Tutorial

2

SAN JOSE STATE UNIVERSITY ELECTRICAL ENGINEERING DEPARTMENT

# Getting Started with TCAD, a Simple Bar of Silicon

PROCESS INTEGRATION AND IC DESIGN GROUP SAN JOSE STATE UNIVERSITY

# A tutorial guide for using Synopsys TCAD tools

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# Chapter 1: Starting the Sentaurus TCAD Tutorials

### *Opening the tools in a webbrowser*

Synopsys has on-line training that can be accessed from a web browser. There are a few typos here and there, but it should be easy to follow. The tutorials are quite lengthy so give yourself plenty of time to complete them. If you already know a TCAD tool and process engineering you probably can reduce your completion time from the estimated completion time in half.

1. First log (ssh or vnc) in remotely or at a Unix station and star a terminal

2. Start a web browser (Figure 1).

3. Go to File... Open File (Figure 2).

4. Click on Filesystem in the left control area of Figure 3.

5. Click on apps in the right control area of Figure 3.

6. Click on apps, synopsys, TCAD, tcad, current, Example_Library, Sentaurus_Training (Figure 4).

7. Double Click on main_menu.html (Figure 4).

8. The web browser should look like Figure 5. Bookmark the page by going to Bookmarks.. Book mark this page (Figure 6).

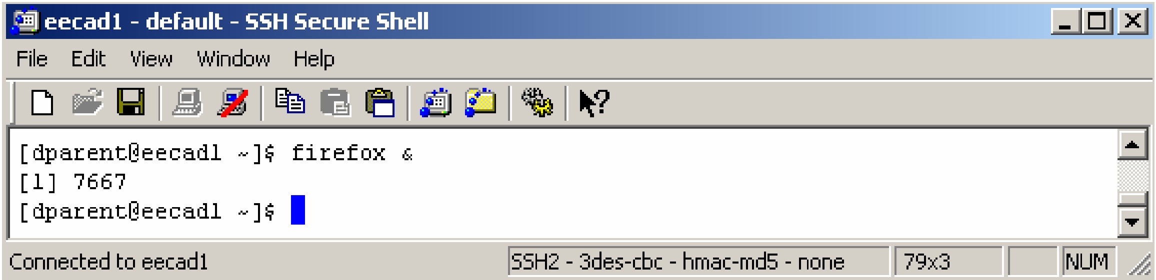



Figure 1. Starting a Web Browser.

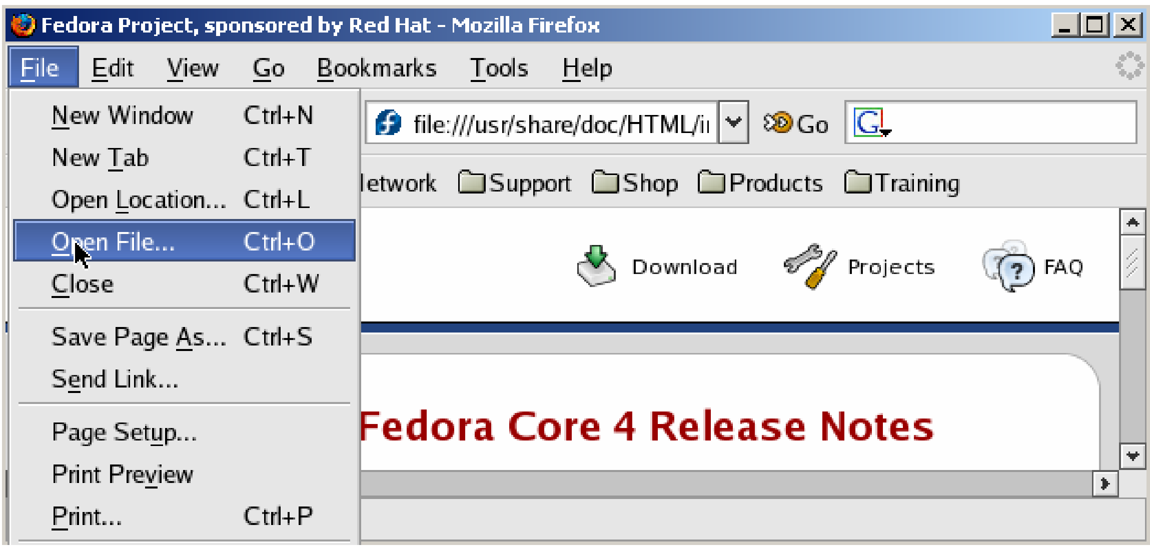



Figure 2: Open a file in a Web Browser.

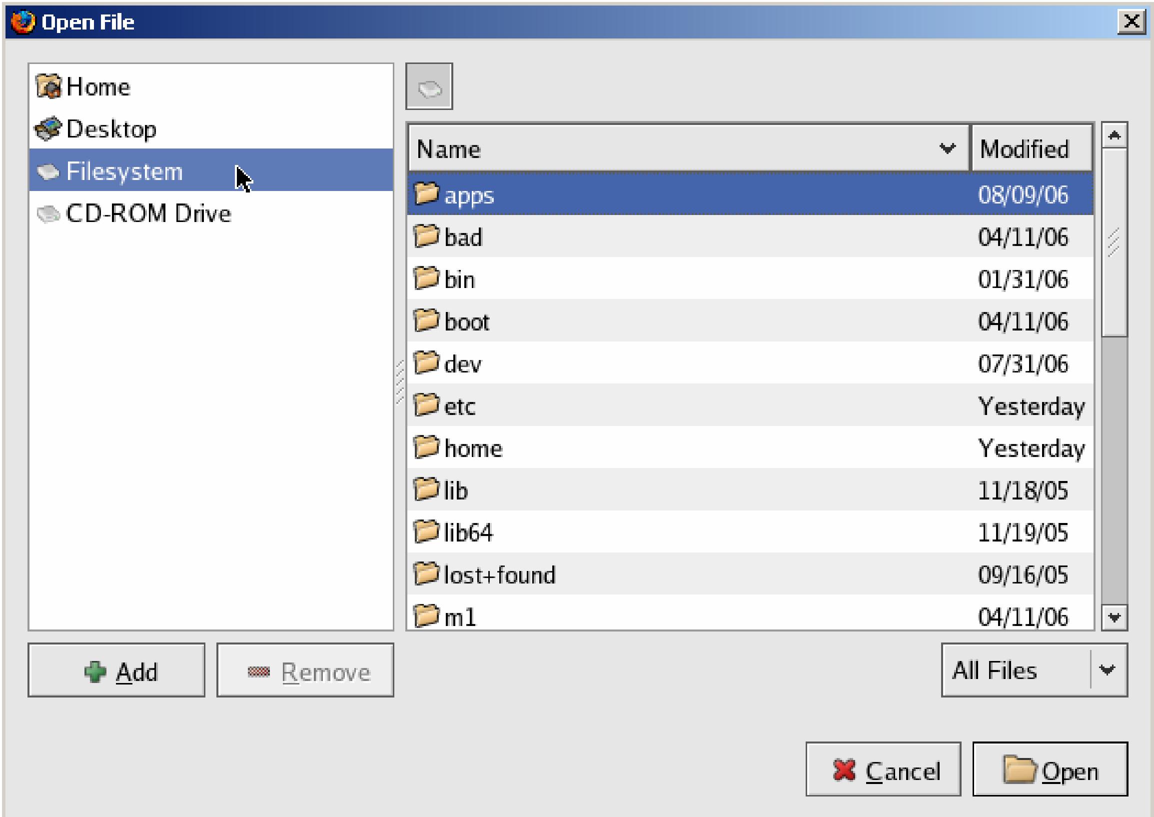



Figure 3: Open a file (File system).

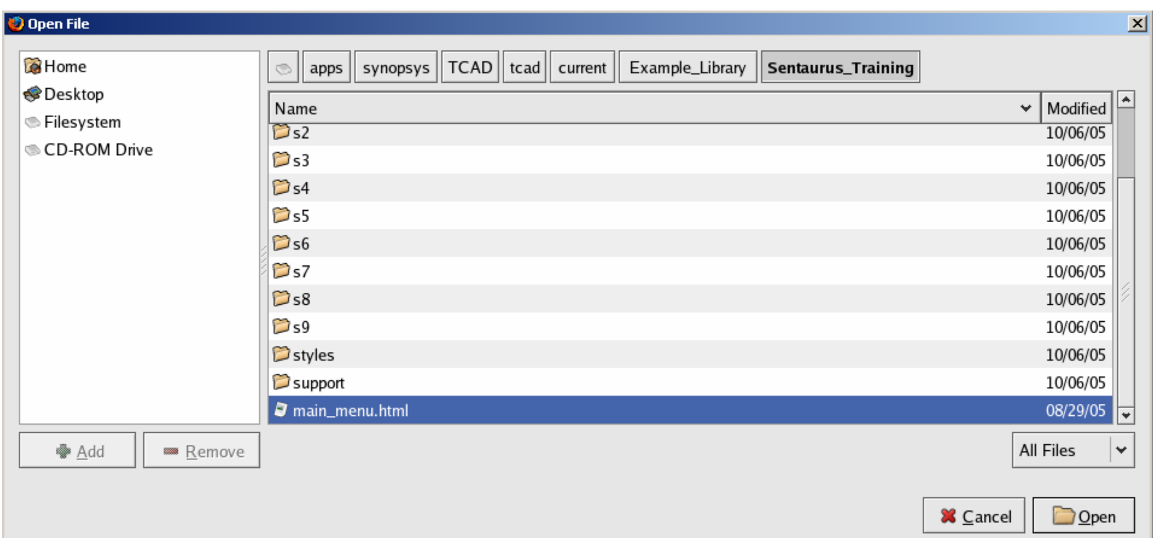



Figure 4: Location of Sentaurus Training.

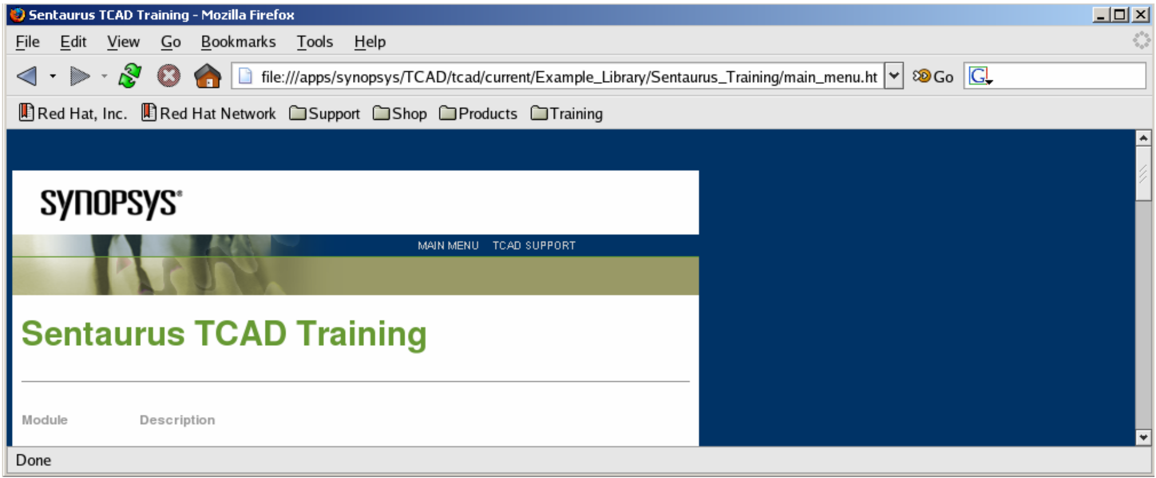



Figure 5: Main Menu of Sentaurus Training.


Figure 6: Bookmark this page.

*Doing the tutorials:*

In order to understand this tutorial, you should do the following tutorials provided by Synopsys

1. Tool Overview
2. Sentaurus Workbench

Chapter
2

# Chapter 2: Simple example showing how to simulate a bar of silicon

### *Downloading the Example File:*

Make a directory in your home directory call Sentaurus.  (Figure 1Figure 7)

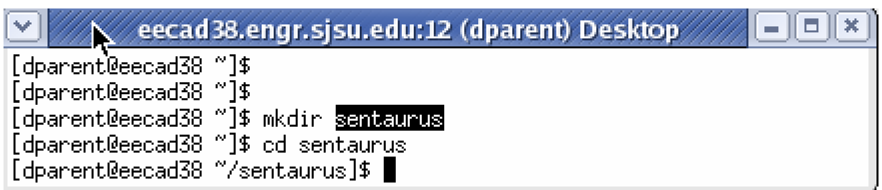



Figure 7: Making a directory.

Using a web browser, download into your account the sample file:

www.engr.sjsu.edu/dparent/ee221/res_bar.gzp

Download the file into your sentaurus directory (Figure 8 and Figure 9)

Start Sentaurus workbench by typing *swb &* at the command line (Figure 10).

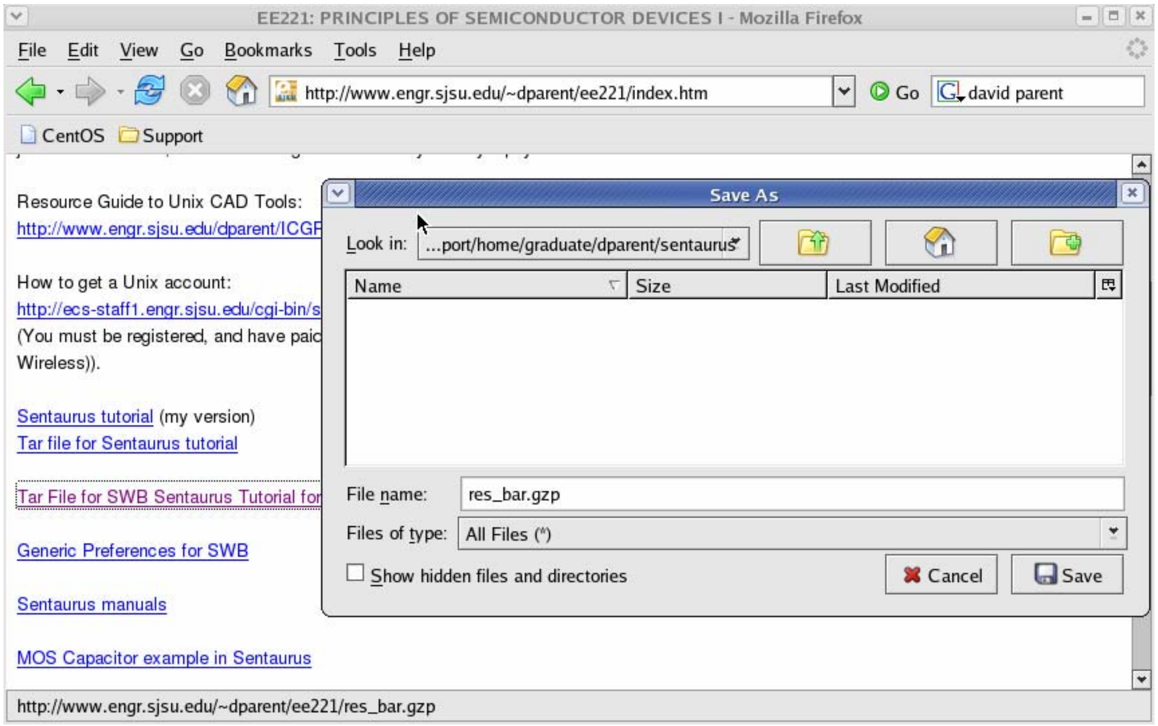



Figure 8: Navagting to the sentaurus directory.

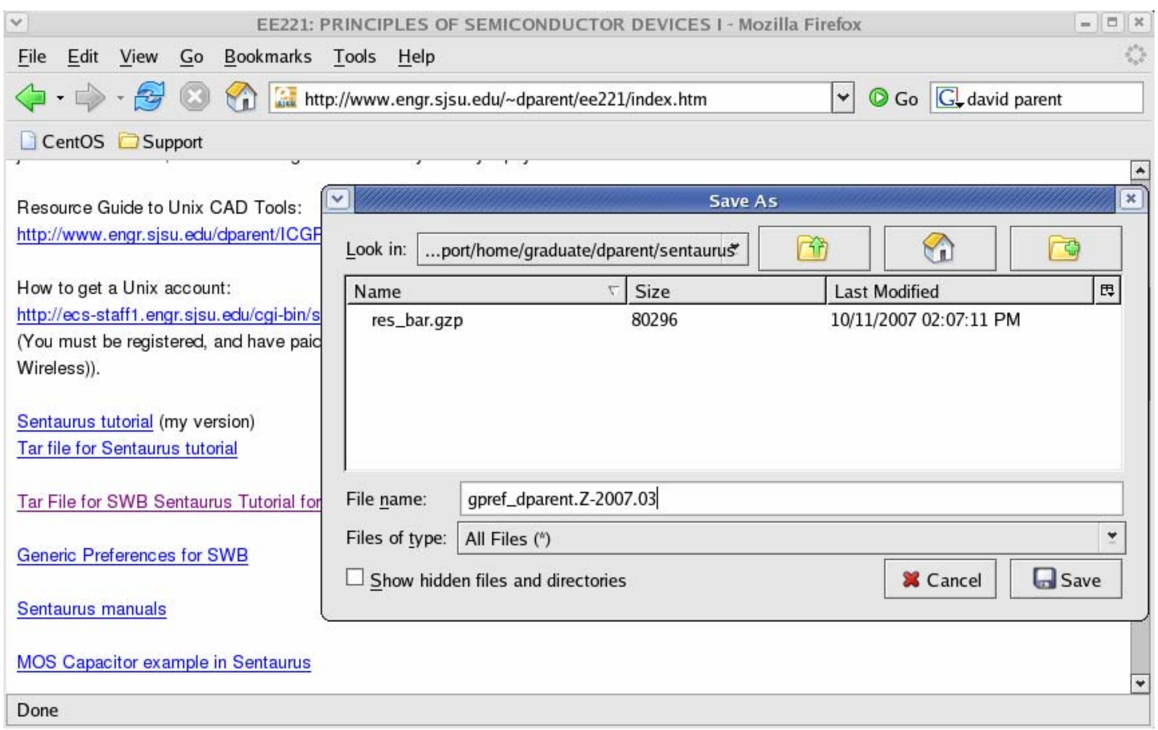



Figure 9: Saving as res_bar.gzp.

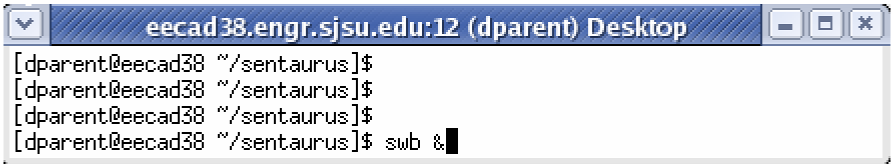



Figure 10: Starting Sentaurus Workbench.

After starting Sentaurus Workbench you should see the interface as in Figure 11.

*Double left click on res_bar.gzip* to unpack the sample files you will need for this example (Figure 11).

You should see a pop-up (Figure 13), *select unpack*.

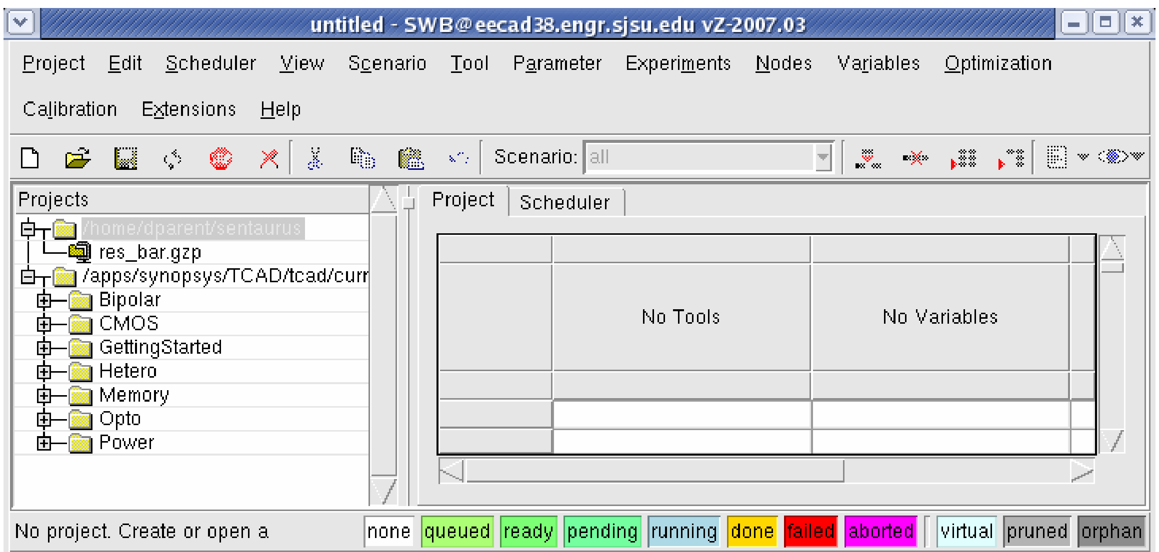



Figure 11: Sentaurus Workbench.

Another pop-up will appear, click twice to save the file (Figure 13). Note: /dparent is my directory, your directory will automatically by entered in.

If done properly you should see the project loaded into the SWB interface (Figure 14).

Table 1 shows what each parameter means (W, H, MGSX, MGSY, NA).

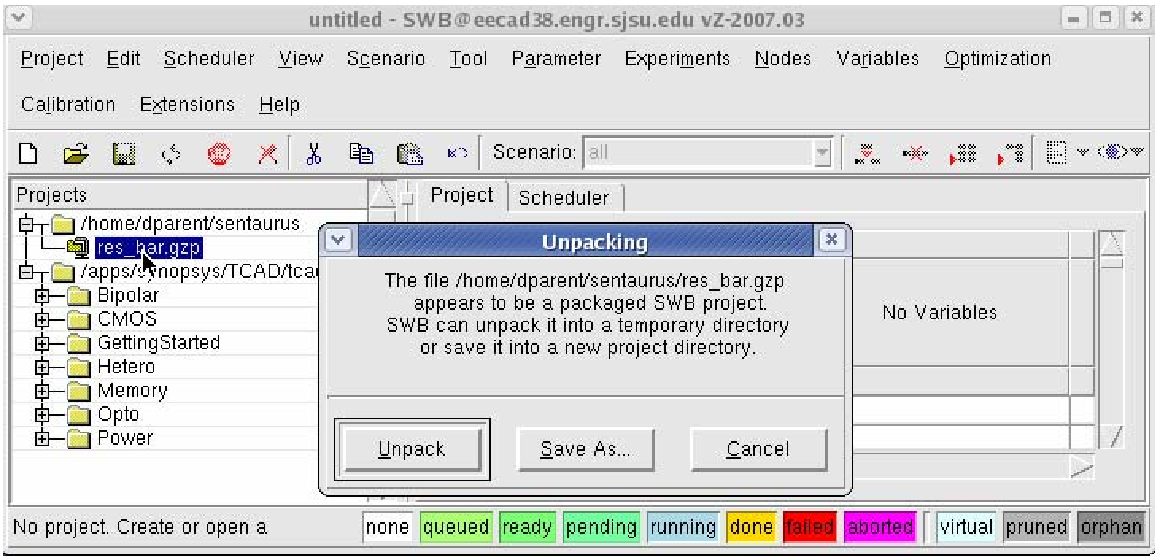



Figure 12: Click on Unpack.

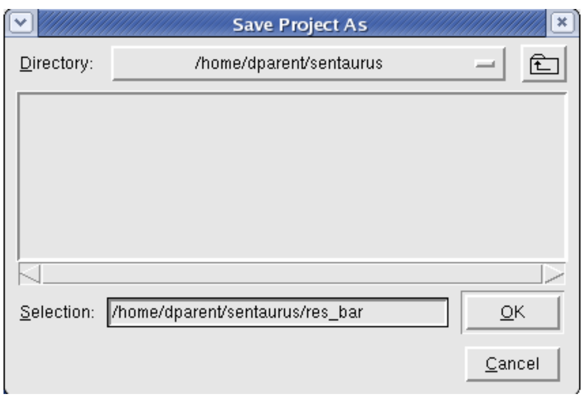



Figure 13:. Click OK twice.

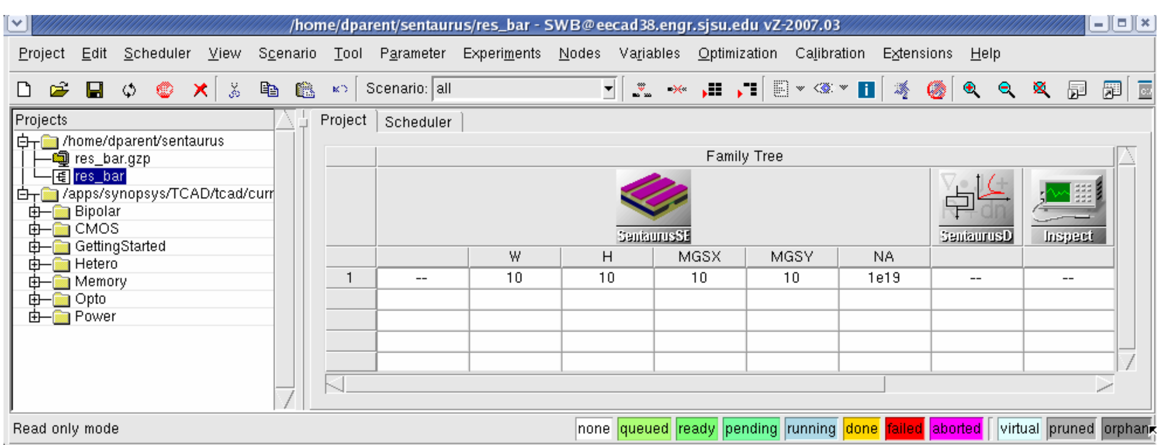



Figure 14: The resistor bar project is loaded.

Table 1: Parameter Names and Meanings.

| Parameter Name | Meaning |
|---|---|
| W | Width of the Silicon Bar. Note: Current flows from top to bottom so the larger the width, the more current can flow. |
| H | Height of the silicon Bar. Note: Current flows from top to bottom so the larger the Height, the less current can flow. |
| MGSX | Maximum Grid Spacing in the X direction. How many grids along the width. |
| MGSY | Maximum Grid Spacing in the Y direction. How many grids along the Height. |
| NA | Substrate doping of the p-Substrate. |

To see/edit the Sentaurus Structure Editor commands on the SWB interface, left click on the Sentaurus Structure Editor Icon and go to Edit Input… Commands (Figure 15). You should see the code in Figure 16.

To see/edit the Sentaurus Device commands on the SWB interface, left click on the Sentaurus Device Icon and go to Edit Input… Commands (Figure 17). You should see the code in Figure 18.

To see/edit the Inspect commands on the SWB interface, left click on the Inspect Icon and go to Edit Input… Commands (Figure 19). You should see the code in Figure 20.

**Do not edit anything at this time!**

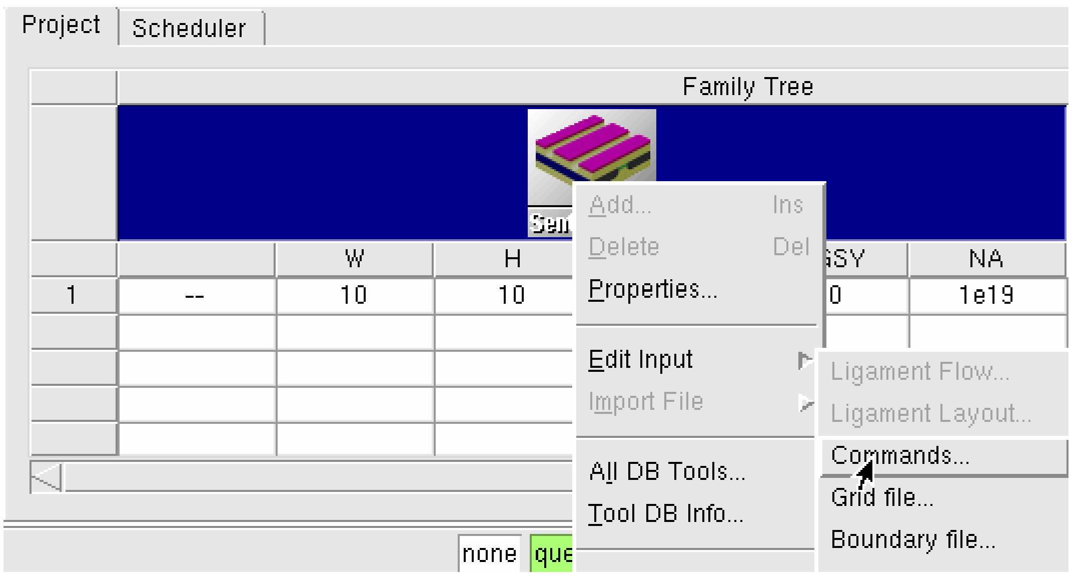
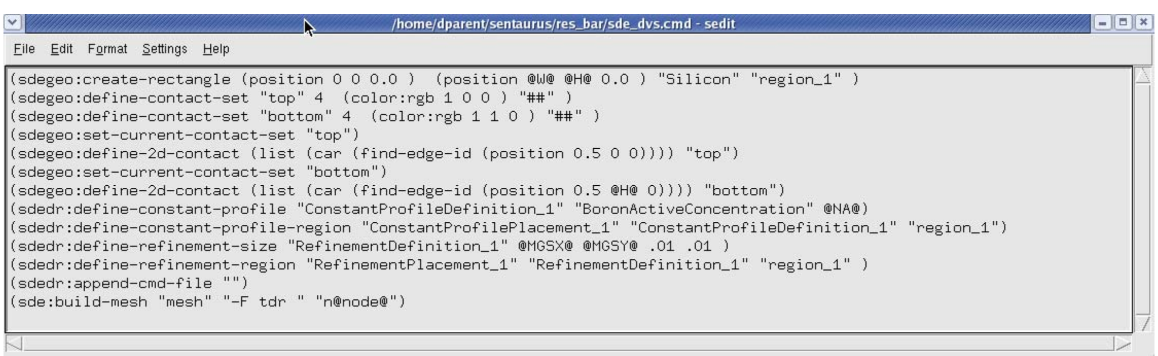



Figure 15: Showing Sentaurus Structure Editor commands.




```
(sdegeo:create-rectangle (position 0 0 0.0 )  (position @W@ @H@ 0.0 ) "Silicon" "region_1" )
(sdegeo:define-contact-set "top" 4  (color:rgb 1 0 0 ) "##" )
(sdegeo:define-contact-set "bottom" 4  (color:rgb 1 1 0 ) "##" )
(sdegeo:set-current-contact-set "top")
(sdegeo:define-2d-contact (list (car (find-edge-id (position 0.5 0 0)))) "top")
(sdegeo:set-current-contact-set "bottom")
(sdegeo:define-2d-contact (list (car (find-edge-id (position 0.5 @H@ 0)))) "bottom")
(sdedr:define-constant-profile "ConstantProfileDefinition_1" "BoronActiveConcentration" @NA@)
(sdedr:define-constant-profile-region "ConstantProfilePlacement_1" "ConstantProfileDefinition_1" "region_1")
(sdedr:define-refinement-size "RefinementDefinition_1" @MGSX@ @MGSY@ .01 .01 )
(sdedr:define-refinement-region "RefinementPlacement_1" "RefinementDefinition_1" "region_1" )
(sdedr:append-cmd-file "")
(sde:build-mesh "mesh" "-F tdr " "n@node@")
```

Figure 16: Commands for Sentaurus Structure Editor.

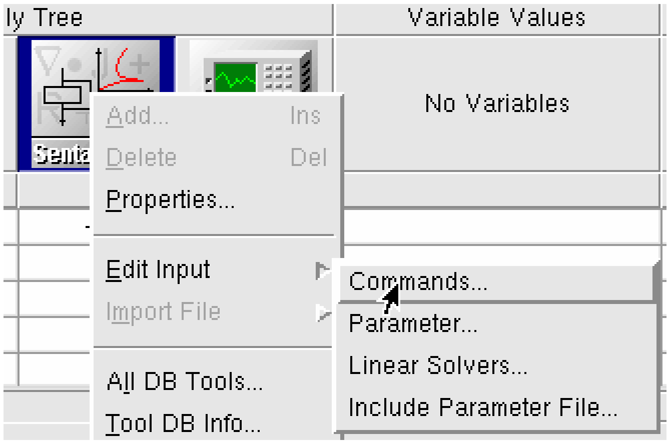



Figure 17: Showing Sentaurus Device commands.


Figure 18: Commands for Sentaurus Device.

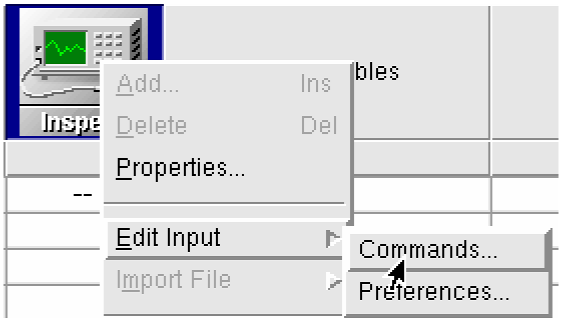
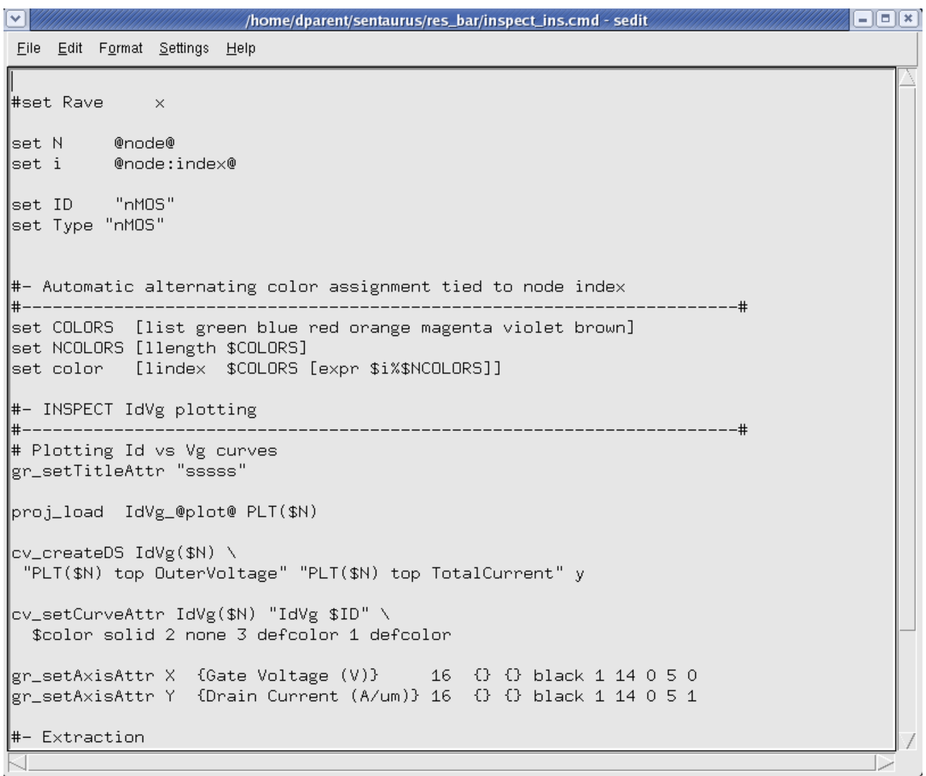



Figure 19: Showing commands for Inspect.




```
#set Rave     x

set N      @node@
set i      @node:index@

set ID     "nMOS"
set Type "nMOS"


#- Automatic alternating color assignment tied to node index
#----------------------------------------------------------------------#
set COLORS  [list green blue red orange magenta violet brown]
set NCOLORS [llength $COLORS]
set color   [lindex  $COLORS [expr $i%$NCOLORS]]

#- INSPECT IdVg plotting
#----------------------------------------------------------------------#
# Plotting Id vs Vg curves
gr_setTitleAttr "sssss"

proj_load  IdVg_@plot@ PLT($N)

cv_createDS IdVg($N) \
 "PLT($N) top OuterVoltage" "PLT($N) top TotalCurrent" y

cv_setCurveAttr IdVg($N) "IdVg $ID" \
  $color solid 2 none 3 defcolor 1 defcolor

gr_setAxisAttr X  {Gate Voltage (V)}      16  {} {} black 1 14 0 5 0
gr_setAxisAttr Y  {Drain Current (A/um)} 16  {} {} black 1 14 0 5 1

#- Extraction
```

Figure 20: Inspect Commands.

To Run the project, first unlock it (Figure 21).

The in the SWB go to Project…Project Operations… Run.. (Figure 22).

You should see a pop-up (Figure 23), select ok.

After some time you should be able to see the results (Figure 24).

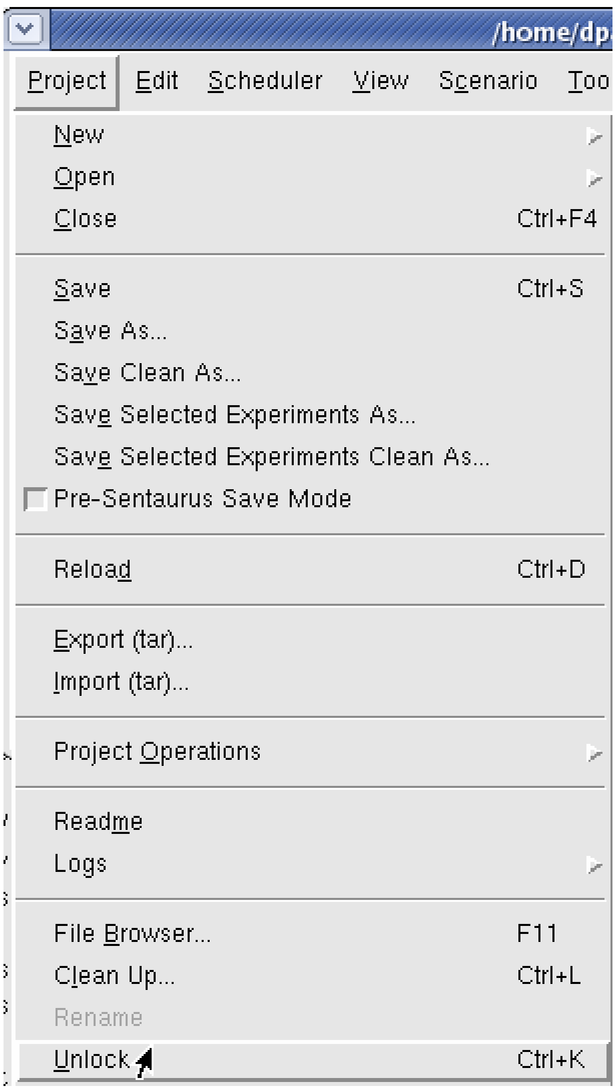



Figure 21: Unlocking the project.

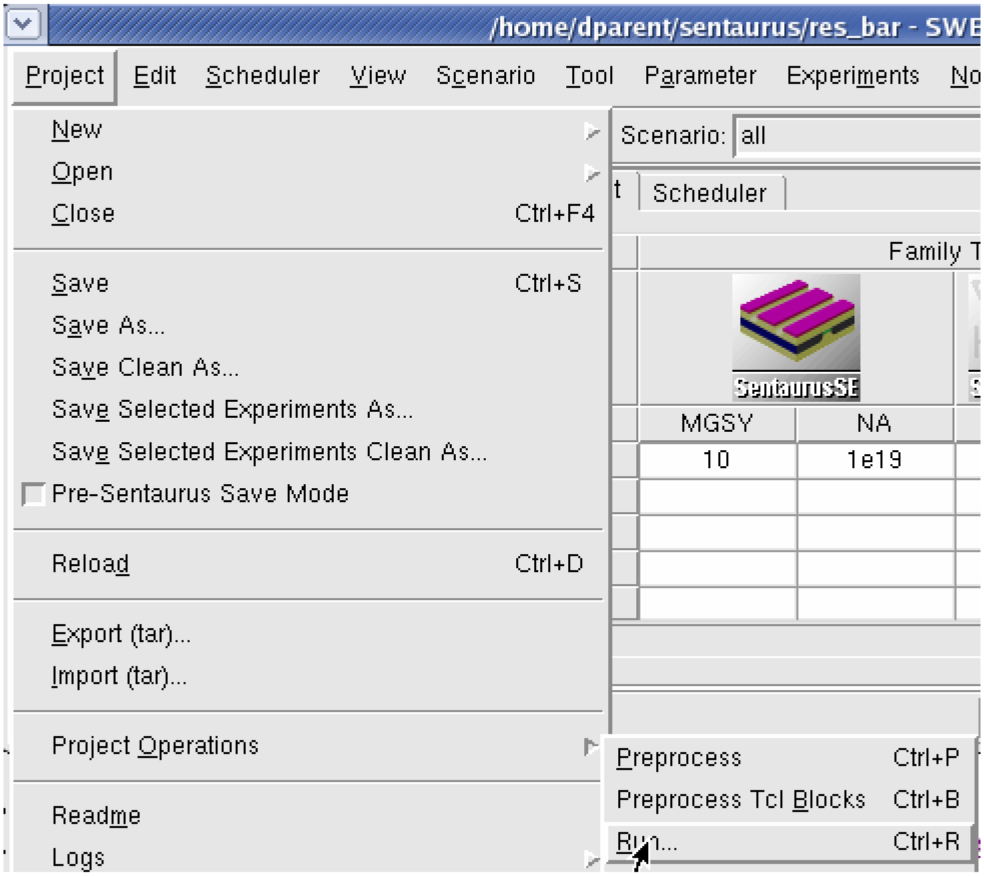



Figure 22: Running the project.

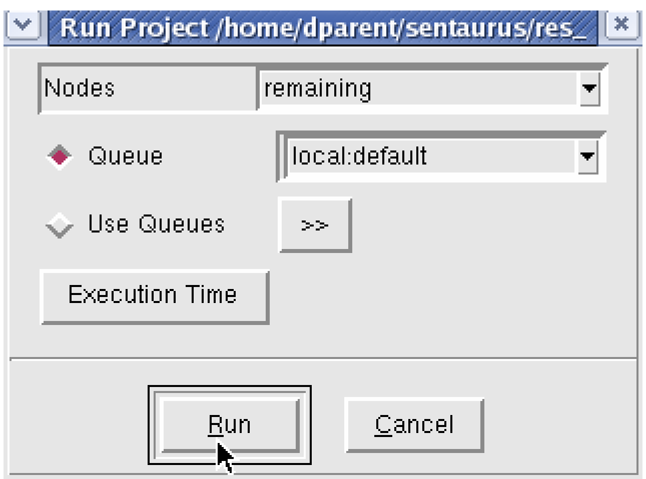



Figure 23:Setting the Queue to use for the project.

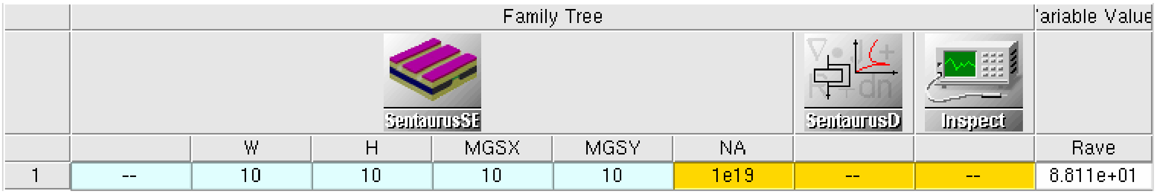



Figure 24: Results of one run of the project.

To be able to see the 2-D cross sections down load the following file into your Sentaurus directory:

http://www.engr.sjsu.edu/dparent/ee221/gpref_dparent.Z-2007.03

Go to Edit …User preferences to verify all tech plot commands are of the type techplot_sv – mesa (Figure 25). An example is in Figure 26.

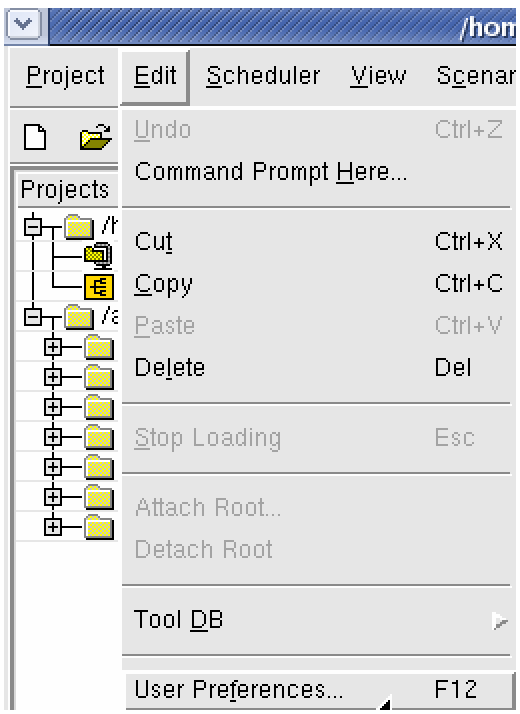
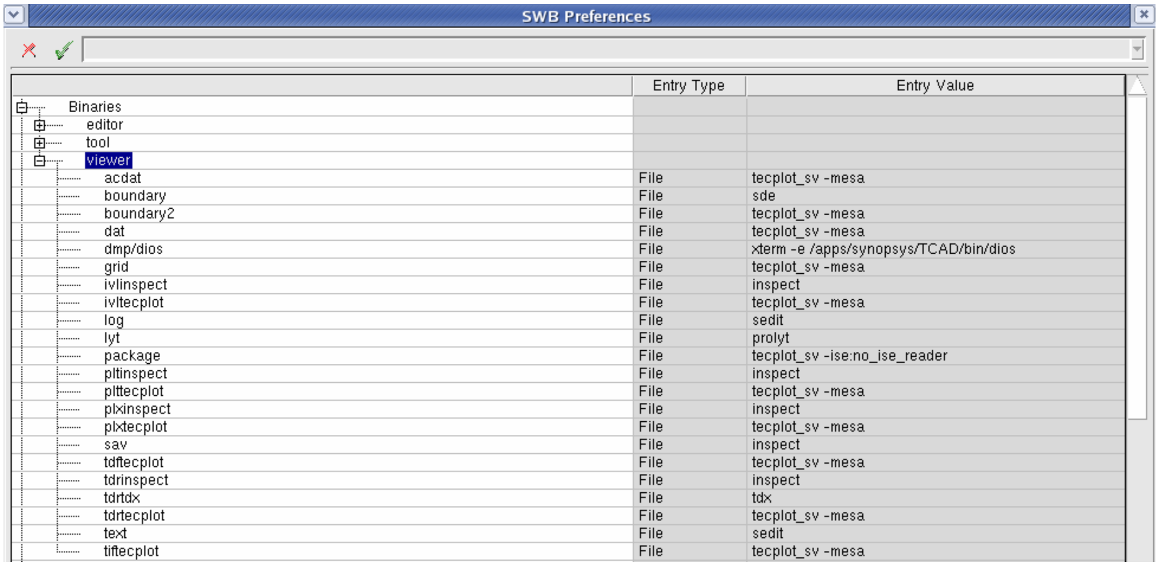



Figure 25: User Preferences.


SWB Preferences

| | Entry Type | Entry Value |
|---|---|---|
| Binaries | | |
| editor | | |
| tool | | |
| viewer | | |
| acdat | File | tecplot_sv -mesa |
| boundary | File | sde |
| boundary2 | File | tecplot_sv -mesa |
| dat | File | tecplot_sv -mesa |
| dmp/dios | File | xterm -e /apps/synopsys/TCAD/bin/dios |
| grid | File | tecplot_sv -mesa |
| ivlinspect | File | inspect |
| ivltecplot | File | tecplot_sv -mesa |
| log | File | sedit |
| lyt | File | prolyt |
| package | File | tecplot_sv -ise:no_ise_reader |
| pltinspect | File | inspect |
| plttecplot | File | tecplot_sv -mesa |
| plxinspect | File | inspect |
| plxtecplot | File | tecplot_sv -mesa |
| sav | File | inspect |
| tdftecplot | File | tecplot_sv -mesa |
| tdrinspect | File | inspect |
| tdrtdx | File | tdx |
| tdrtecplot | File | tecplot_sv -mesa |
| text | File | sedit |
| tiftecplot | File | tecplot_sv -mesa |

Figure 26: Set all Tech_plot to tecplot_sv -mesa

To view the structure created by Sentaurus Structure Editor, left click on the 1e19 node and select tecplot SV (Figure 27). The results appear in Figure 28.

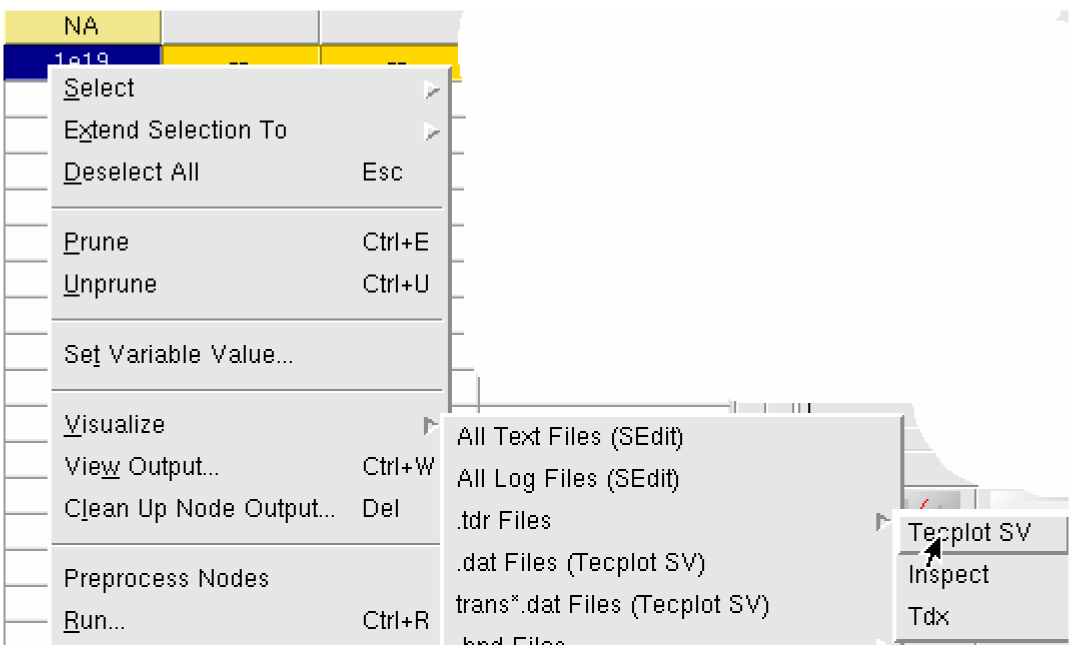



Figure 27: Viewing with tecplot_sv -mesa.

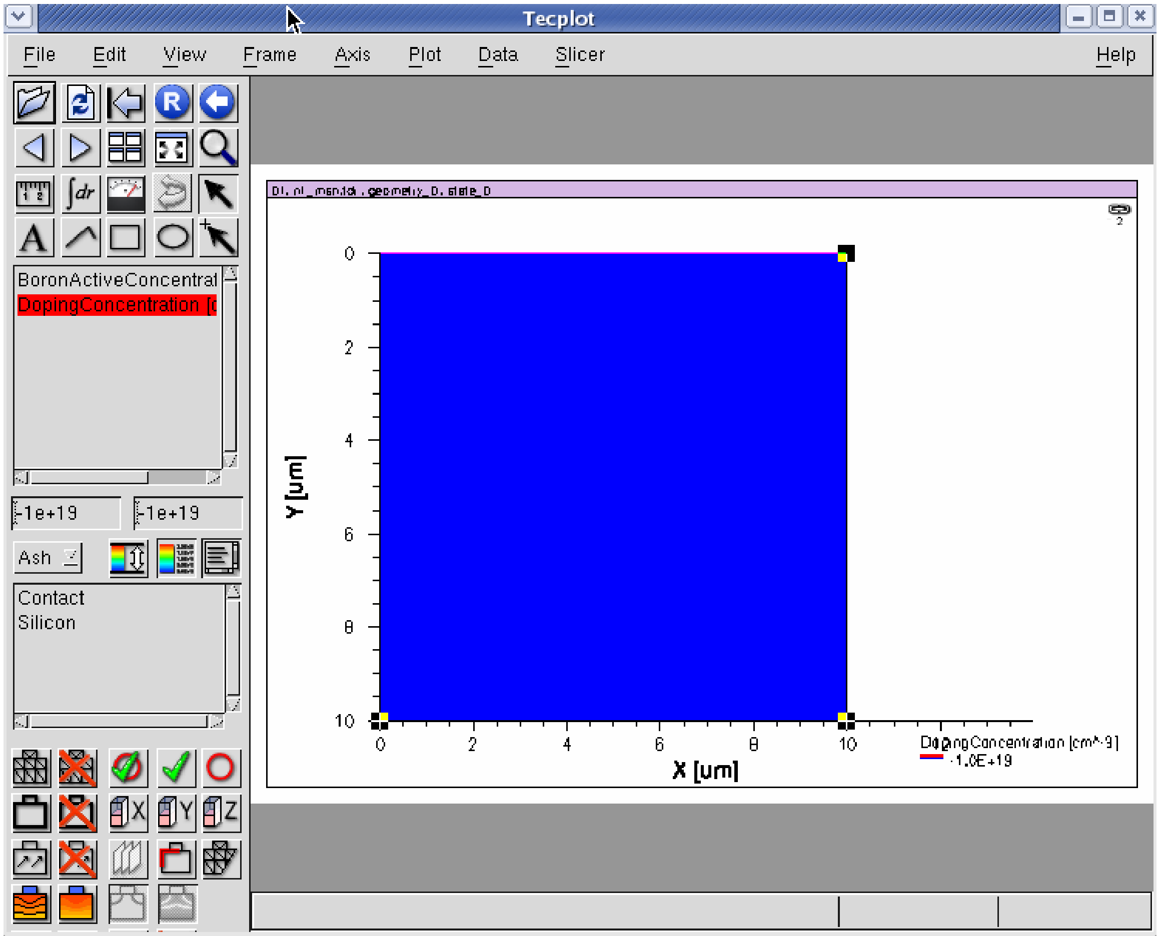



Figure 28: SDE results.

To view the electrical results right click on the SDevice node and go to Visualize, plt. Files… Inspect ans in XX.. Ispect should appear as in ..

To plot the results click on the node IDVG_n10_des , then top, then OuterVoltage as in Figure 30, and then click X-axis. Repeat for Total current but click n Y axis (Figure 31). The results should appear as in Figure 32.

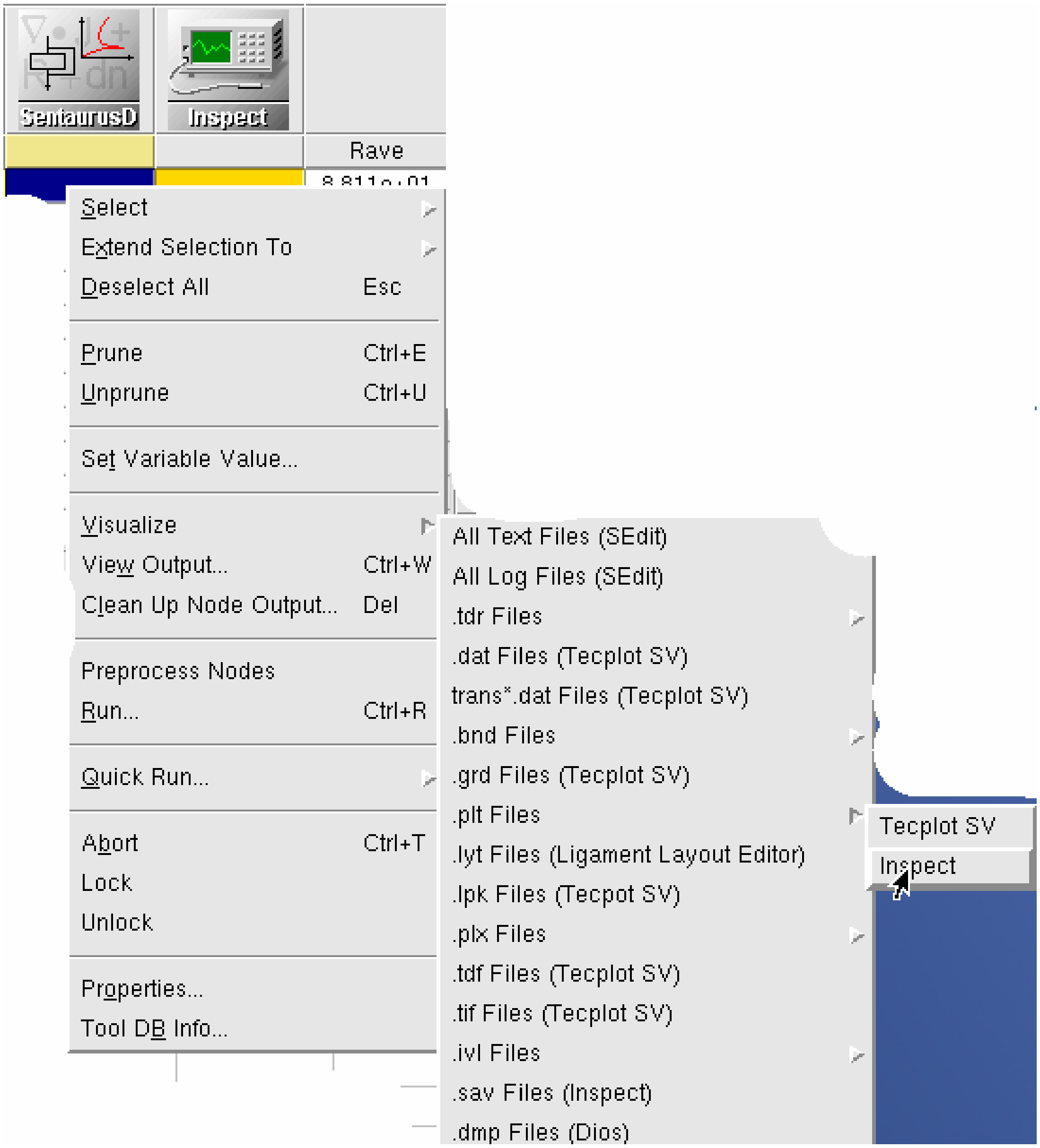



Figure 29: Plotting Results from SDevice with Inspect.

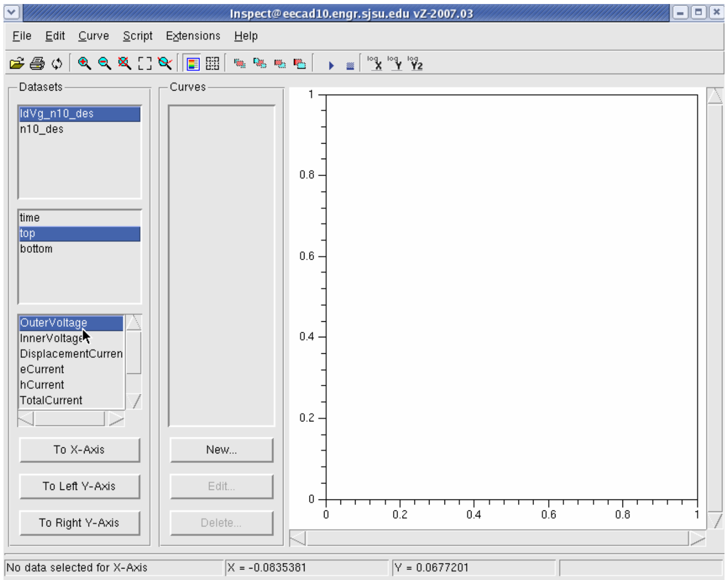



Figure 30: Setting X-Axis.

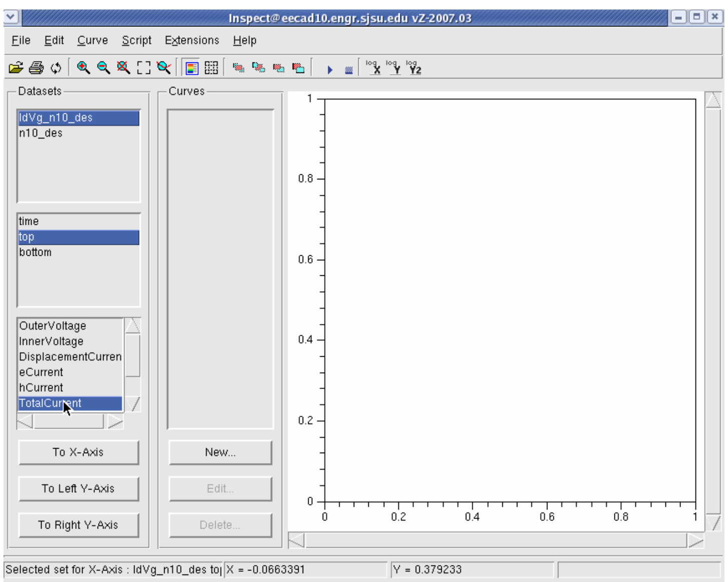



Figure 31: Setting Y-Axis

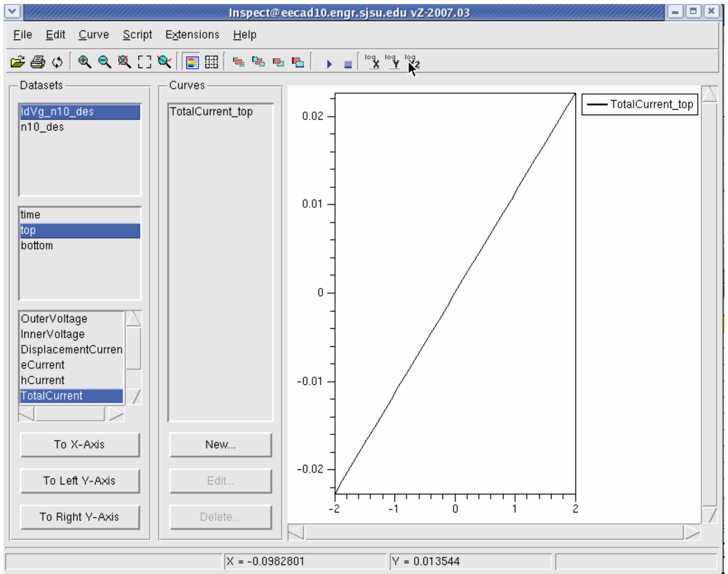



Figure 32: Electrical Results for a Bar of Silicon.

To see the affect on simulation time a accuracy of results change the variables MGSX and MGSY variables to .1 as in Figure 33 to Figure 36. Your SWB interface should look like Figure 37.

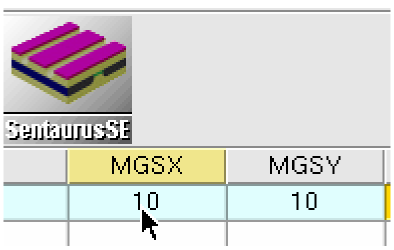



Figure 33: Changing MGSX to .1um.

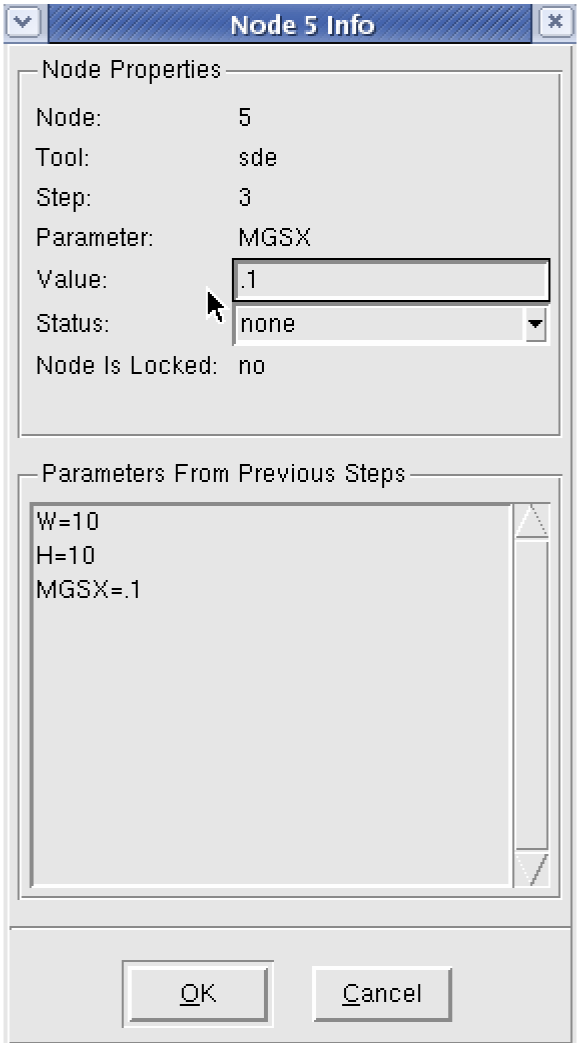



Figure 34: Change value of MGSX.

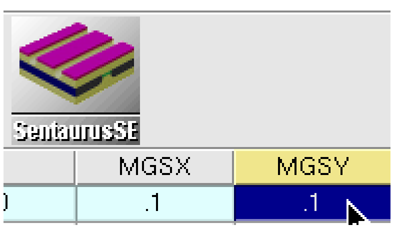



Figure 35: MGSY to .1um.

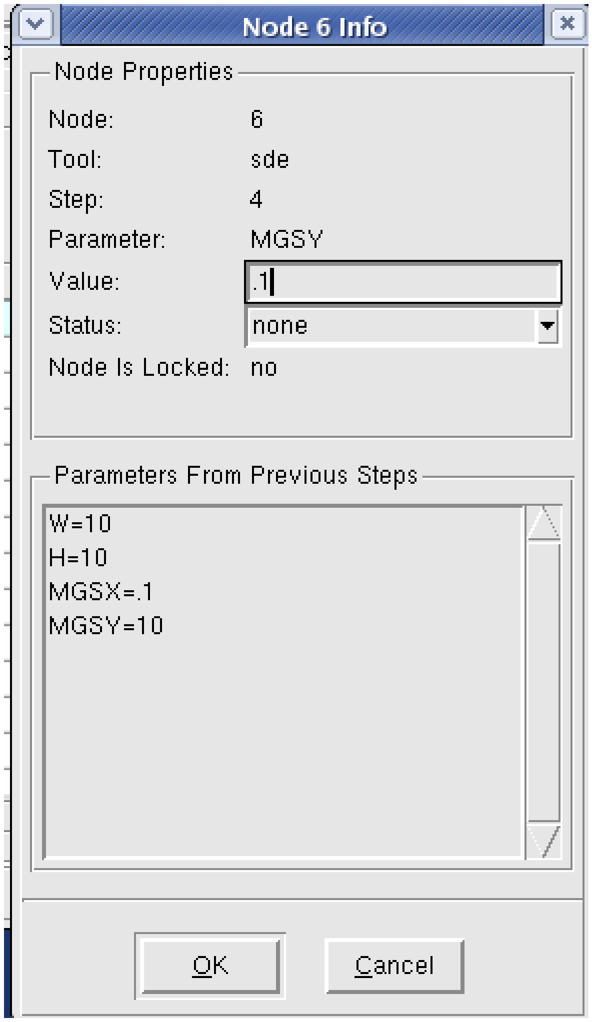



Figure 36: Change value of MGSY.

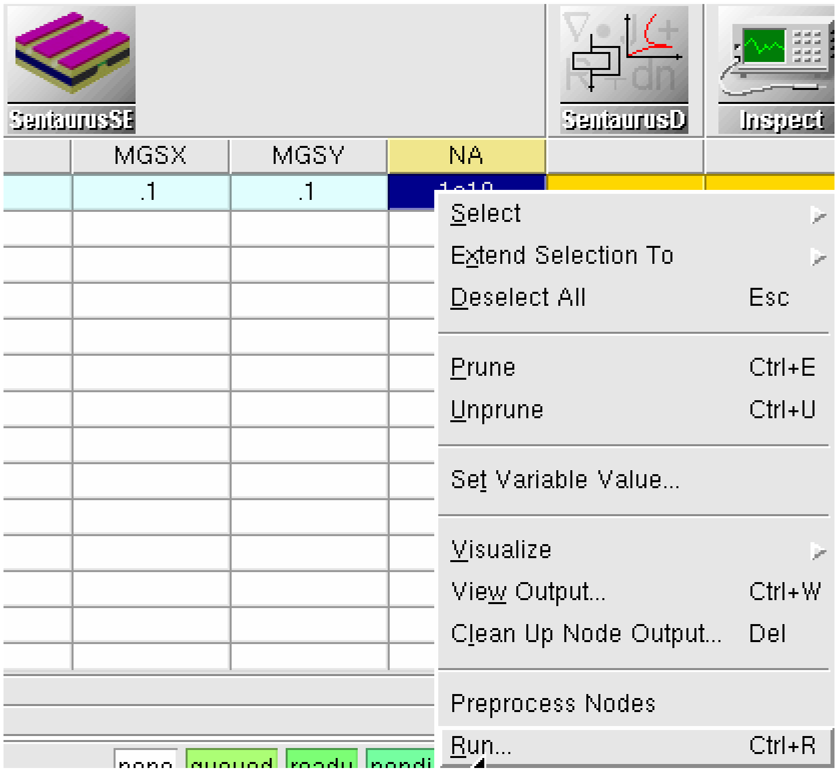



Figure 37: Rerun the project.

To rerun the project node click on the node and select run (Figure 37). Click yes to save the project (Figure 38). When complete use tecplot to view the results. When tecplot appears click on the grid icon and you should get the results shown in Figure 39.

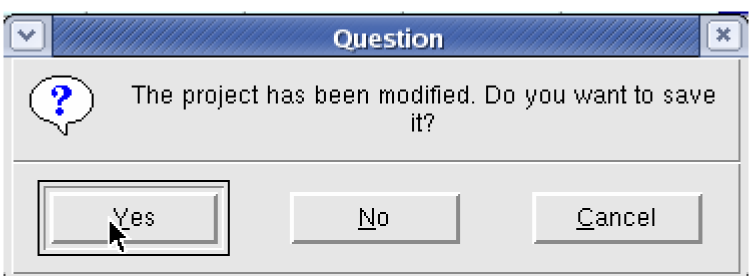



Figure 38: Saving Project.

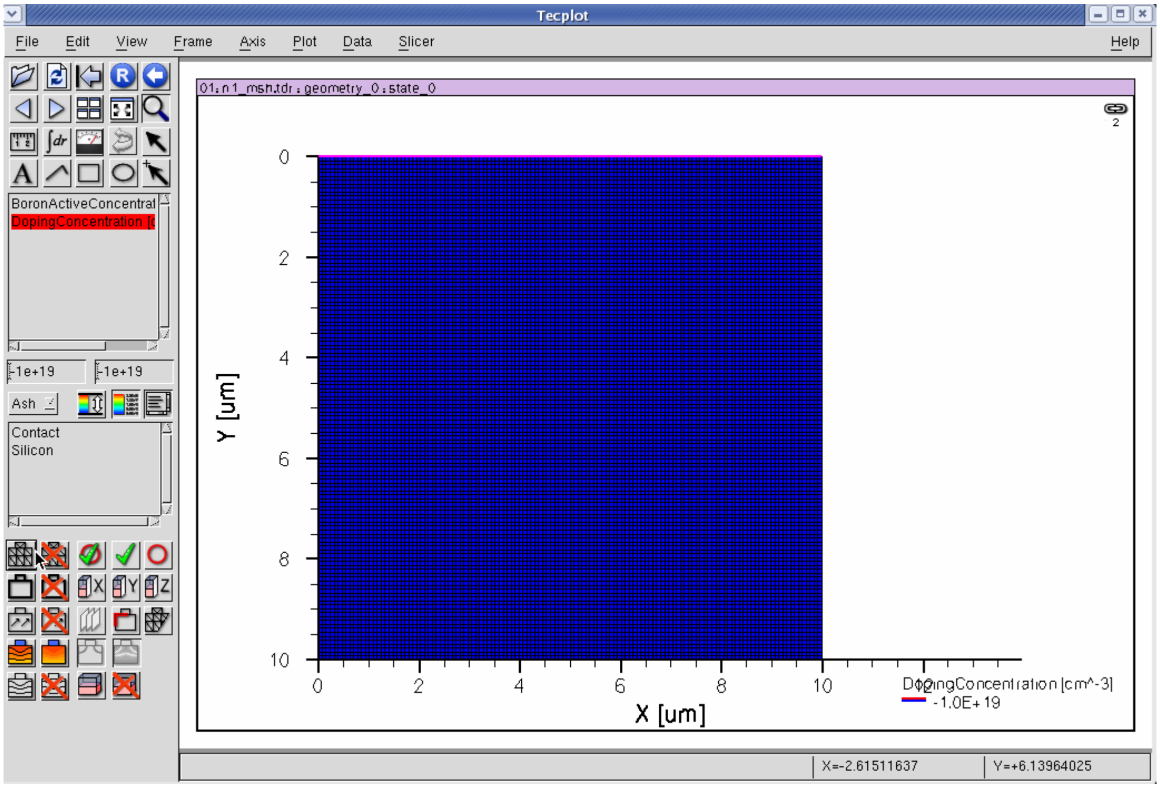


Figure 39: Results of finer grid.

To view the run time statistics, click on the proper node in the SDevice column, and goto view output (Figure 40). You should see the start of your project (Figure 41), and the end (Figure 42).

**Note, even though the project took significantly longer to run the results are the same (Figure 43)! Why????**

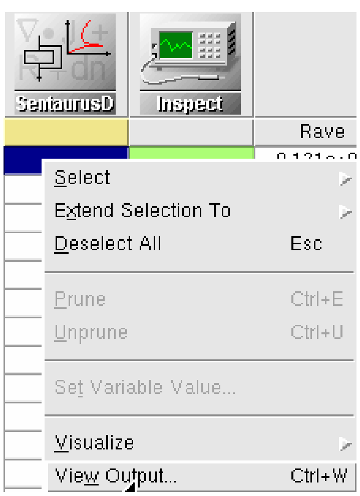
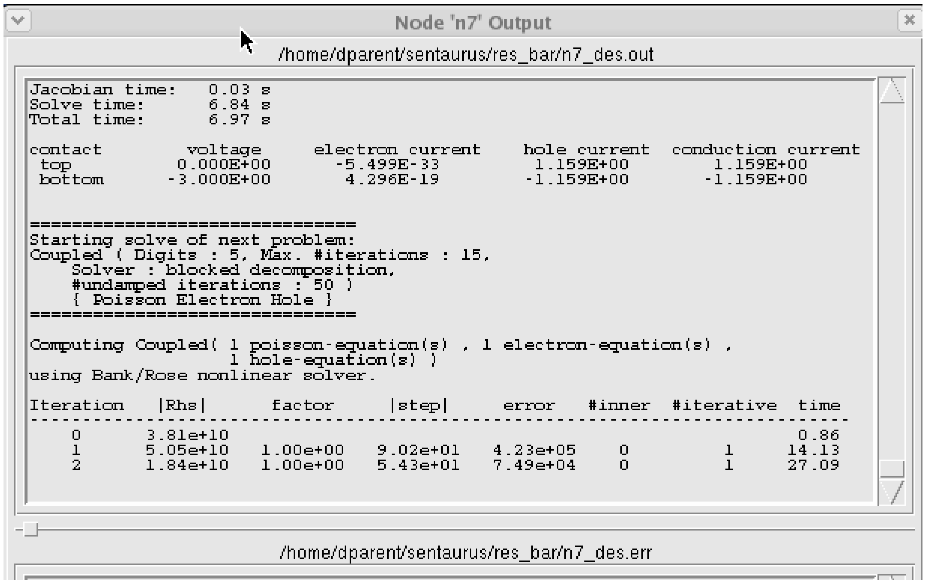


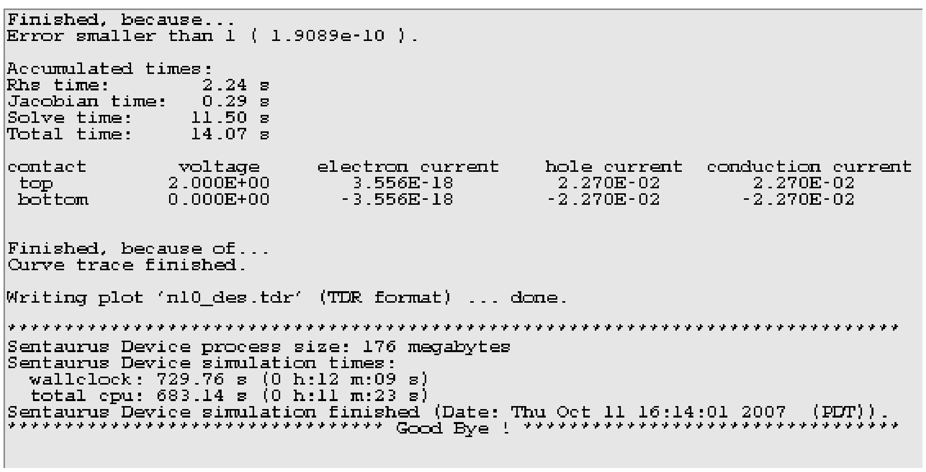
Figure 40: Viewing the SDevcie run time.





```
Jacobian time:    0.03 s
Solve time:       6.84 s
Total time:       6.97 s

contact          voltage       electron current    hole current   conduction current
 top            0.000E+00        -5.499E-33        1.159E+00         1.159E+00
 bottom        -3.000E+00         4.296E-19       -1.159E+00        -1.159E+00


===============================
Starting solve of next problem:
Coupled ( Digits : 5, Max. #iterations : 15,
    Solver : blocked decomposition,
    #undamped iterations : 50 )
    { Poisson Electron Hole }
===============================

Computing Coupled( 1 poisson-equation(s) , 1 electron-equation(s) ,
                   1 hole-equation(s) )
using Bank/Rose nonlinear solver.

Iteration    |Rhs|      factor     |step|      error    #inner  #iterative  time
--------------------------------------------------------------------------------
    0       3.81e+10                                                        0.86
    1       5.05e+10   1.00e+00   9.02e+01   4.23e+05     0          1     14.13
    2       1.84e+10   1.00e+00   5.43e+01   7.49e+04     0          1     27.09
```

Figure 41: Sdevice starts.



```
Finished, because...
Error smaller than 1 ( 1.9089e-10 ).

Accumulated times:
Rhs time:          2.24 s
Jacobian time:     0.29 s
Solve time:       11.50 s
Total time:       14.07 s

contact          voltage       electron current    hole current   conduction current
 top            2.000E+00         3.556E-18        2.270E-02         2.270E-02
 bottom         0.000E+00        -3.556E-18       -2.270E-02        -2.270E-02


Finished, because of...
Curve trace finished.

Writing plot 'n10_des.tdr' (TDR format) ... done.

******************************************************************************
Sentaurus Device process size: 176 megabytes
Sentaurus Device simulation times:
  wallclock: 729.76 s (0 h:12 m:09 s)
  total cpu: 683.14 s (0 h:11 m:23 s)
Sentaurus Device simulation finished (Date: Thu Oct 11 16:14:01 2007  (PDT)).
********************************* Good Bye ! *********************************
```

Figure 42: Run statistics for Sdevcie.

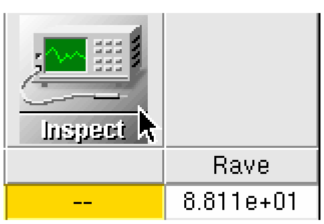




Figure 43: No change in results!

To make a series of experiments you need to add values to the variable columns. For example we wish to see how resistance of the bar charges with doping levels from $10^{14}cm^{-3}$ to from $10^{19}cm^{-3}$ .

First change the 1e19 node to 1e14 as in Figure 44. Ad values by clicking on NA, and going to Add Values (Figure 45). Fill out the pop-up according to Figure 46. The SWB manager should look like Figure 47. Change the MGSX, and MGSY back to 10 and you should be ready to simulate (Figure 48).

Before you can run the project you need to "clean it up". In the SWB manager go to Project Cleanup (Figure 49), and click OK on the pop-up (Figure 50), your SWB manager should look like Figure 51. Run the project and you should see the results as in Figure 52.

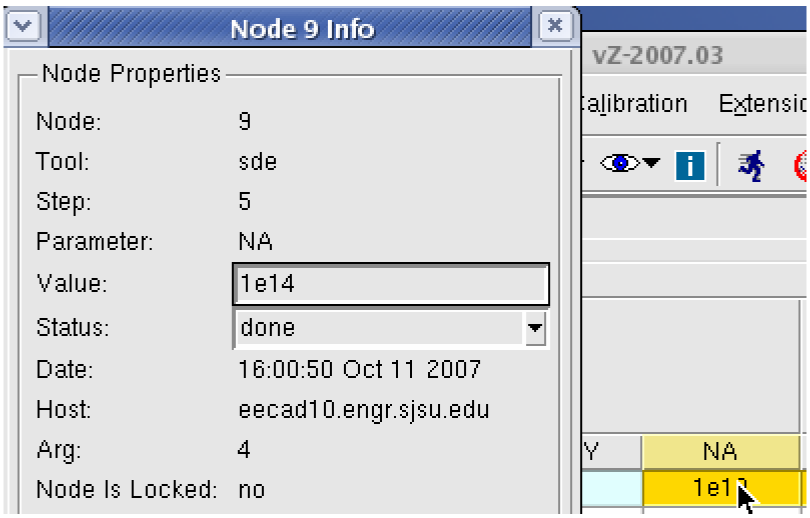



Figure 44: Editing a variable.

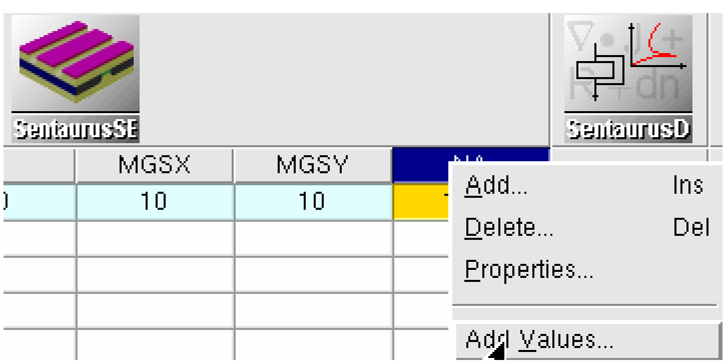



Figure 45: Adding experimental values.

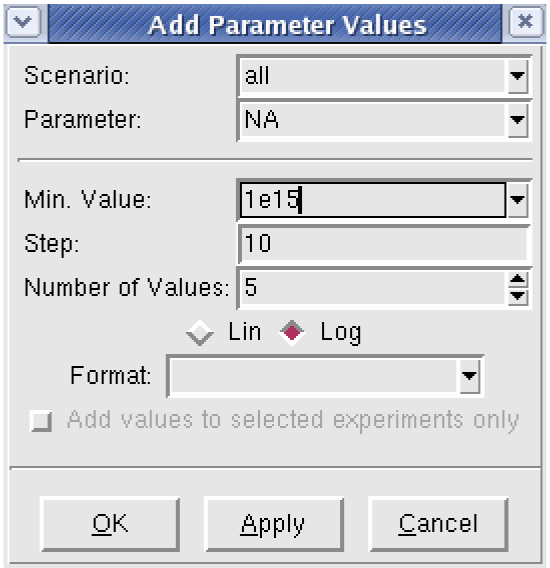



Figure 46: Add 5 values at powers of 10 doping levels.

| SentaurusSE | | | | | | SentaurusD | Inspect | |
|---|---|---|---|---|---|---|---|---|
| | W | H | MGSX | MGSY | NA | | | Rave |
| -- | 10 | 10 | .1 | .1 | 1e14 | -- | -- | 8.811e+01 |
| | | | | | 1e15 | -- | -- | |
| | | | | | 1e+16 | -- | -- | |
| | | | | | 1e+17 | -- | -- | |
| | | | | | 1e+18 | -- | -- | |
| | | | | | 1e+19 | -- | -- | |

Figure 47: Experiments almost all set up.

| SentaurusSE | | | | | | SentaurusD | Inspect | |
|---|---|---|---|---|---|---|---|---|
| | W | H | MGSX | MGSY | NA | | | Rave |
| -- | 10 | 10 | 10 | 10 | 1e14 | -- | -- | 8.811e+01 |
| | | | | | 1e15 | -- | -- | |
| | | | | | 1e+16 | -- | -- | |
| | | | | | 1e+17 | -- | -- | |
| | | | | | 1e+18 | -- | -- | |
| | | | | | 1e+19 | -- | -- | |

Figure 48: Change MGSX and MGSY back to 10.

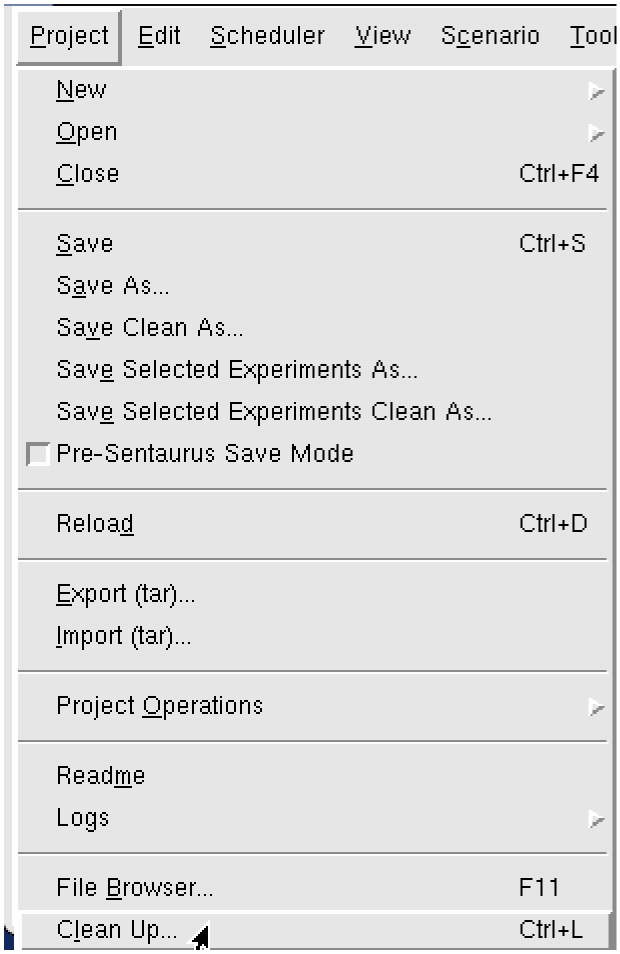



Figure 49: Cleanup project.

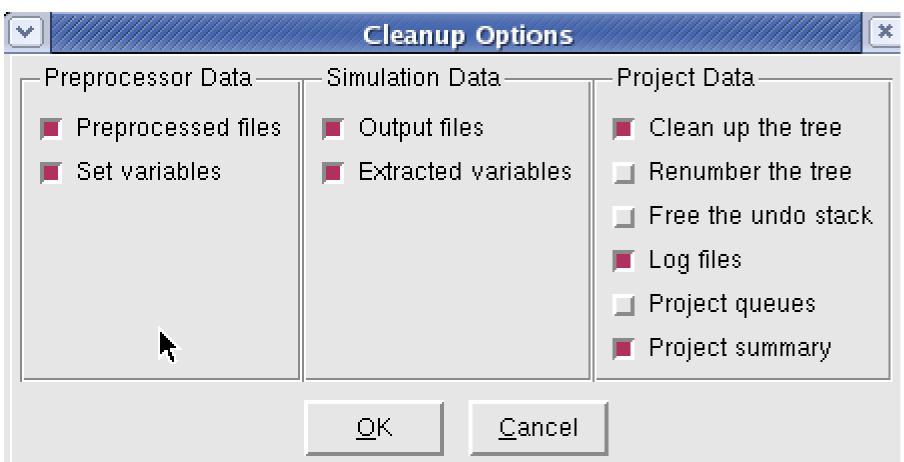



Figure 50: Clean up results.

| SentaurusSE | | | | | | SentaurusD | Inspect |
|---|---|---|---|---|---|---|---|
| | W | H | MGSX | MGSY | NA | | |
| -- | 10 | 10 | 10 | 10 | 1e14 | -- | -- |
| | | | | | 1e15 | -- | -- |
| | | | | | 1e+16 | -- | -- |
| | | | | | 1e+17 | -- | -- |
| | | | | | 1e+18 | -- | -- |
| | | | | | 1e+19 | -- | -- |

Figure 51: Project ready to run.

| | W | H | MGSX | MGSY | NA | | | Rave |
|---|---|---|---|---|---|---|---|---|
| -- | 10 | 10 | 10 | 10 | 1e14 | -- | -- | 1.331e+06 |
| | | | | | 1e15 | -- | -- | 1.351e+05 |
| | | | | | 1e+16 | -- | -- | 1.454e+04 |
| | | | | | 1e+17 | -- | -- | 1.966e+03 |
| | | | | | 1e+18 | -- | -- | 4.083e+02 |
| | | | | | 1e+19 | -- | -- | 8.811e+01 |

Figure 52: Results.

Once can cut and past the doping levels and R values into open office.Calc(Figure 53). One can plot the results as in (Figure 54). **What is the kink in R at the doping level of $10^{17}$cm$^{-3}$?**

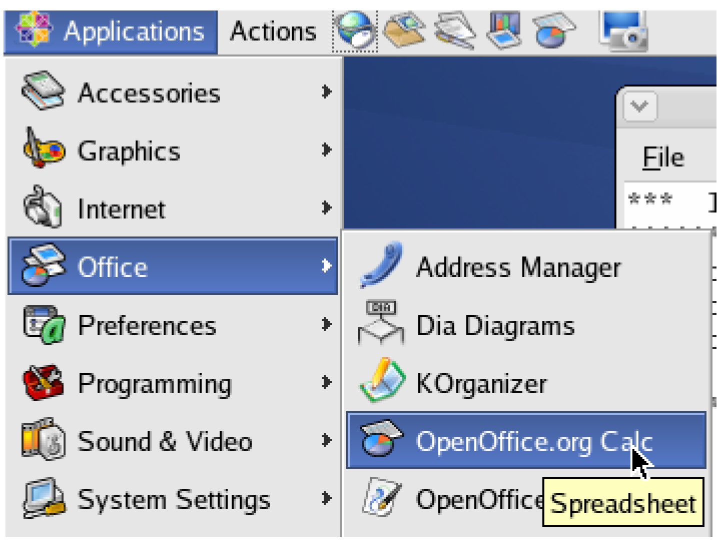



Figure 53: Opening Open Office Calc

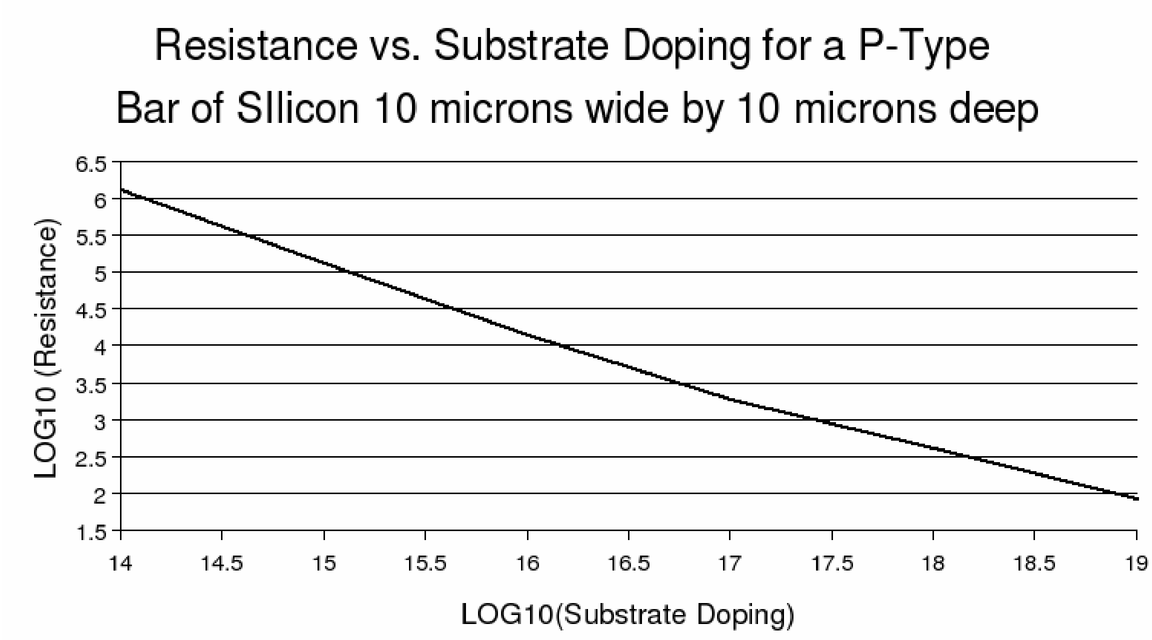



Figure 54: Results of varying the doping levels of a Silicon Bar.

In order to run another one parameter experiment we need to delete the values for NA. To do this, click on NA and delete it (Figure 55). You can keep the suggested value in pop up Figure 56.

Add NA back this time with a value of $10^{16}cm^{-3}$ (Figure 57). Your SWB manager should look like Figure 58.

To vary H, the height of the bar of silicon, click on H and add the values according to pop up Figure 59. Your SWB manager should look like Figure 60. Cleanup the project and re-run it. You should get results like Figure 61.

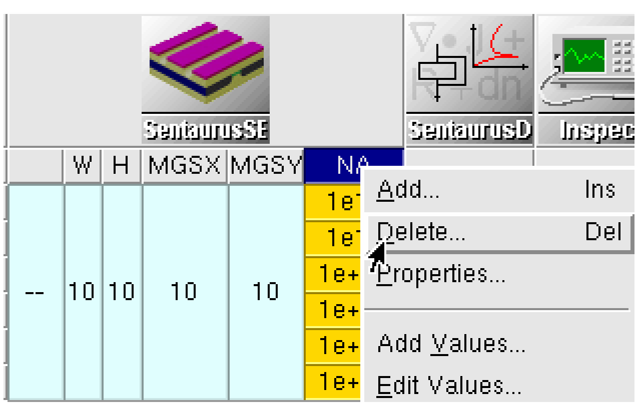



Figure 55: Deleting a variable.

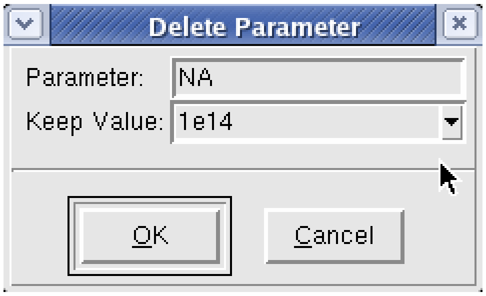



Figure 56: Slecting which vlaue to keep.

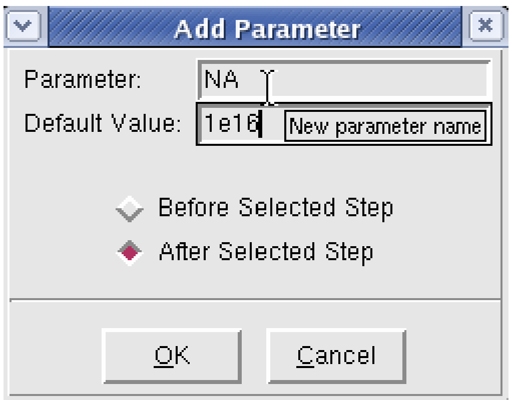



Figure 57: Adding the paramter back.

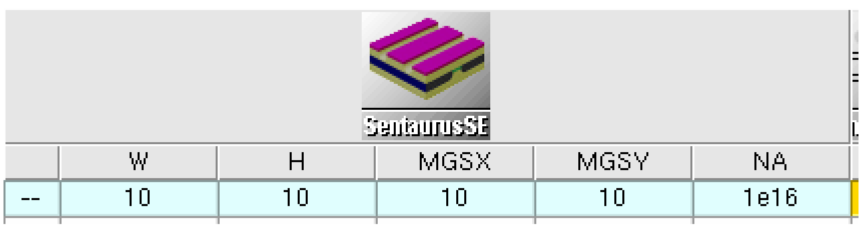



Figure 58: NA added back.

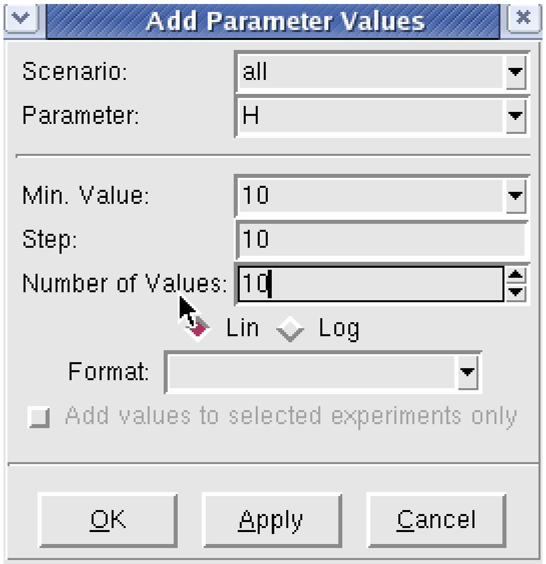



Figure 59: Adding vlaues to the H.

| | | | SentaurusSE | | | SentaurusD | Inspect | |
|---|---|---|---|---|---|---|---|---|
| | W | H | MGSX | MGSY | NA | | | Rave |
| -- | 10 | 10 | 10 | 10 | 1e16 | -- | -- | 1.812e+06 |
| | | 20 | 10 | 10 | 1e16 | -- | -- | |
| | | 30 | 10 | 10 | 1e16 | -- | -- | |
| | | 40 | 10 | 10 | 1e16 | -- | -- | |
| | | 50 | 10 | 10 | 1e16 | -- | -- | |
| | | 60 | 10 | 10 | 1e16 | -- | -- | |
| | | 70 | 10 | 10 | 1e16 | -- | -- | |
| | | 80 | 10 | 10 | 1e16 | -- | -- | |
| | | 90 | 10 | 10 | 1e16 | -- | -- | |
| | | 100 | 10 | 10 | 1e16 | -- | -- | |

Figure 60: Varying H in the SWB manager.

| | | | SentaurusSE | | | SentaurusD | Inspect | |
|---|---|---|---|---|---|---|---|---|
| | W | H | MGSX | MGSY | NA | | | Rave |
| -- | 10 | 10 | 10 | 10 | 1e16 | -- | -- | 1.924e+04 |
| | | 20 | 10 | 10 | 1e16 | -- | -- | 3.306e+04 |
| | | 30 | 10 | 10 | 1e16 | -- | -- | 4.725e+04 |
| | | 40 | 10 | 10 | 1e16 | -- | -- | 6.156e+04 |
| | | 50 | 10 | 10 | 1e16 | -- | -- | 7.594e+04 |
| | | 60 | 10 | 10 | 1e16 | -- | -- | 9.035e+04 |
| | | 70 | 10 | 10 | 1e16 | -- | -- | 1.048e+05 |
| | | 80 | 10 | 10 | 1e16 | -- | -- | 1.192e+05 |
| | | 90 | 10 | 10 | 1e16 | -- | -- | 1.337e+05 |
| | | 100 | 10 | 10 | 1e16 | -- | -- | 1.482e+05 |

Figure 61: Results of Varying H.

Looking a Figure 62it seems the R is linear with H (Note: the current flow in from top to bottom of this structure so in the case L=H  Since R=ρ x L / Area).  This makes sense according to the equation but what about the mobility reduction to velocity saturation?  If we edit the SDevice command file we see Figure 63, with no mobility flag for this effect.  Add the effect in by changing the SDevice command file to HighFieldSaturation Figure 64.

After editing the command file select the nodes and preprocess them to update the changes in the command file (Figure 66).  Select the nodes again and run.  This will only run Sdevcie and Nspect.  The structures re the same so do not re-run them.  This saves quite a bit of time.

You should get the results as shown in Figure 65 .  Note that if you plot it out against the last run there is not much difference, why?  Hint: Try running the simulation with H from 1 to 10 in steps of ten.  Make sure to change MGSY to 1 (Figure 67)!  Note you will not see much difference in R as in the way it is extracted.  Look at the plots of current to see what is going on.

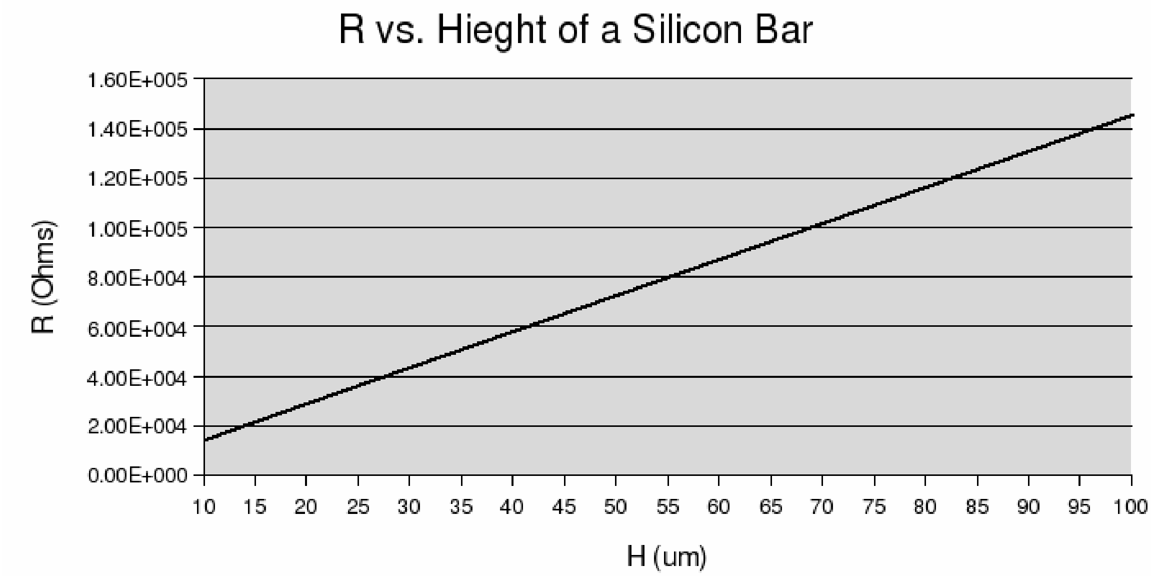



Figure 62: R. Vs H.

```
}

Physics{
   EffectiveIntrinsicDensity( OldSlotboom )
}


Physics(Material="Silicon"){
   MLDA
   Mobility(
      PhuMob
```

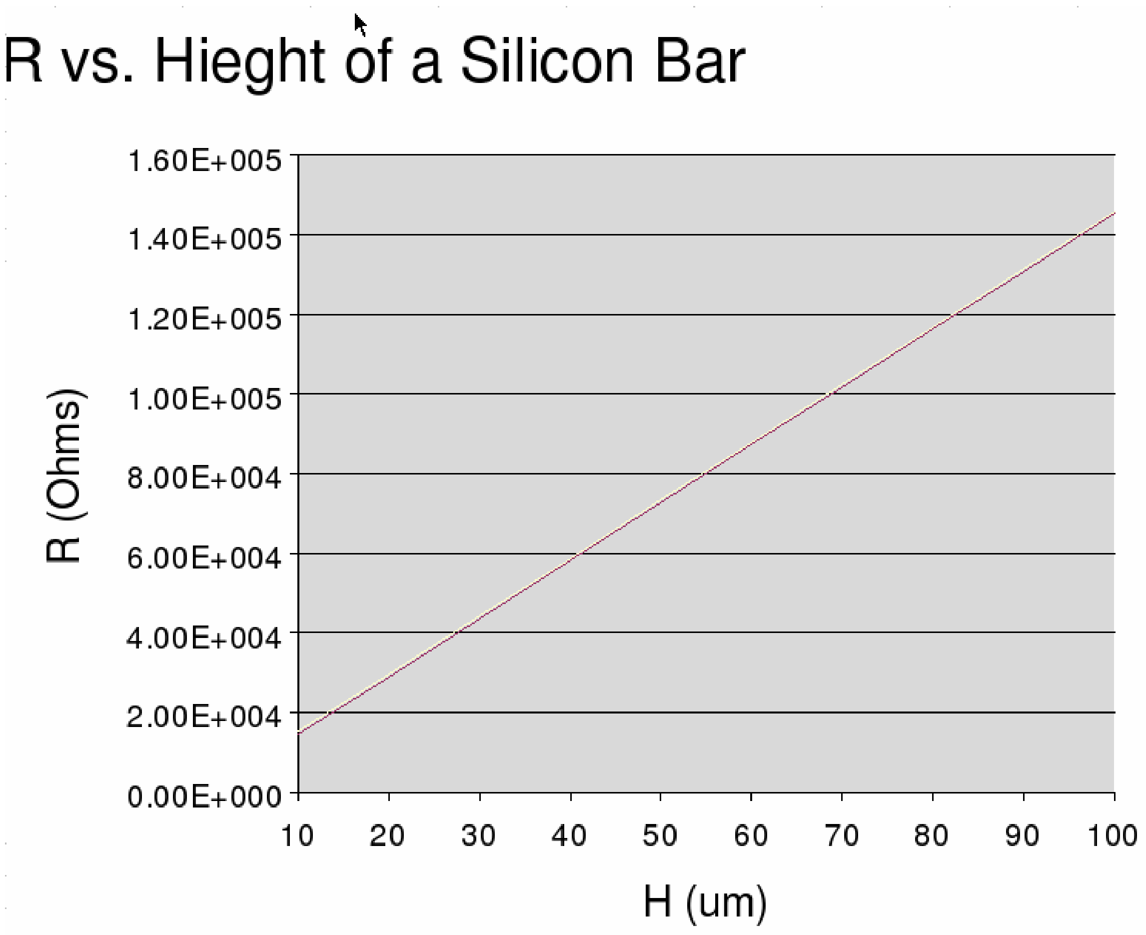
Figure 63: Physics statement.

```
Physics(Material="Silicon"){
   MLDA
   Mobility(
      PhuMob
      HighFieldSaturation

   )
```

Figure 64: HighFieldSaturation Flag.

| | | | | | |
|---|---|---|---|---|---|
| 10 | 10 | 1e16 | -- | -- | 1.534e+04 |
| 10 | 10 | 1e16 | -- | -- | 2.978e+04 |
| 10 | 10 | 1e16 | -- | -- | 4.426e+04 |
| 10 | 10 | 1e16 | -- | -- | 5.877e+04 |
| 10 | 10 | 1e16 | -- | -- | 7.328e+04 |
| 10 | 10 | 1e16 | -- | -- | 8.780e+04 |
| 10 | 10 | 1e16 | -- | -- | 1.023e+05 |
| 10 | 10 | 1e16 | -- | -- | 1.168e+05 |
| 10 | 10 | 1e16 | -- | -- | 1.314e+05 |
| 10 | 10 | 1e16 | -- | -- | 1.459e+05 |

Figure 65: Results with High Field Mobility.



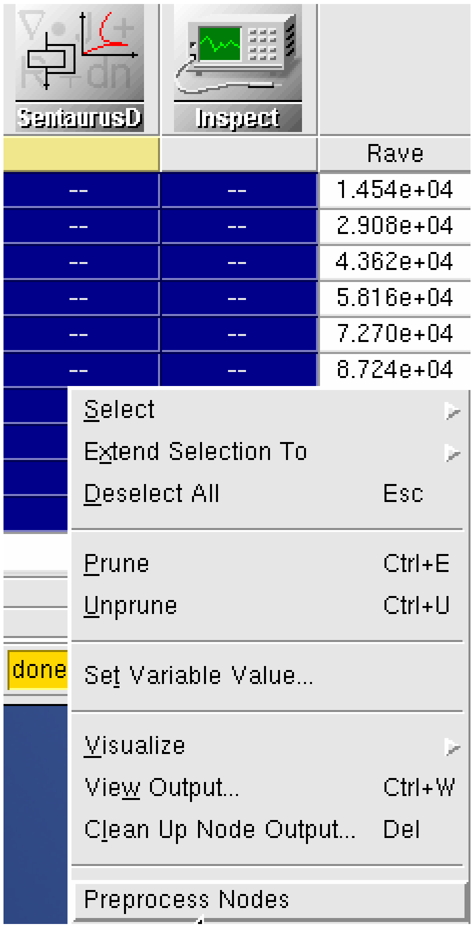



Figure 66: Preprocess Nodes.

| | W | H | MGSX | MGSY | NA | SentaurusD | Inspect |
|---|---|---|---|---|---|---|---|
| -- | 10 | 1 | 10 | 1 | 1e16 | -- | -- |
| | | 2 | 10 | | 1e16 | -- | -- |
| | | 3 | 10 | 1 | 1e16 | -- | -- |
| | | 4 | 10 | 1 | 1e16 | -- | -- |
| | | 5 | 10 | 1 | 1e16 | -- | -- |
| | | 6 | 10 | 1 | 1e16 | -- | -- |
| | | 7 | 10 | 1 | 1e16 | -- | -- |
| | | 8 | 10 | 1 | 1e16 | -- | -- |
| | | 9 | 10 | 1 | 1e16 | -- | -- |
| | | 10 | 10 | 1 | 1e16 | -- | -- |

Figure 67: New Experiment H=1-10um, and MSGY=1um.