raised by the application of a reverse polarity bias. Therefore, carriers crossing the depletion region are accelerated to high velocity. **At a critical field, the carriers have enough kinetic energy to create electron-hole pairs by collisions with the lattice silicon atoms**. These carriers create in turn other carriers before leaving the depletion region (critical field in the order of 2 x10^5 V/cm for impurity in the order of 10^{16}cm^{-3})
While avalanche in itself is not destructive and its effect disappears after the reverse bias is removed, maintaining a diode for a long time in avalanche condition can lead to a permanent damage of the structure owing to Joule heating.

Zener breakdown.
Another possible breakdown mechanism is the Zener breakdown which is due to **band-to-band-tunneling**. Also Zener breakdown is triggered by the high electric fields occurring in the space-charge region. Zener breakdown yields lower current than Avalanche breakdown and it is not supposed to produce damage in the lattice structure (for Zener, the word "breakdown" is more to be intended as "breakdown of the ideal characteristics"). The occurrence of first avalanche or first Zener breakdown by increasing the reverse voltage depends on the characteristics of the diode (materials, doping..). Diode in which Zener occurs first are referred to "Zener diodes". If biased at the Zener breakdown voltage they can serve as batteries (*almos*t fixed V_D independent from I passing through the device)



in this example the breakdown voltage is -20V

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SWB: project tools & parameters (1)

OPEN SWB FROM THE LINUX COMMAND LINE

```
swb &
```

STARTING (AND SAVING) A NEW SWB PROJECT

`Project → New → New Project`

`Project→ Save as → Project → pn_ideale`

ADD TOOLS

left click on `No tools` → right click → `Add` → Name, scroll for `Sde` → select `Batch` → `Ok`

left click on `Sde` → right click → `Add` → Name → scroll for `Sdevice` → `Ok`

BATCH MODE MEANS “COMMAND FILE MODE”, i.e. NOT INTERACTIVE

ADD PARAMETERS (WITH THEIR DEFAULT VALUES): SDE /GEOMETRY AND DOPING

Right click in the box just below `SDE` tool → `SRH` → `default value` → `0`

`Parameter→ Add → Parameter→ material → default value → Silicon → Ok`

Right click on `material` → `Add` → `Parameter` →`Wp` → `default value` → `10`

IN SENTAURUS, THE GEOMETRICAL DIMENSIONS ARE INTENDED IN MICRON (=1x10^{-6} m)

Right click on `Wp` → `Add` → `Parameter` →`Wn`→ `default value` → `50`

Right click on `Wn` → `Add` → `Parameter` →`p_doping`→ `default value` → `1e16`

IN SENTAURUS, DOPING IS INTENDED IN cm^{-3}

Right click on `p_doping` → `Add` → `Parameter` →`n_doping`→`1e16`

ADD PARAMETERS (WITH THEIR DEFAULT VALUES): SDEVICE /MODELS AND VOLTAGES

Right click in the box just below `Sdevice` tool → `SRH` → `default value` → `0`

FLAG FOR ACTIVATING SHOCKLEY-READ-HALL GENERATION-RECOMBINATION MODEL

SWB: project tools & parameters (2)

Right click on SRH → V_start → default value → -1
IN SENTAURUS VOLTAGE IS INTENDED IN VOLTS
Right click on V_start → V_stop → default value → 1.5

ADD A NEW EXPERIMENT (A WHOLE LINE)
Experiments → Add New Experiment → material → Germanium → Apply → Ok
Experiments → Add New Experiment → material→ GaAs → Apply → Ok

EXPERIMENT RAMIFICATION
Left click just below the box p_doping **of first line** →Nodes → Extend Selection To Experiments → Experiments → Add Values → Parameter → p_doping → Min. Value: 1e18 → Step: 0 → Number of values: 1 → Apply → Ok

CHANGING A SINGLE NODE VALUE
Left click on the box containing the n_doping value of the second row →F6 → 1e18 → enter

MAKING A TREE
Left click below SRH **of first line** →Nodes → Extend Selection To Experiment → Experiments → Add Values → Parameter → SRH → Min. Value: 1 → Step: 0 → Number of values :1 → Apply → Ok

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SDE: writing the command file (1)

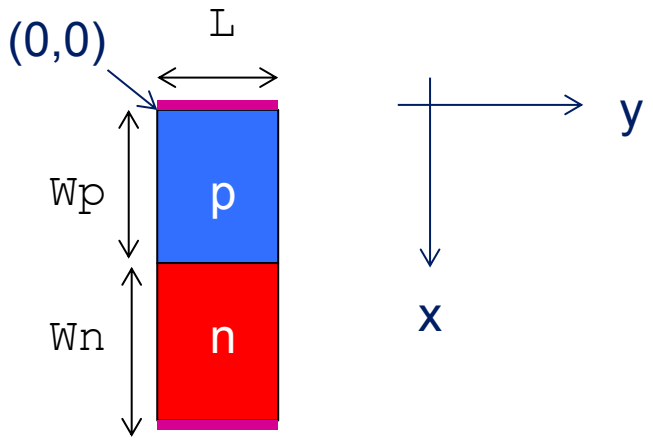
OPEN A TEXT EDITOR FROM THE COMMAND LINE

```
gedit &
File → Save As → sde_dvs.cmd
```

TYPE :

to include line of comment in the code

```
; *** IDEAL PN JUNCTION - sde_dvs.cmd ***
; *** INITIALIZATION ***
; clear structure
(sde:clear)
; New-replace-old option (default)
(sdegeo:set-default-boolean "ABA")
; *** DEFINITIONS ***
; MATERIAL
(define material "@material@")
; define length
(define L 50)
; p region thickness
(define Wp @Wp@)
; region thickness
(define Wn @Wn@)
; DOPING PARAMETERS
(define p_doping @p_doping@)
(define n_doping @n_doping@)
```



write variables defined in the SWB tree between "@"

in this way, at the preprocessing steps, Sentaurus will automatically write a file for each possible combination of variable, making easier the solution of complex project trees

SDE command file (2)

```
; MESH PARAMETERS
(define xmax 10)
(define xmin 0.1)
(define ymax 1)
(define ymin 0.1)
; *** GEOMETRY ***
; convention: x=length y=thickness
; create p region
(sdegeo:create-rectangle (position 0 0 0) (position L Wp 0) material "p-region")
; create n region
(sdegeo:create-rectangle (position 0 Wp 0) (position L (+ Wn Wp) 0) material "n-
region")
; *** CONTACTS ***
; a) SET VERTEXES
; 1st vertex on p_contact
(sdegeo:insert-vertex (position 0 0 0))
; 2nd vertex on p_contact
(sdegeo:insert-vertex (position L 0 0))
; 1st vertex on n_contact
(sdegeo:insert-vertex (position 0 (+ Wn Wp) 0))
; 2nd vertex on n_contact
(sdegeo:insert-vertex (position L (+ Wn Wp) 0))
```

SDE command file (3)

```
; b) SET EDGE (DECLARATION, ACTIVATION AND DEFINITION)
; p_contact
(sdegeo:define-contact-set "p_contact" 4 (color:rgb 1 0 0) "##")
(sdegeo:set-current-contact-set "p_contact")
(sdegeo:define-2d-contact (find-edge-id (position (* L 0.5) 0 0)) "p_contact")
; n_contact
(sdegeo:define-contact-set "n_contact" 4 (color:rgb 1 0 0) "##")
(sdegeo:set-current-contact-set "n_contact")
(sdegeo:define-2d-contact (find-edge-id (position (* L 0.5) (+ Wn Wp) 0))
"n_contact")
; *** DOPING ****
; p-region
(sdedr:define-constant-profile "p-doping-profile" "BoronActiveConcentration"
@p_doping@)
(sdedr:define-constant-profile-region "p-doping-placement" "p-doping-profile" "p-
region")
(sdedr:define-constant-profile-placement "p-doping-placement" "p-doping-profile"
"p-doping-window")

; n-region
(sdedr:define-constant-profile "n-doping-profile" "PhosphorusActiveConcentration"
@n_doping@)
```

keyword for p-doping of EACH material

keyword for n-doping of EACH material

SDE command file (4)

```
(sdedr:define-constant-profile-region "n-doping-placement" "n-doping-
profile" "n-region")
(sdedr:define-constant-profile-placement "n-doping-placement" "n-doping-
profile" "n-doping-window")
; *** MESH ***
; * WHOLE DOMAIN
(sdedr:define-refeval-window "domain-ref" "Rectangle" (position 0 0 0)
(position L (+ Wn Wp) 0))
(sdedr:define-refinement-size "domain-ref-size" xmax ymax xmin ymin)
(sdedr:define-refinement-placement "domain-ref-pl" "domain-ref-size"
"domain-ref")
; * p-n JUNCTION REFINEMENT
(sdedr:define-refeval-window "junction-ref" "Rectangle" (position 0 (- Wp
0.050) 0) (position L (+ Wp 0.050) 0))
(sdedr:define-refinement-size "junction-ref-size" (/ xmax 10) (/ ymax 10)
(/ xmin 10) (/ ymin 10))
(sdedr:define-refinement-placement "junction-ref-pl" "junction-ref-size"
"junction-ref")
; * BUILDING MESH
(sde:build-mesh "snmesh" "-a -c boxmethod" "n@node@")
```

- Save → Quit

means the current node

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Sdevice: writing the command file (1)

```
*** PN JUNCTION - sdevice_des.cmd ***
File
{
    **** INPUT FILES
    * geometry, contacts, doping and mesh
    Grid ="@tdr@"
    * physical parameters
    Parameter = "@parameter@"
    **** OUTPUT FILES
    * to visualize distributed variables
    Plot = "n@node@_des.tdr"
    * to visualize electrical characteristics at the electrodes
    Current= "n@node@_des.plt"

}
Electrode
{
    * defines which contacts have to be treated as electrodes
    * & initial boundary conditions
    * obviously, electrode names must match the contact names of the
    * sde_dvs.cmd file
    { name="p_contact" voltage=0.0 }
    { name="n_contact" voltage=0.0 }
}
```

comment here is * and no more ; as it was in SDE!

automatically get the _msh.tdr file of the experiment

automatically get parameter file of the experiment

distributed quantity (field, potential, carrier concentrations..)

electrical characteristics

Sdevice input file (2)

```
Physics
{
        Mobility (
                 DopingDependence
                   )
        Recombination (
                       #if @SRH@ == 1
                        SRH
                       #endif
                       )


AreaFactor=2
}
```

activation of physical models

the device in this example is 2D. By default, the width in the third dimension is taken to be equal to 1μm. By specifying this value, on the contrary, currents are multiplied by `AreaFactor`, which in this example with take equal to 2 μm

Sdevice command file (3)

```
Plot
{
* On-mesh-defined variables to be saved in the .tdr output file
*- Doping Profiles
        Doping DonorConcentration AcceptorConcentration
*- Charge, field, potential and potential energy
        SpaceCharge
        ElectricField/Vector Potential
        BandGap EffectiveBandGap BandGapNarrowing ElectronAffinity
        ConductionBandEnergy ValenceBandEnergy
*- Carrier Densities:
        EffectiveIntrinsicDensity IntrinsicDensity
        eDensity hDensity
        eQuasiFermiEnergy hQuasiFermiEnergy
*- Currents and current components:
        eGradQuasiFermi/Vector hGradQuasiFermi/Vector
        eMobility hMobility eVelocity hVelocity
        Current/Vector eCurrent/Vector hCurrent/Vector
        eDriftVelocity/Vector hDriftVelocity/Vector
*- SRH & interfacial traps
        SRHrecombination
        tSRHrecombination
```

These keywords under the Plot section allow plotting the distributed quantities simulated (both scalar and vectors).
Some of the keywords refer to quantities that are calculated only if the respective physical model are activated. Anyway, the keywords can be included in the Plot section command file even if the respective models have not been activated (useful to have a standard template of Plot section)

Sdevice command file (4)

```
*- Band2Band Tunneling & II
        eBand2BandGeneration hBand2BandGeneration Band2BandGeneration
        eAvalanche hAvalanche Avalanche
}
Math
{
  * use previous two solutions (if any) to extrapolate next
  Extrapolate
  * use full derivatives in Newton method
  Derivatives
  * control on relative and absolute errors
  -RelErrControl
  * relative error= 10^(-Digits)
  Digits=5
  * absolute error
  Error(electron)=1e8
  Error(hole)=1e8
  * numerical parameter for space-charge regions
  eDrForceRefDens=1e10
  hDrForceRefDens=1e10
  * maximum number of iteration at each step
  Iterations=20
  * choosing the solver of the linear system
  Method=ParDiSo
```

Sdevice command file (5)

```
  * display simulation time in 'human' units
  Wallclock
  * display max.error information
  CNormPrint
  * to avoid convergence problem when simulating defect-assisted tunneling
  NoSRHperPotential
}

Solve
{
        * EQUILIBRIUM
        coupled {poisson}

        * TURN-ON
        * decreasing p_contact to goal
        quasistationary (InitialStep = 0.010 MaxStep = 0.050 MinStep=0.005
                         Goal {name= "p_contact" voltage = @V_start@}
                         plot { range=(0, 1) intervals=1 }
                          )
                         {coupled {poisson electron hole} }
```

MaxStep must be higher than MinStep

Newton iteration

Sdevice command file (6)

```
* raising p_contact to goal
        * negative part
        quasistationary (InitialStep = 0.010 MaxStep = 0.050 MinStep=0.005
                        Goal {name= "p_contact" voltage = 0}
                         )
                        {coupled {poisson electron hole} }

        quasistationary (InitialStep = 0.010 MaxStep = 0.050 MinStep=0.001
                        Goal {name= "p_contact" voltage = @V_stop@}
                        plot { range=(0, 1) intervals=15 }
                         )
                        {coupled {poisson electron hole} }

}
```

- Save → Quit

Sdevice: write the parameter file (1)

- How to get the material parameters for Silicon, Germanium and GaAs and assembly a single parameter file for Sdevice simulation containing all the parameters for physical models:

from the terminal command-line

GO TO PROJECT DIRECTORY

```
cd ~/TCAD/pn_ideale
```

PRODUCE TEXT FILES WITH PARAMETERS. ONE FOR EACH MATERIAL

```
sdevice -P:Silicon > sdevice.par
sdevice -P:Germanium >> sdevice.par
sdevice -P:GaAs >> sdevice.par
```

OPEN FILES `sdevice.par` AND CUT THE LOG INFORMATION, that is:

CUT THE HEADERS FOR EACH MATERIAL AND CONSERVE ONLY THE PART STARTING FROM

```
Material= "Silicon" {
```

TO LAST `}`

→ DO THE SAME FOR EACH MATERIAL (see next slide)

Sdevice parameter file (2)

- The `sdevice.par` file should appear like this:

```
Material = "Silicon" {
Epsilon {
…
}
}
Material = "Germanium" {
Epsilon {
…
}
}
Material = "GaAs" {
Epsilon {
…
}
}
```

SWB needs at least an empty file.
If material parameters must not be modified compared to the default values, even an empty file will do the job.
However, create the parameter files is useful to check which parameters are used for a given material for a given model (and, in case, change their values)

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Run the simulation

- on SWB interface

PREPROCESS ALL NODES (software writes sde, sdevice and parameters file for each experiment)

`CTRL-P`

- RUN SDE

Select all real(*) nodes of Sde → `CTRL-R` → `Run`

→ wait for the real nodes becoming yellow (i.e. simulation done successfully)

- RUN Sdevice

Select all real(*) nodes of Sdevice→ `CTRL-R` → `Run`

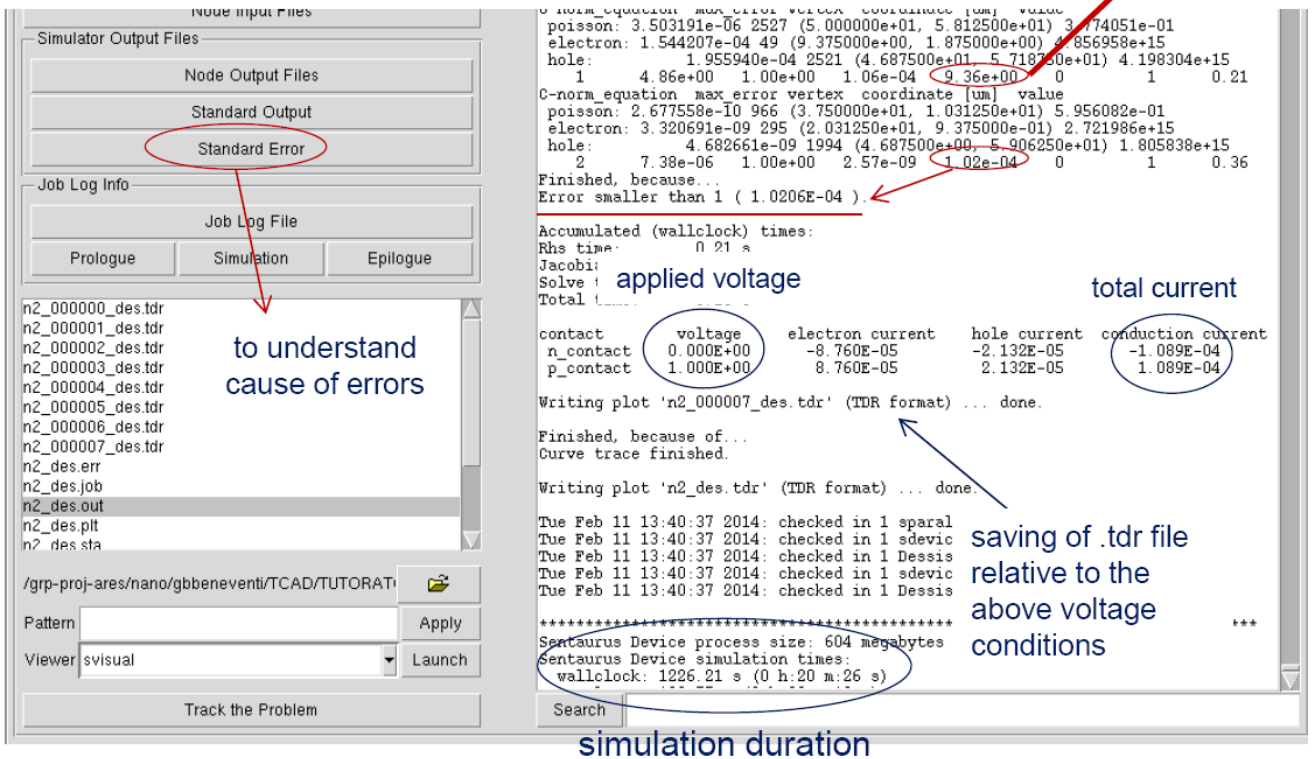
(*) “real” nodes are the very last (meaning at the right-end side) nodes of a tools. The other ones are defined as “virtual” nodes.

➢ The problem is now solved

`F7` on the Sdevice real node allows examining the details of the problem solution by looking at `n@node@_des.out`

Simulation output file

- Select `Standard Output` to explore:
  - Host name (machine used), process ID
  - used models and material parameters
  - monitoring of the boundary conditions (like bias sweeps)
  - information about numerical convergence



`Error` column: indication of convergence.
It is a "normalized" error indication.
Convergence is achieved if error is smaller than one.

The coordinate of maximum error for each equation is also specified thanks to the use of the keyword `CNormPrint` in the Sdevice command file. This information is particularly useful in case of non-convergence, since it gives indication of where the numerical mesh could need revision

Outline

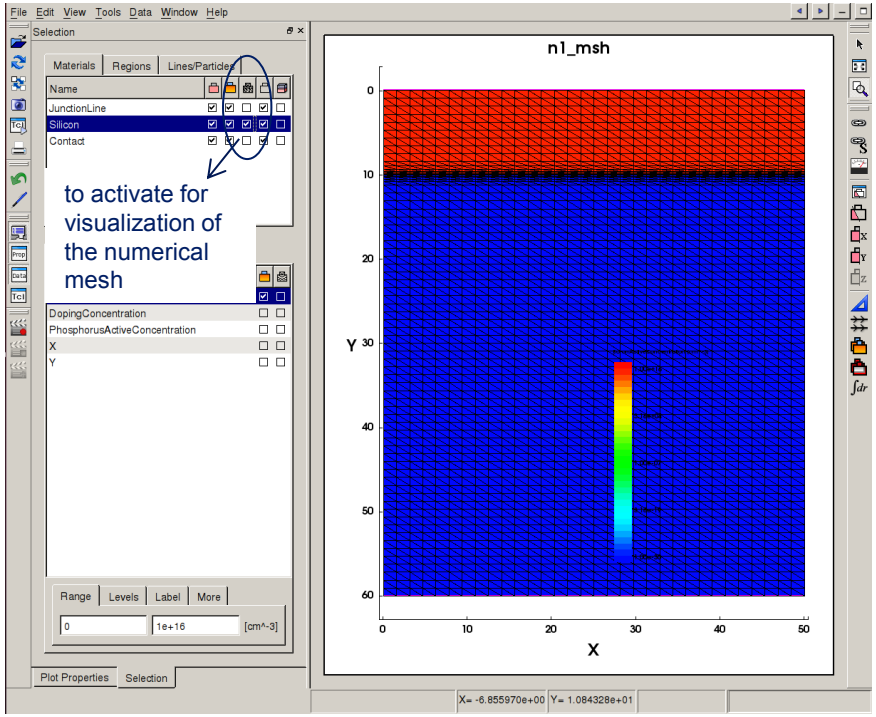
- Review of basic properties of the diode
- Sentaurus Workbench setup (SWB)
- Implementation of Input files
  - Sentaurus Structure Editor (SDE) command file
  - Sentaurus Device (SDevice)
    - command file
    - parameter file
- Run the simulation
- ✓ ***Post-processing of results***

Output of the simulation: Svisual (1)

- Geometry, doping & mesh

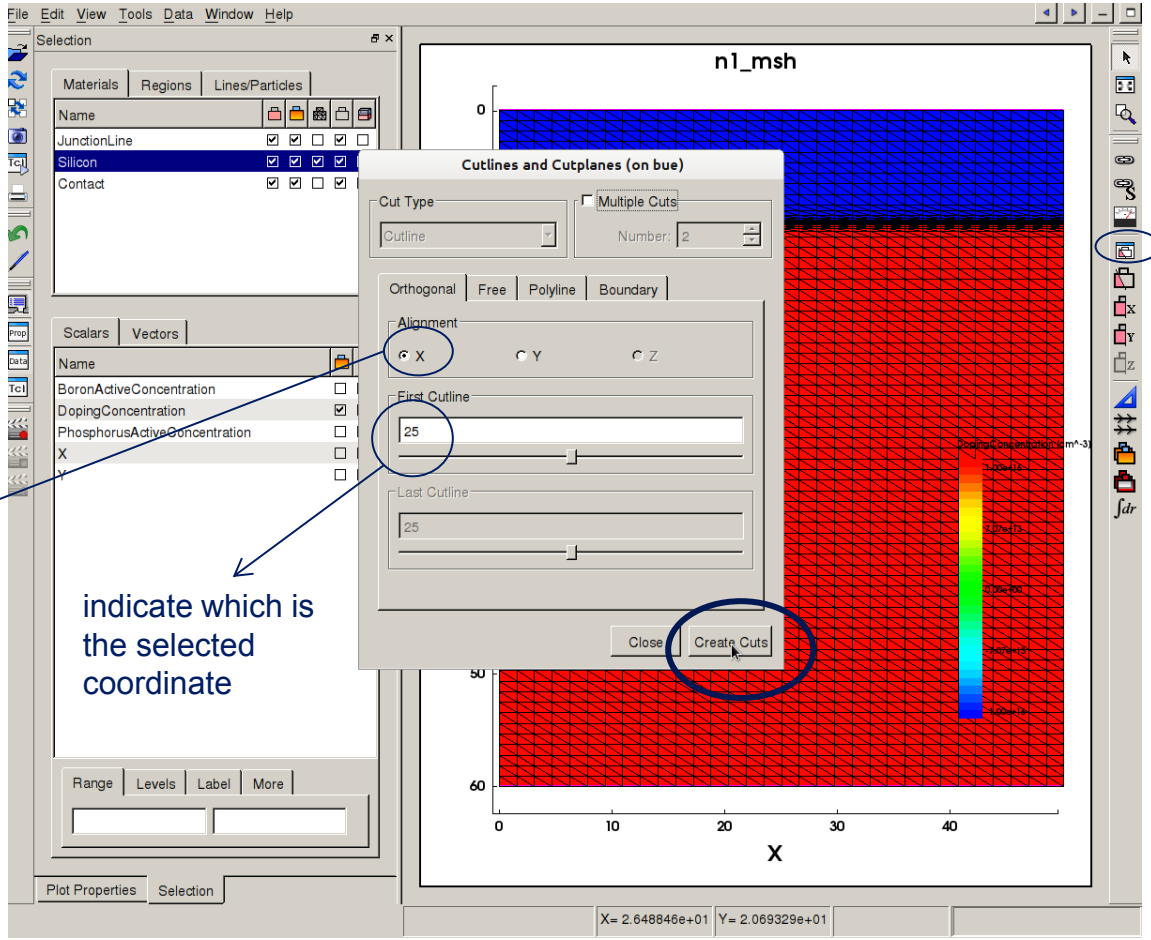
Select the first SDE real node (`n1`) then click on the “eye” button at the top of the bar → `Sentaurus Visual (Select File)` → `n1_msh.tdr` → `new S-Visual instance` → `Ok`

- Explore the Svisual tool functionalities to obtain the visualization of doping and mesh on the whole geometry..



Output of the simulation: Svisual (2)

- Visualization of a cut-line of the doping concentration (i.e. doping concentration profile at a given `x`)
- Select on the right-hand side toolbar `Precision Cut` → `Create Cuts`



indicate which coordinate is constant in the cut

indicate which is the selected coordinate

precision cut tool

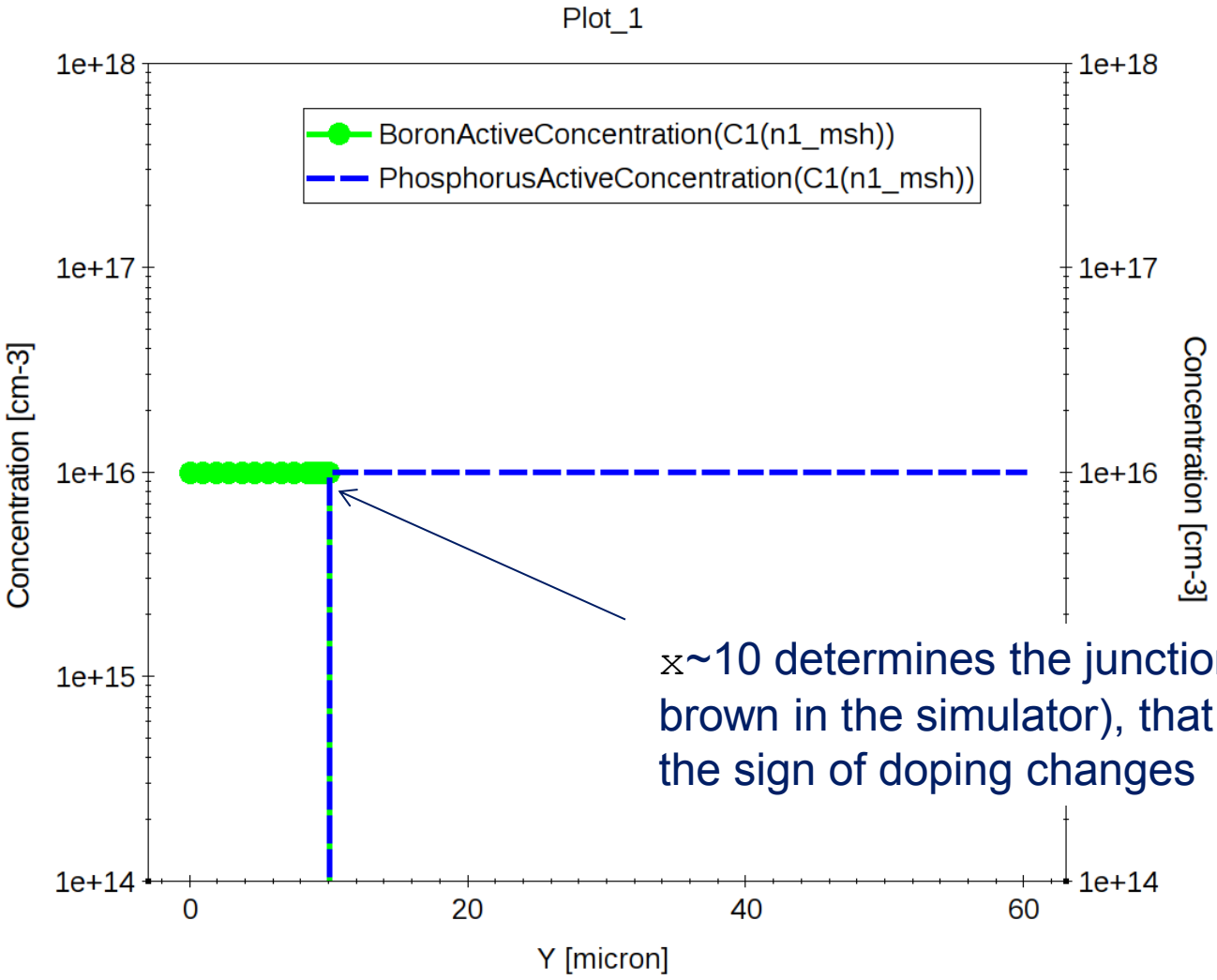
Output of the simulation: Svisual (3)

- Window→ Plot_n1_msh (deselect) → Selection → BoronActiveConcentration → To Left Y-Axis → PhosphorusActiveConcentration → To Left Y-Axis
- Select on right hand side bar, logY, logY2
- Click on the legend, then Legend properties → Position → Lower Right
- Double click on the graph on the left Y axis → set Min. 1e14 and Max. 1e18. Do the same for the right Y2 axis
- Select Title/Scale, in title attributes of Y axis → Concentration → enter
- Select Title/Scale, in title attributes of Y2 axis → Concentration→ enter
- Selection → Curves → DopingConcentration → Delete
- BoronActiveConcentration → Curve Properties → Shape → Solid → increase up to 4 → Markers → CircleF, write 10 in the cell
- Close the data window (click on Data on the left hand-side toolbar)
- Close the property window (click on Prop on the left hand-side toolbar)
- Export the figure: ExportPlot (the camera)→ n1_msh_doping_X=25μm→ save (by default files are exported in the .png format)
- Use the Probe (the speedometer) to determine the location of the junction, verify that the junction is located around X ~ 10

left-hand side toolbar

right-hand side toolbar

Saved image file



x~10 determines the junction line (in brown in the simulator), that is, where the sign of doping changes

Post-processing: Svisual (4)

- ## Band diagram at equilibrium (1)

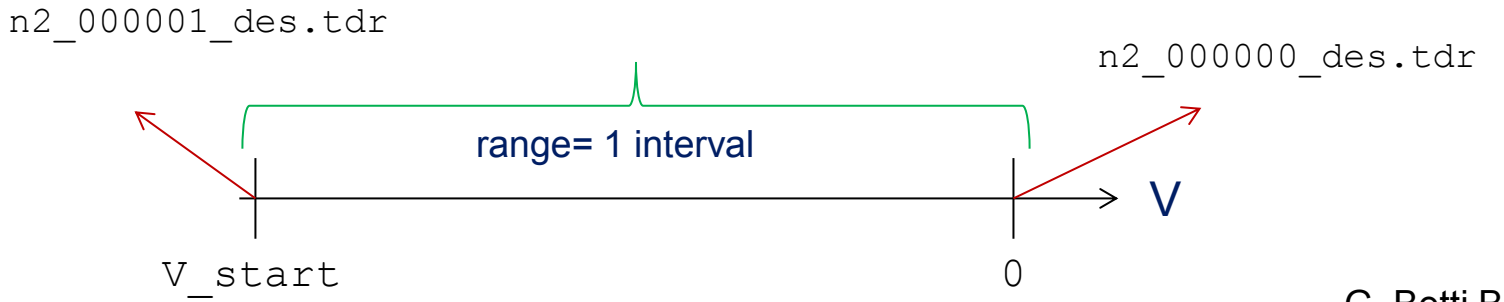
- Select the first real node of Sdevice (`n2`) → click on the "eye" button → `Sentaurus Svisual (Select File …)` → `n2_000000_des.tdr` → `new S-Visual instance` → `Ok`

➢ N.B. `n2_000000_des.tdr` is the Equilibrium solution → see the correspondence in the Sdevice command file

To find out the correspondence, reconsider for example the first quasistationary ramp:

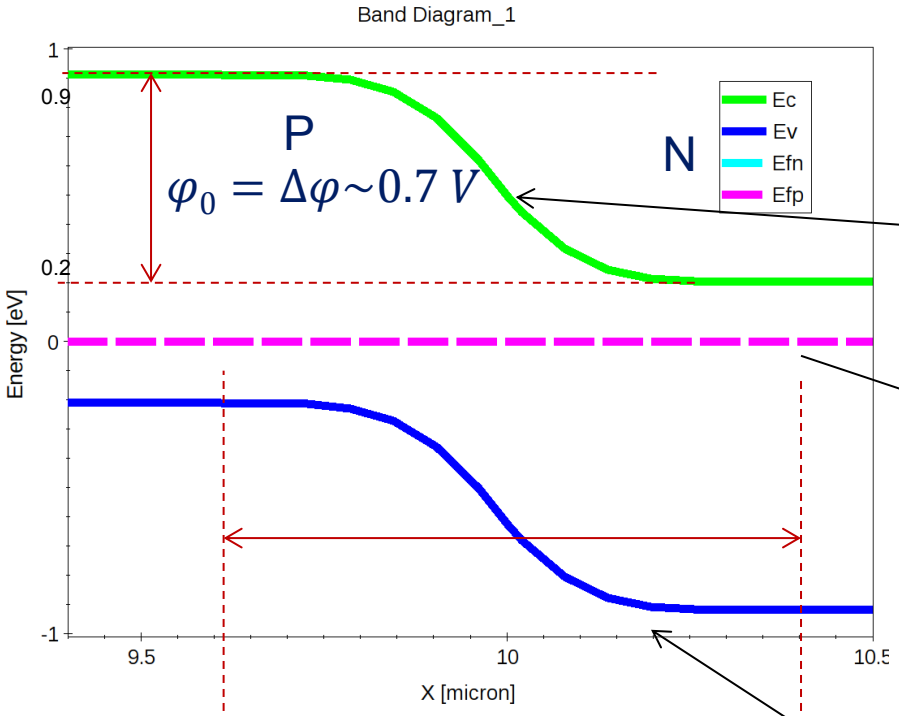
```
quasistationary (InitialStep = 0.010 MaxStep = 0.005 MinStep=0.005
                        Goal {name= "p_contact" voltage = @V_start@}
                        plot { range=(0, 1) intervals=1 }
                          )
                         {coupled {poisson electron hole} }
```

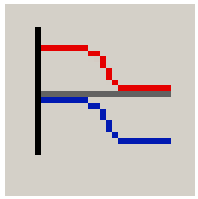
normalized units: it means that from V_start=0 to V_start=V_start/V_start there is 1 interval, so the files will be saved as (note that V_start is negative)



Post-processing: Svisual (5)

- Band diagram at equilibrium (2)
  - Select `Precision cuts` → `Create cuts` → `Plot Band Diagram` → `ok`
  - `Window` → select `Plot_n2_000000_des`
  - `Zoom` on the plot to magnify the junction





Energy

length

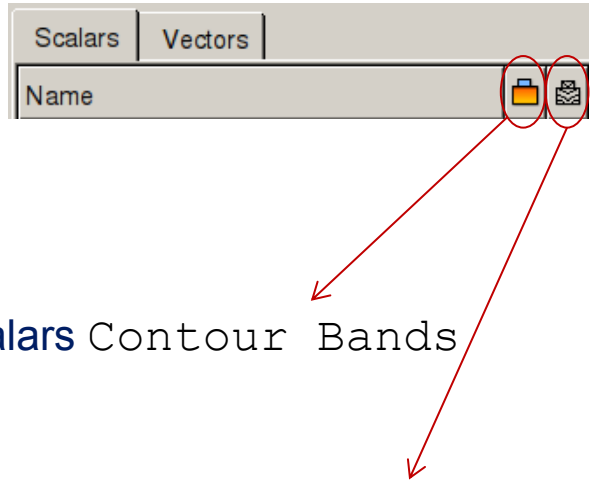
as we calculated with the compact formula

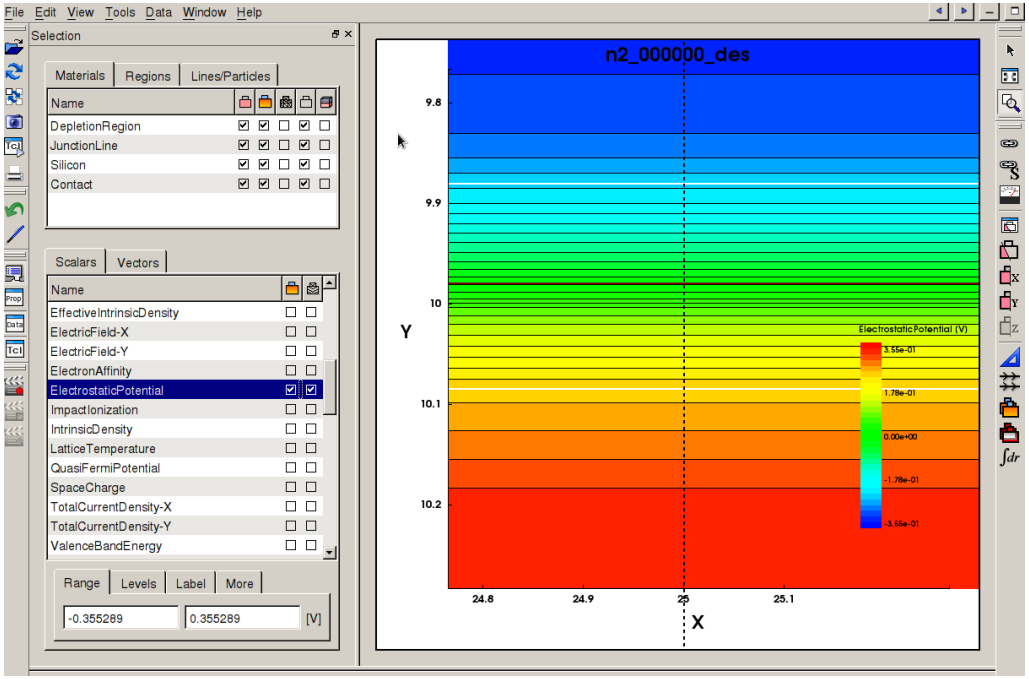
there is a single *flat* quasi Fermi level because we are at equilibrium

junction width (region where bands are bended) ~ 800nm wrt to a total length of 60 μm! (`Wp`+`Wn`)

Post-processing: Svisual (6)

- Electrostatic Potential
  - `Window` → select `Plot_n2_000000_des`
  - `Window` → select `Plot_1`
  - Open the data window (click on `Data` on the left hand-side toolbar)
  - Click on `ElectrostaticPotential`, enable `Contour Bands` and `Contour Lines` and zoom at the junction → see that electrostatic potential gradient is practically zero on the `x` axis → the device could have been further approximated to 1D !!



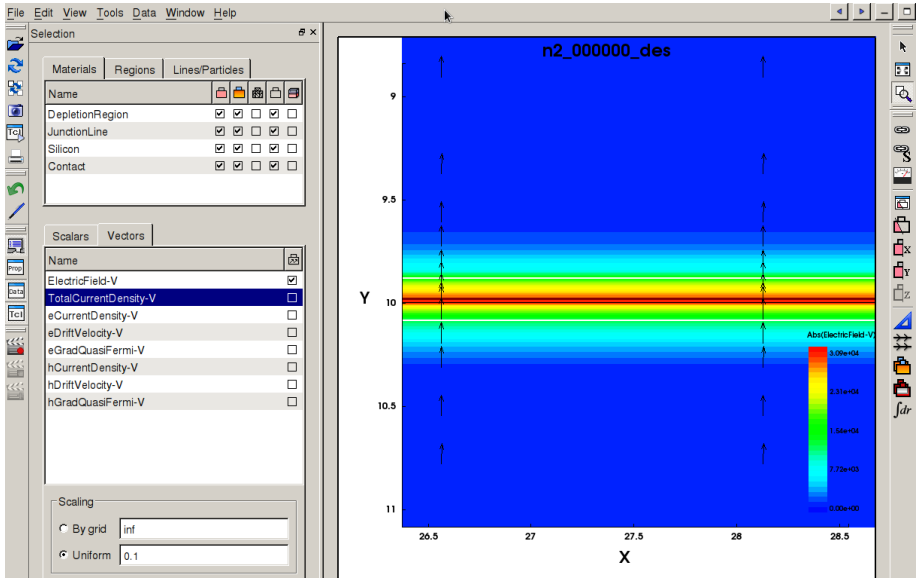


Post-processing: Svisual (7)

- Electric Field

- See how the `Contour Lines` of the `Electrostatic Potential` are much closer around the junction line → since the `Contour Lines` are traced for a fixed potential difference it means that the electric field is higher at the junction
- Deselect `Contour Bands` and `Contour Lines` in the `Electrostatic Potential`
- Select `Contour Bands` in `Abs(ElectricField-V)` then switch to `Vector` and select `Contour Lines` in `ElectricField-V.` Then zoom-out.
- Note how the electric field is parallel to the Y axis, and how it goes from n-region (doped acceptor, positive charge) to p-region (doped donors, negative charge)

Vectors `Contour Lines`

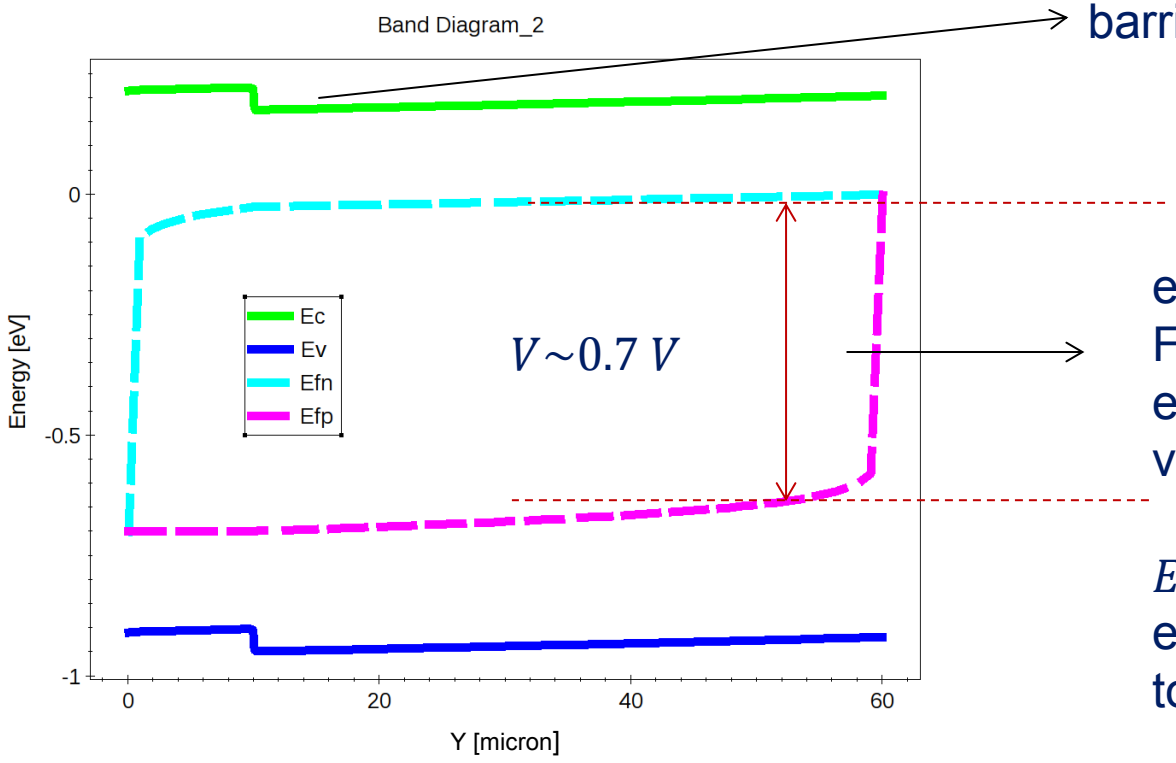


Post-processing: Svisual (8)

- Band diagram in forward bias (at threshold)

- Close the Svisual instance
- Select the first real node of Sdevice (`n2`) → click on the "eye" button → `Sentaurus Svisual (Select File …)` → `n2_000009_des.tdr` → `new S-Visual instance` → `Ok`
- Select `Precision cuts` → `Create cuts` → `Plot Band Diagram` → `Ok`
- `Window` → deselect `Plot_n2_000009_des`

bands are almost flat: no barrier anymore



energetic gap between Fermi levels (in eV) equals the applied voltage

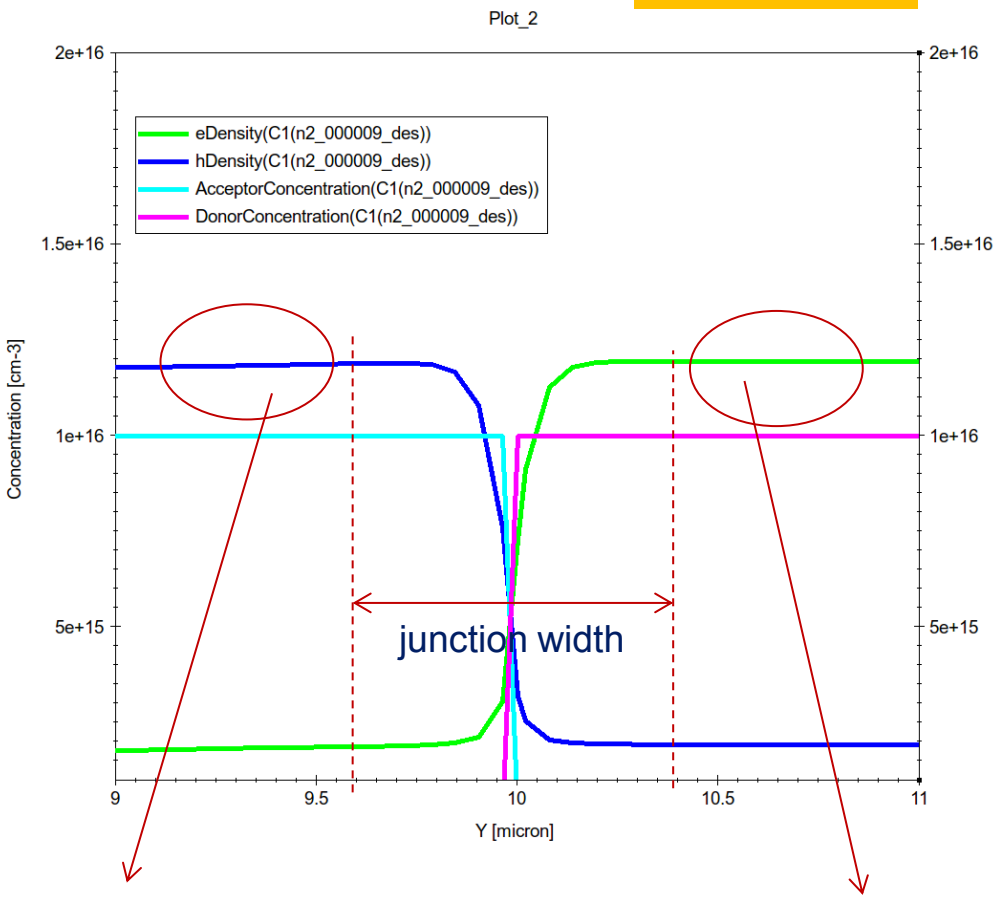
$E_{fn} > E_{fp}$ → injection of excess carriers compared to equilibrium

Post-processing: Svisual (9)

- Minority carries in forward bias

- `Curves` → `select all curves` → `Delete` → `Data` → `hDensity` → `To Left Y-Axis` → `eDensity` → `To Left Y-Axis`
- `AcceptorConcentration` → `To Left Y-Axis` → `DonorConcentration` → `To Left Y-Axis`
- Zoom around `10` value on x-axis and check the profiles to be approximately linear (no physical model for generation recombination has been implemented!)

linear scale

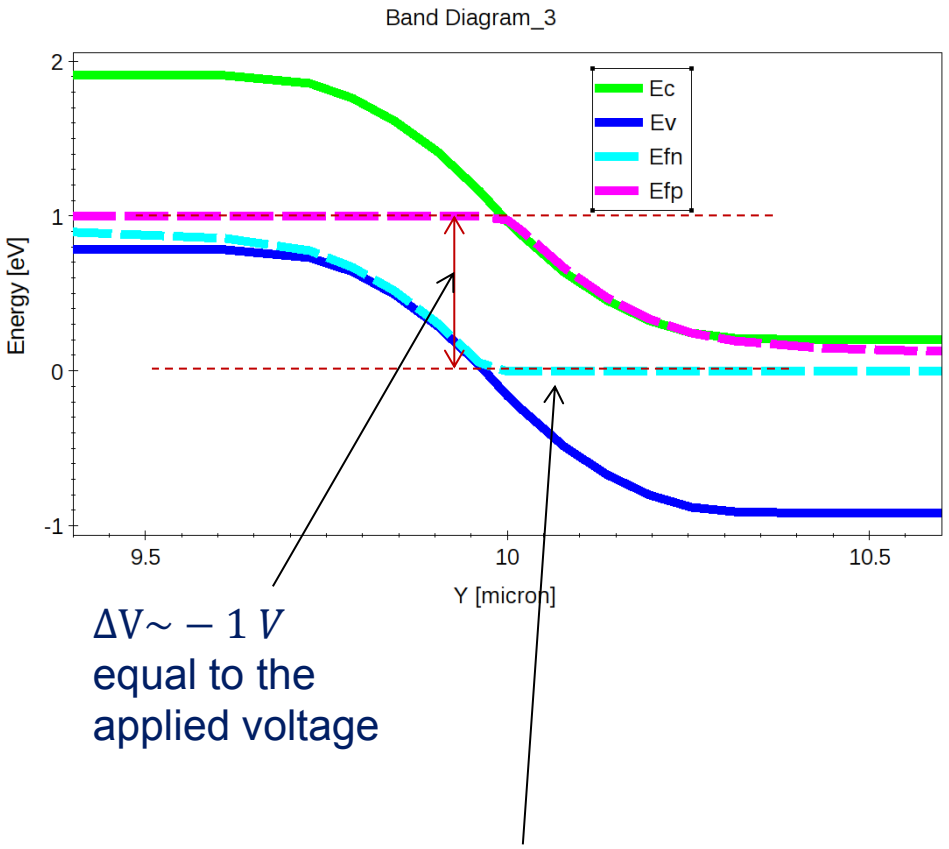


excess carrier with respect to equilibrium

Post-processing: Svisual (10)

- Band diagram in reverse bias

- Close Svisual instance
- Choose the right tdr file. Check on the Sdevice file: First quasistationary ramp is about decreasing `p_contact` to goal, and the number of intervals is 1 (i.e. two tdr files are saved: `n2_000000_des.tdr` and `n2_000001_des.tdr`). Thus, we are interested in the `n2_000001_des.tdr` node, which has `V=V_start=-1V`.
- Select the first real node of Sdevice (n2) → click on the "eye" button → `Sentaurus Svisual (Select File …)` → `n2_000001_des.tdr` → `new S-Visual instance` → `Ok`
- Select `Precision cuts` → `Create cuts` → `Plot Band Diagram` → `ok`
- `Window` → select `Plot_n2_000001_des`
- `Zoom` on the plot to magnify the junction

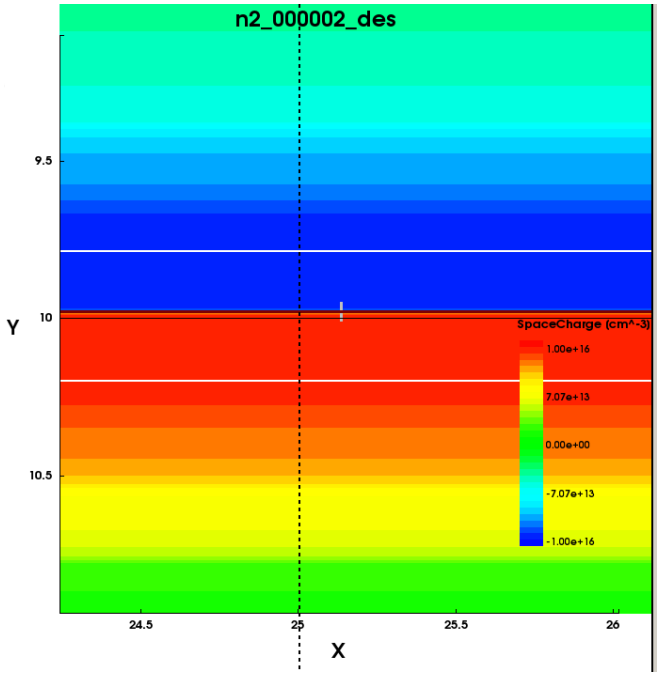


The fact that near the junction $E_{fn} < Efp$ indicates the presence of a depletion region

Post-processing: Svisual (11)

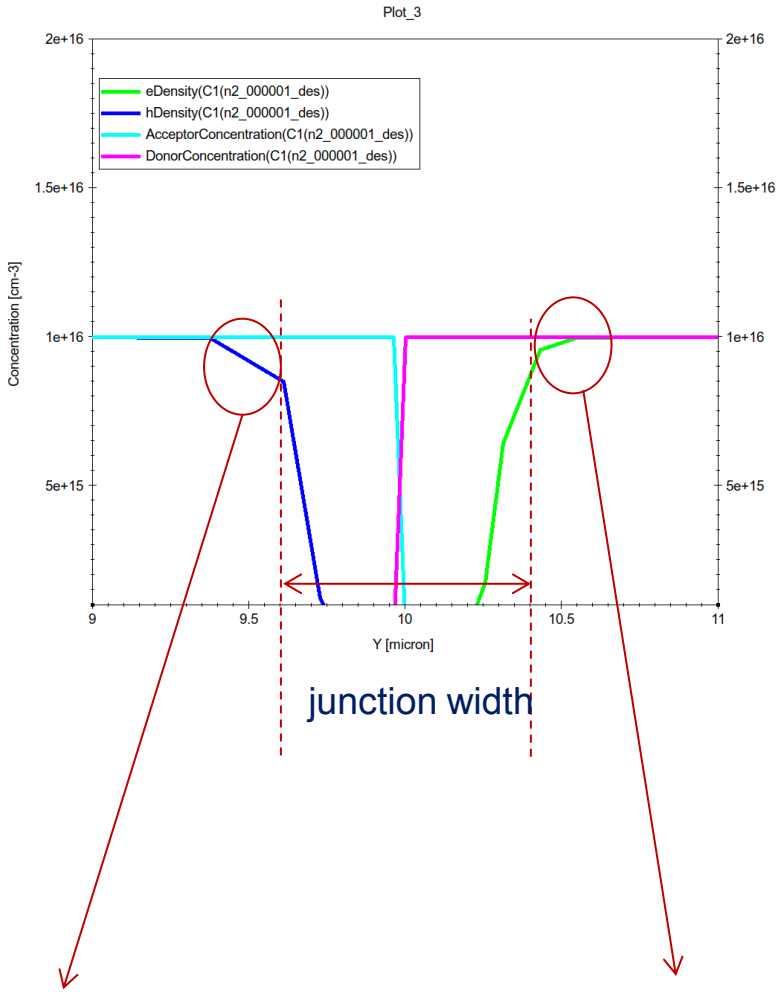
- ## Depletion region and junction line

- `Window` → `Plot_1` → `Window` → `Plot_n2_000001_des`
- Zoom at the junction → Select `SpaceCharge` in the `Scalars` field
- Probe inside the region delimited by the white lines (indicating the electrostatic space-charge region) around the brown line (indicating the junction line):
- Check that `eDensity` and `hDensity` values are well below the doping values, that is check that $n, p \ll N_D, N_D$ (definition of electrostatic space-charge region)



Post-processing: Svisual (12)

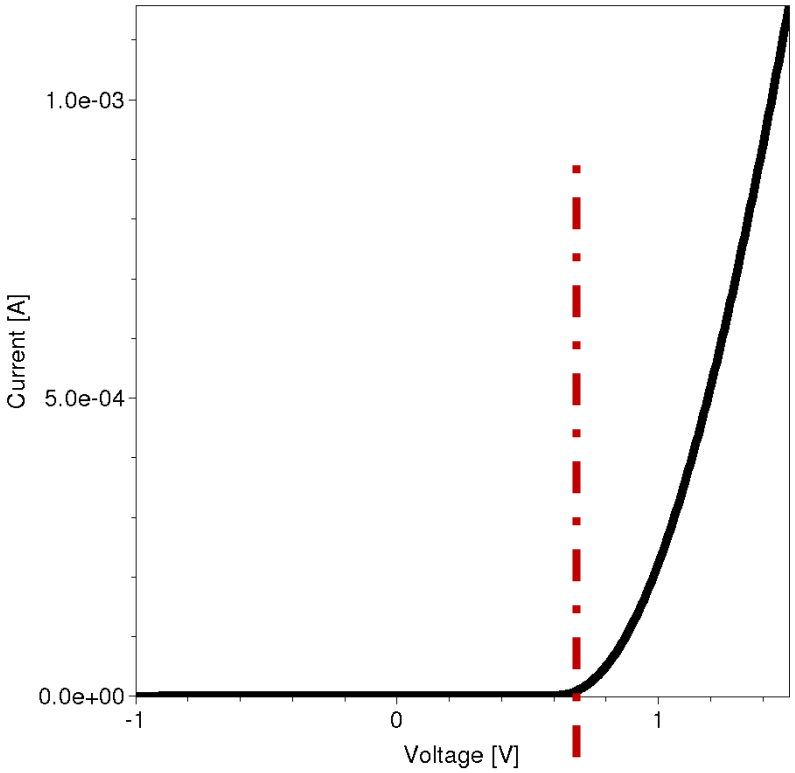
- Minority carries in reverse bias
- `Curves → select all curves → Delete → Data → hDensity → To Left Y-Axis → eDensity → To Right Y-Axis`
- `AcceptorConcentration → To Left Y-Axis → DonorConcentration → To Right Y-Axis`
- Zoom around 10 and check the profiles to be approximately linear (no physical model for generation recombination has been implemented!)
- N.B. The fact that the profiles do not appear identically symmetrical is only due to different mesh discretization

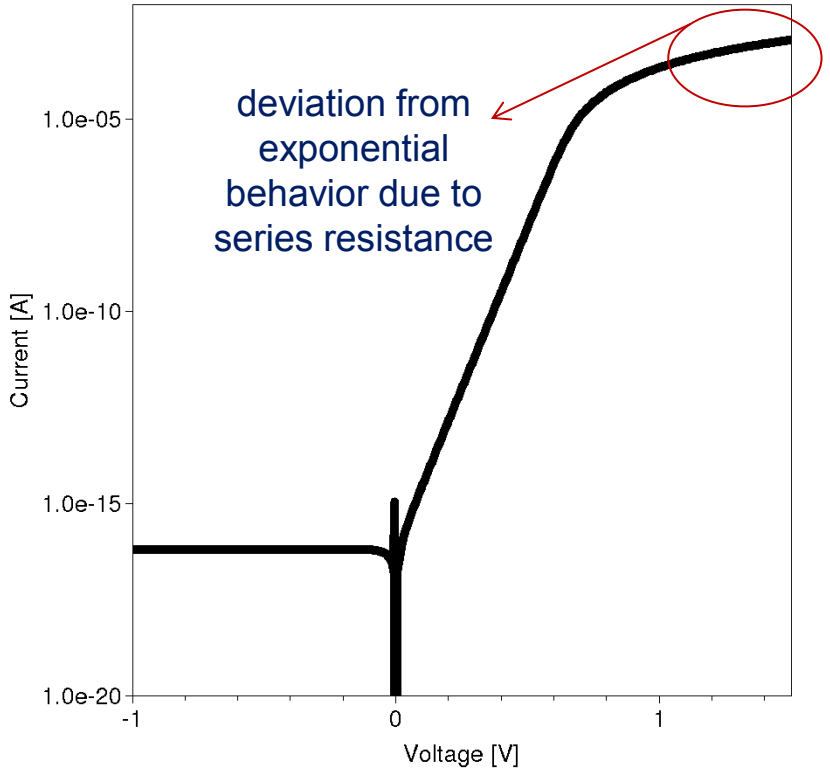


carrier depletion with respect to equilibrium

Electrical characteristics: Inspect (1)

- Diode IV characteristics
  - Click on `n2` node → click on "eye" button → `Inspect (All Files…)`
  - Select `n2_des.plt` dataset → `p_contact` → `OuterVoltage` → `To X-Axis` → `TotalCurrent` → `To Left-Y-Axis`
  - Set `logY` on the upper toolbar to plot the characteristics in log scale

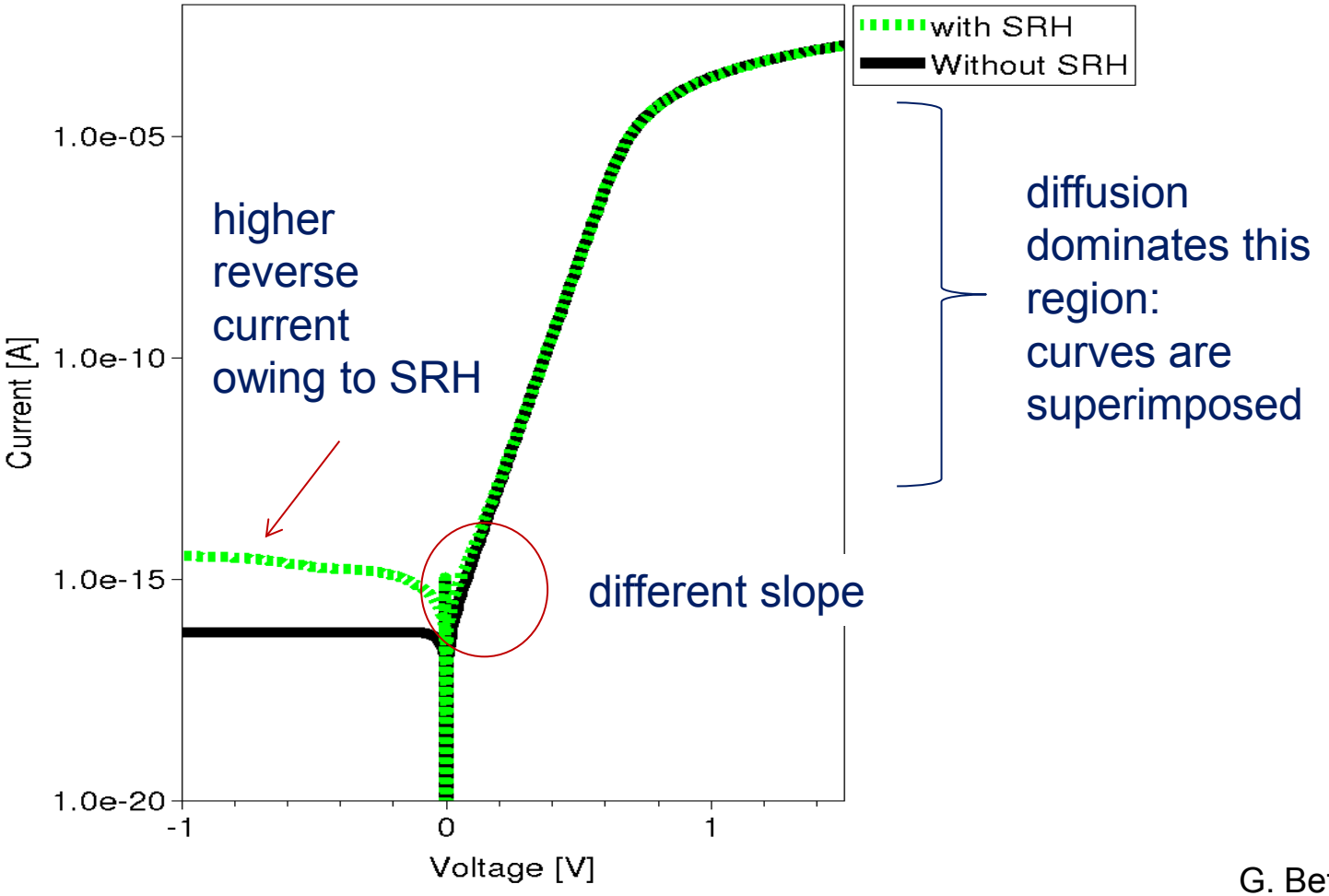




threshold voltage ~ 0.7 V

Electrical characteristics: Inspect (2)

- Diode IV characteristics with SRH
- `File` → `Load Dataset` → go to Project folder → select `n37_des.plt` dataset → `p_contact` → `OuterVoltage` → `To X-Axis` → `TotalCurrent` → `To Left-Y-Axis`



Electrical characteristics: Inspect (3)

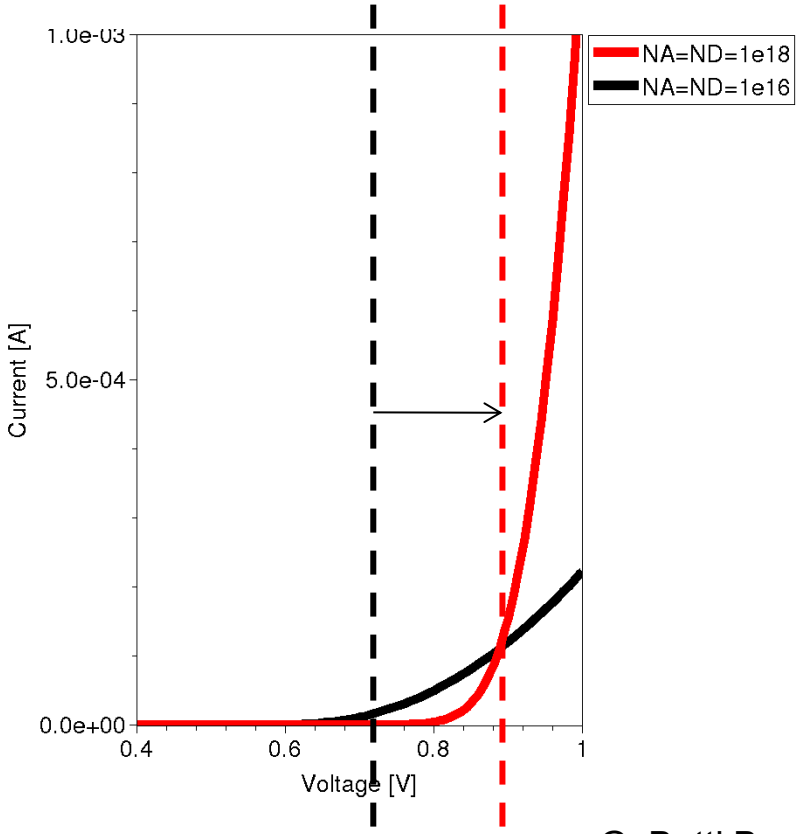
- What if we increase doping? Threshold increases

$$\varphi_0 = \varphi_T \ln\left(\frac{N_A N_D}{{n_i}^2}\right)$$

$$N_A N_D = 10^{16} \times 10^{16} \rightarrow \varphi_0 \sim 697\ \text{mV}$$

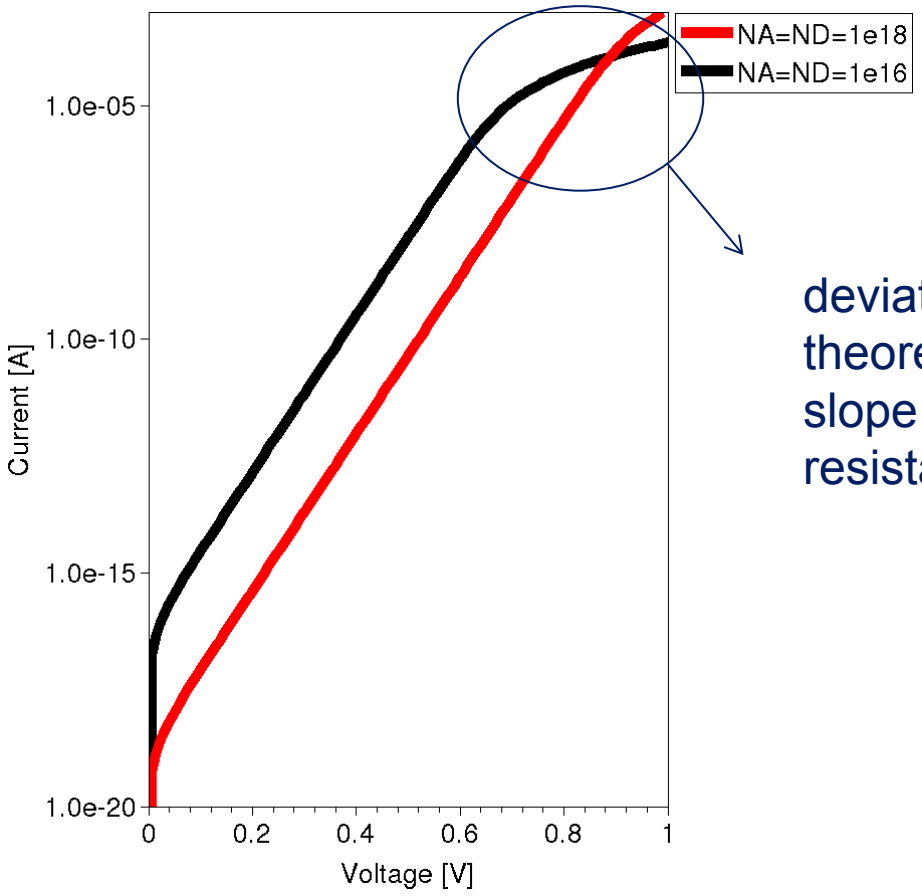
$$N_A N_D = 10^{18} \times 10^{18} \rightarrow \varphi_0 \sim 937\ \text{mV}$$

- Click on `n2,n34` nodes holding `CTRL` → click on "eye" button → `Inspect (All Files…)`
- Select all dataset holding `CTRL` → `p_contact` → `OuterVoltage` → `To X-Axis` → `TotalCurrent` → `To Left-Y-Axis`



Electrical characteristics: Inspect (4)

- … but slope does not change: check it out by plotting Y in log-scale. Slope is always the same and it is equal to 60 mV/decade of current. This is related to the physics of charge injection (thermionic emission) in non-degenerate semiconductors.



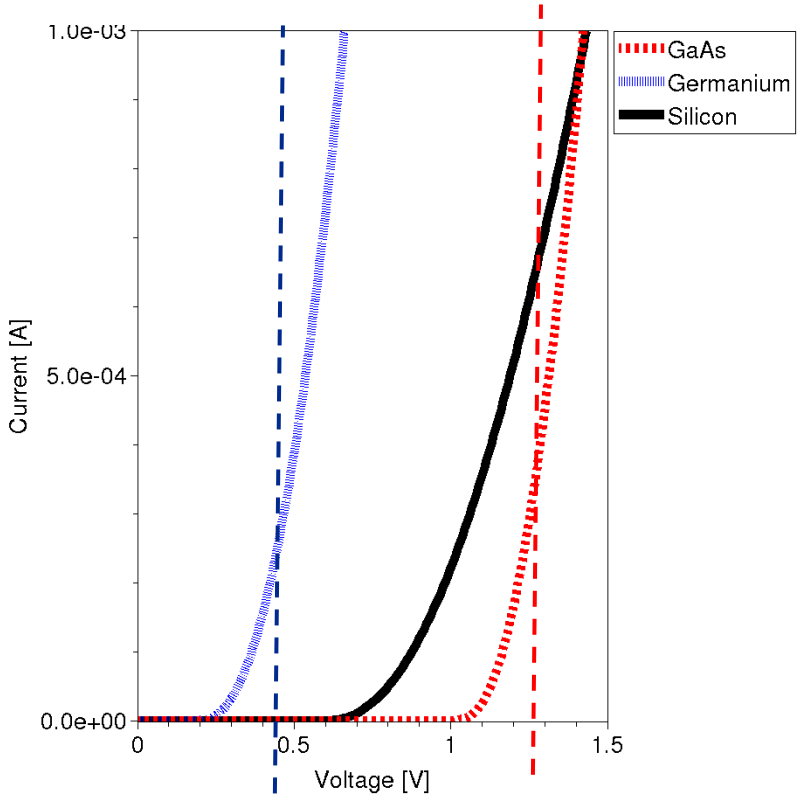
deviation from theoretical slope due to series resistance effect

Electrical characteristics: Inspect (5)

- Germanium and GaAs diodes

$$\varphi_0 = \varphi_T \ln\left(\frac{N_A N_D}{{n_i}^2}\right) \begin{cases} n_i = 1.79x10^6 \rightarrow \varphi_0 \sim 1.287 \text{ mV (GaAs)} \\ n_i = 2.4x10^{13} \rightarrow \varphi_0 \sim 434 \text{ mV (Ge)} \end{cases}$$

- Click on `n2,n19,n28` nodes holding `CTRL` → click on "eye" button → `Inspect (All Files…)`
- Select all dataset holding `CTRL` → `p_contact` → `OuterVoltage` → `To X-Axis` → `TotalCurrent` → `To Left-Y-Axis`



Uniform doping: resistors (1)

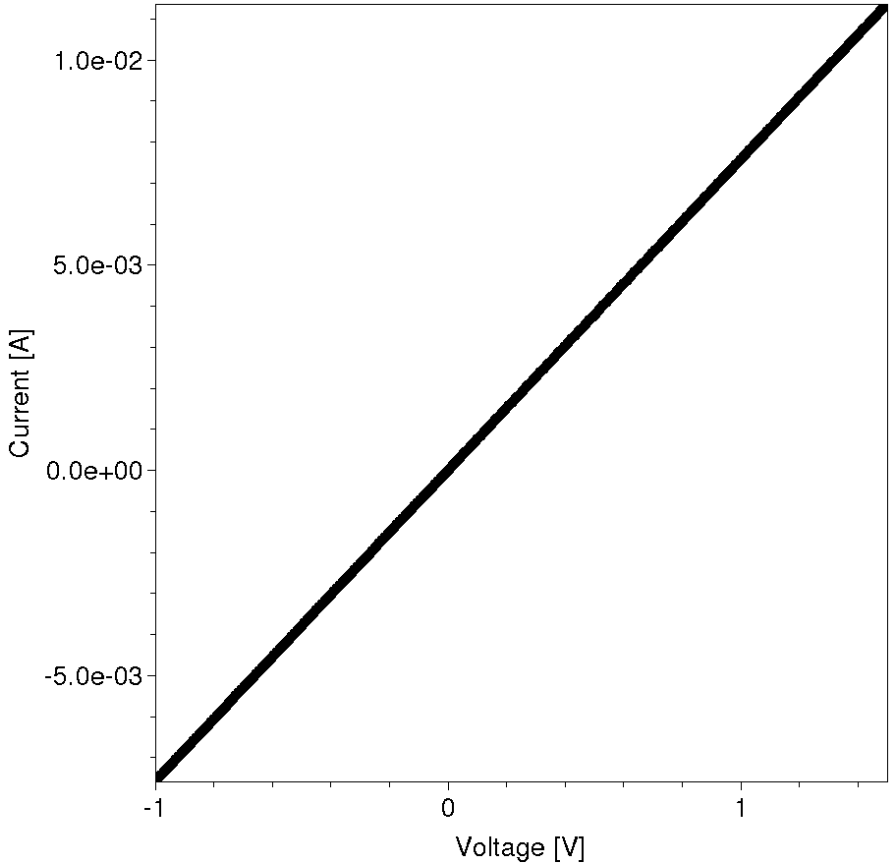
- From SWB interface double click on SDE symbol → `Input Files` → `Edit…`
- Go to p-region doping section
- Modify `(sdedr:define-constant-profile "p-doping-profile" BoronActiveConcentration @p_doping@)` into `(sdedr:define-constant-profile "p-doping-profile" "@p_doping_type@" @p_doping@)`
- From SWB interface, click on `p_doping` → right click → `Add` → `Parameter` → `p_doping_type` → `Default value` → `BoronActiveConcentration` → `ok`
- Click on `n29` node → `PhosphorusActiveConcentration`
- Click on `n30` → `CTRL-R` → `Yes` → `Run`
- Click on `n34` → `CTRL-R` → `Run`

no junction anymore, uniform n-doping

Uniform doping: resistors (2)

- IV characteristics is linear

- Click on `n34` node → click on "eye" button → `Inspect (All Files…)`
- Select `n34_des.plt` dataset → `p_contact` → `OuterVoltage` → `To X-Axis` → `TotalCurrent` → `To Left-Y-Axis`



no junction → uniform material

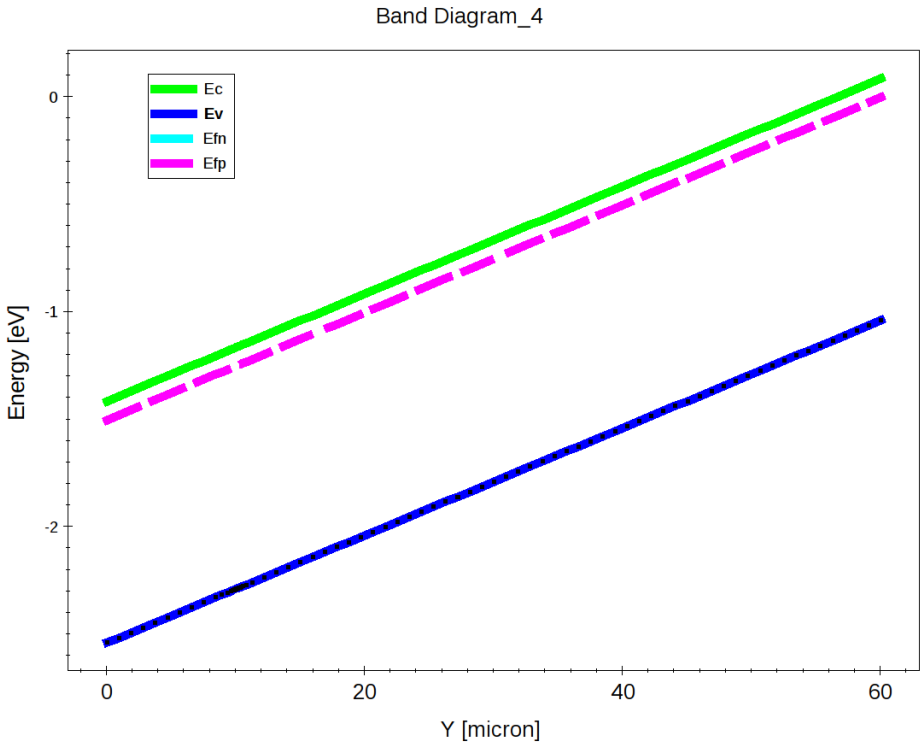
mobility field-independent

carrier concentration field-independent

→ linear I-V characteristics

Uniform doping: resistors (3)

- Select the node `n34` → click on the "eye" button → `Sentaurus Svisual (Select File …)` → `n34_000019_des.tdr` → `new S-Visual instance` → `Ok`
- Select `Precision cuts` → `Create cuts` → `Plot Band Diagram` → `Ok`
- `Window` → deselect `Plot_n34_000017_des`



Spatial uniformity → no junctions → no space-charge regions → no diffusion → only drift

$$\boldsymbol{J_n} = qn\mu_n\boldsymbol{\varepsilon} = n\ \mu_n\boldsymbol{\nabla E_{fn}}$$

No space charge yields (from Poisson's equation) constant $\boldsymbol{\varepsilon}$ which means constant $\boldsymbol{\nabla E_{fn}}$ and thus linear $\boldsymbol{E_{fn}}$. Then, since at the boundary (contacts) we assume equilibrium conditions which imply $\boldsymbol{E_{fn}}$=$\boldsymbol{E_{fp}}$, the only possibility is linear $\boldsymbol{E_{fn}}$=$\boldsymbol{E_{fp}}$.

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- Sentaurus Synopys User's guides