Optimal Device Design for NIPIN Memory Selector

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***Abstract*—This work is an analysis of the NIPIN device structure by changing device parameters like width, temperature and doping proportions of various regions and seeing its effect on the IV characteristics and band diagram.**

***Index Terms*—NIPIN, ideality factor, impact ionization**

I. Introduction

Impact ionization (II) is a crucial requirement for achieving a steeper sub-threshold slope at an operational voltage of a few volts. An NIPIN structure allows II to happen at sub 0.2V. NIPIN is an NPN device with I regions between the N and P. The i-region is not fabricated as an intrinsic (no doping) region. A Gaussian diffusion pattern is followed while moving from n to p to n through the i-region. We want the p-region to be as narrow as possible. This is because the p-region results in a parabolic band diagram as opposed to a linear triangular band diagram, which allows better control over the barrier voltage.

II. Background

Impact Ionization (II) is a process in which a highly energised electrons impact with an atom to generate an electron-hole pair (e-h pair), releasing energy more than the band-gap of the atom. This results in the creation of additional electron-hole pairs, which undergo impact ionization, causing a chain reaction, as shown in Figure 3. This phenomenon is also responsible for Zener and Avalanche breakdown, resulting in large currents in the semiconductor devices. However, an an important requirement for II to be significant is that the band bending should be more than the semiconductor's band gap, Eg. II can be made to take place by applying a large bias. In general, an over-the-barrier-current electron cannot cause II. However, the electrons present at the tail of the Boltzmann distribution can cause II. Once II takes place, electrons escape as electron current while the holes are stored in the valance band well. These stored holes will reduce the barrier height, which causes an exponential increase in the over-the-barrier current, causing an exponential increase in the II, resulting in positive feedback. With barrier lowering, the hole current also increases, which reduces the hole concentration in the valence band and opposes this II chain reaction and a steady state is reached.

III. Experiment

A. Pen and Paper Analysis

The entire literature on NIPIN structure is based on the advantages of a triangular band diagram. Thus, we performed a pen and paper analysis to plot the charge distribution, electric field, potential and, thus, the band diagram.

Following assumptions were made in this analysis

1) We assumed that the structure is devoid of free charge, i.e. only positive and negative ions were taken while drawing the various profiles. The n-type region has fixed positive ions, and the p-type region has fixed negative ions. The intrinsic region is assumed to be neutral.
2) The NIPIN structure was broken into charged rectangular slabs of n+, i(1), p+, i(2), and n+. The electric field of these slabs was first plotted individually. The total field was computed using the superposition principle.

Consider a "uniformly" (it is assumed the doping is uniform for various regions in our structure) charged slab with density ρ parallel to the y-z plane. Assume that the thickness of the slab is 2a units. For simplicity, let x $>$ 0. After computing the field for x $>$ 0, we can use symmetry arguments to calculate the x $<$ 0 field.

1) Electric Field outside the charged slab: Applying Gauss law, we have,

$$\int E \cdot dS = \frac{\rho}{\epsilon_0}$$
$$E \cdot A + E \cdot A = \frac{\rho \cdot A \cdot 2a}{\epsilon_0}$$
$$E = \frac{\rho \cdot a}{\epsilon}$$

2) Electric Field inside the charged slab: Applying Gauss law, we have,

$$\int E \cdot dS = \frac{\rho(x)}{\epsilon_0}$$
$$E \cdot A + E(x) \cdot A = \frac{\rho(a+x) \cdot A}{\epsilon_0}$$
$$E(x) = \frac{\rho \cdot x}{\epsilon}$$

Here, A is the area of the cross-section of a standard Gaussian pillbox.

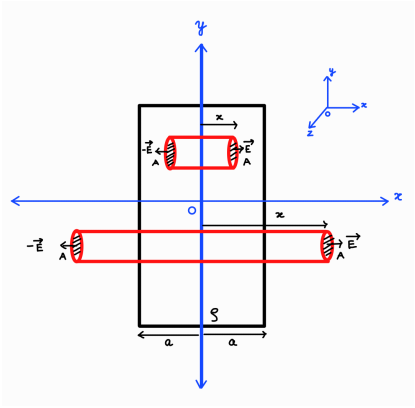

Fig. 1. Pillbox approach to calculate electric field due to a charged slab

3) Verifying the triangular band diagram: Based on the results for the field profile derived above, various other profiles were approximated by methods discussed in the class, as shown in Figure 2. Note the band energy profile (E_c) (TRIANGULAR BAND). The profile is very close to triangular except for the parabolic bulge in the centre.

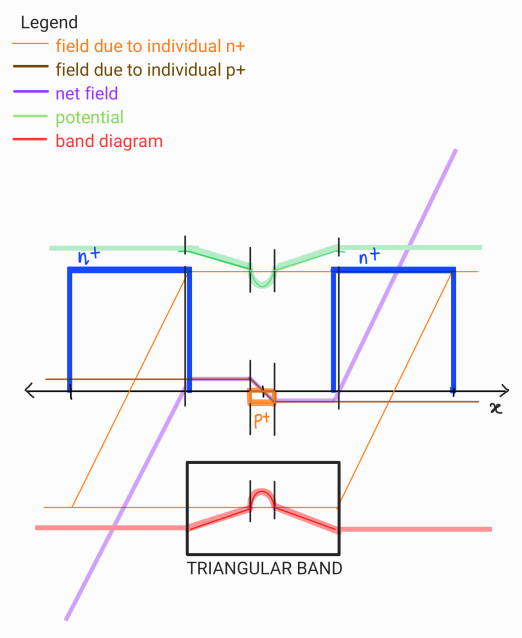

Fig. 2. Pen-and-paper analysis of a NIPIN device.

B. TCAD simulations

1) Uniform distribution of charges:

- We took inspiration from the PIN diode structure to develop an understanding of the NIPIN structure.
- The charges distribution of PIN structure gives the space charge distribution, potential and electric field potential as shown in Figure 4.
- Peaks are due to the presence of sudden changes in charge concentration across the device.
- Reflecting the PIN structure across the centre gives NIPIN structure

2) Gaussian distribution of charges:

- We took inspiration from the uniformly doped NIPIN structure to develop the Gaussian doped NIPIN structure.
- The pointed peaks become smoother because of the gradual transition of charge concentration of the p-doped region into the p-doped i-region.
- The parabolic region is too small to be seen in the scale of Figure 7

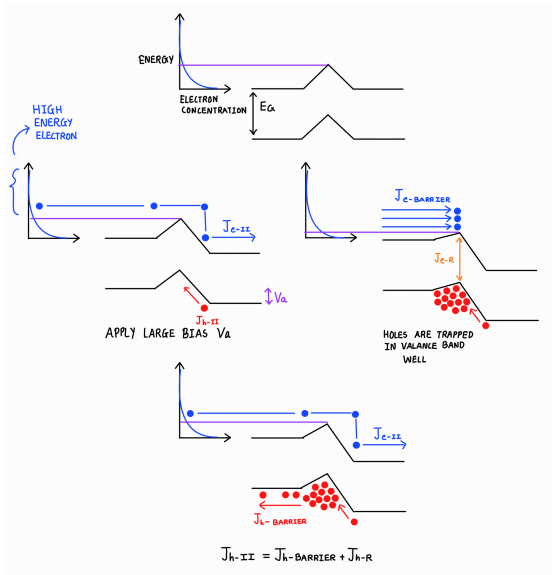

Fig. 3. Impact Ionization in a PIN device.

3) Band diagram:

- We can see that the band diagram is triangular as shown in Figure 8.
- Actually the band diagram is a combination of linear (p- doped i-region) and parabolic (p+ doped p-region) components. However, since the width of the p-region is very small as compared to the surrounding i regions we get an appropriate linear triangular band diagram.
- When we apply an external bias to the n1-contact, we can see that it shifts down by V_a, as observed in Figures 9,10.
- Charge, Electric field, and Potential profiles are also shown in Figures 5,6,7, respectively.

4) Effect of impact ionisation:

- For a given voltage, the current is higher for the case when impact ionisation is included in simulations as compared to the case when there is no impact ionisation. This effect can be seen in Figure 11

5) IV characteristics:

- Current is linear (in log-scale) with voltage for small values of voltage ($< 1V$) and becomes non-linear for high values of voltage, as shown in Figure 12.
- The range over which the current is linear (in log-scale) decreases as we increase the width of the i-regions.

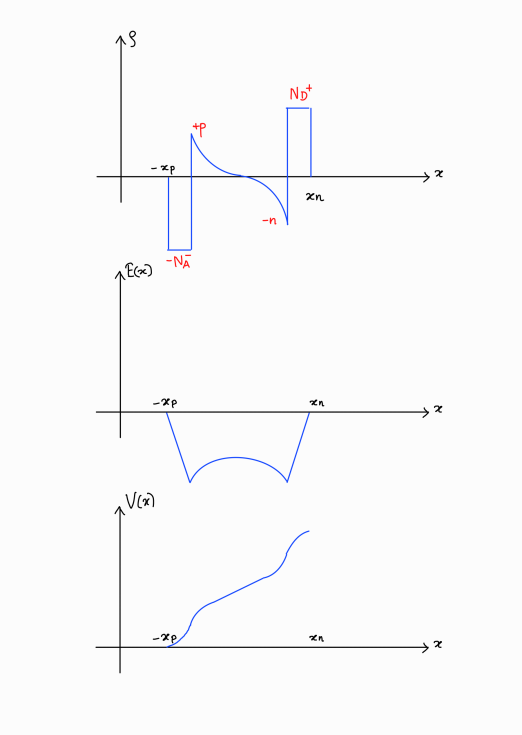

Fig. 4. Uniformly-doped PIN device.

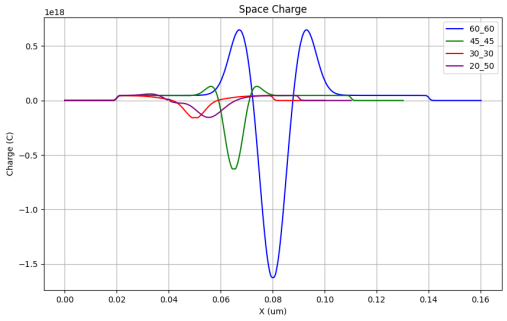

Fig. 5. Charge profiles for different i-region widths.

- Note that the IV characteristics are symmetric about the origin as the NIPIN device is symmetric.
- The current saturates for high voltage levels ($> 1V$) because of impact ionisation as discussed earlier.

6) Effect of changing the operating temperature:

- We studied the effect of changing the operating temperature on the IV characteristics of the device.
- We can observe that current increases faster with increasing temperature until a crossover voltage. After this voltage, the current increases faster with decreasing voltage.

7) Effect of using a combination of using Silicon-Germanium for p region:

- We also tried changing the material for the p region in the NIPIN device by replacing the pure silicon with a mixture of silicon and germanium
- We studied the effect of changing the proportions of silicon and germanium on the band diagram of the device.
- We found that the conduction band changed little as compared to the original band diagram based on silicon material
- However, the valence band changed considerably as we increased the proportion of Germanium in the mixture
- We can see that the depth of the hole well increases with an increase in the proportion of the germanium while the conduction band remains more or less unaffected.
- We hypothesise that such a structure will lead to delayed over-the-barrier current in case of impact ionization and a steady state will be reached much later

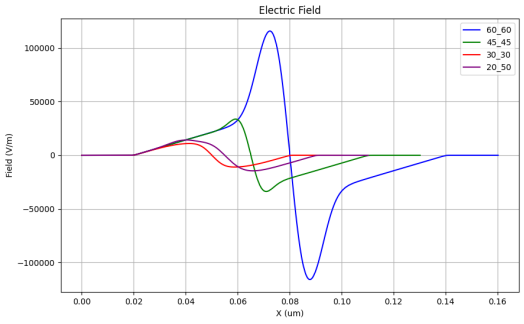

Fig. 6. Electric field profiles for different i-region widths.

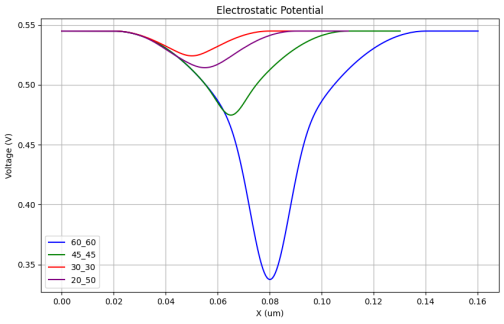

Fig. 7. Potential profiles for different i-region widths.

IV. Results

We have done an intensive review of the NIPIN structure and the effects of changing various parameters associated with it. Future work can be done on studying the effects of using a mixture of Silicon and Germanium in the i-region instead of the p-region.

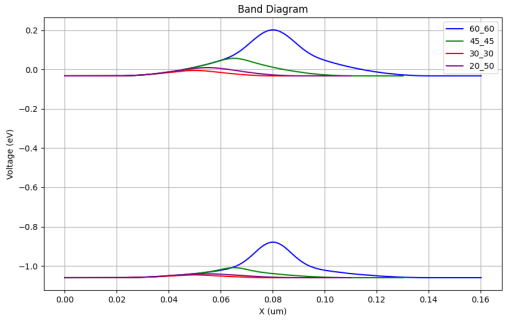

Fig. 8. Band diagram for different i-region widths at external bias $V_a = 0V$.

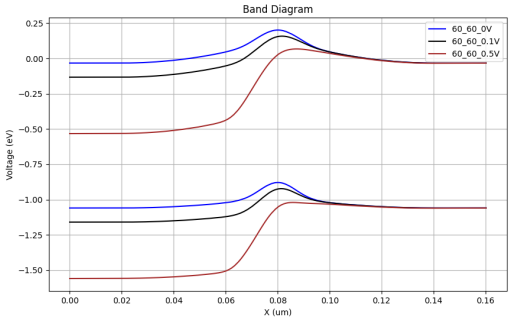

Fig. 9. Band diagram for different bias voltages and i1=i2=60nm.

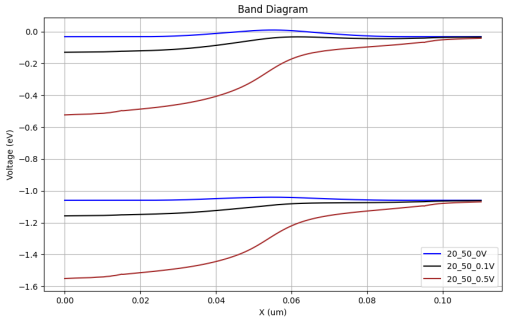

Fig. 10. Band diagram for different bias voltages and i1=20nm, i2=50nm.

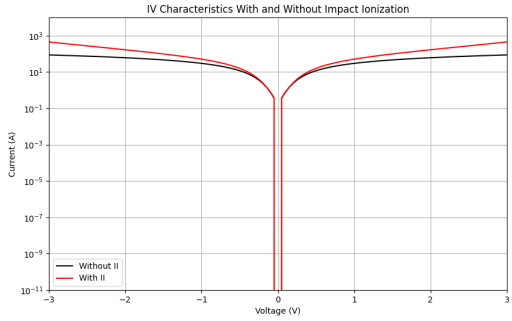

Fig. 11. The effect of impact ionization on the IV-characteristics.

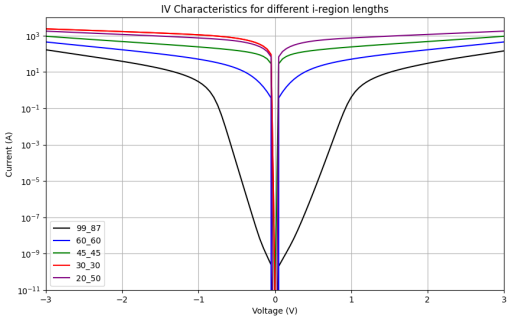

Fig. 12. IV-characteristics for different i-region widths.

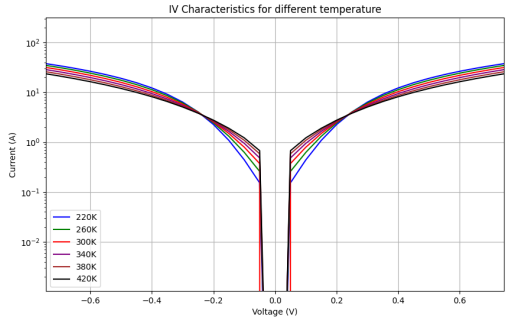

Fig. 13. IV-characteristics for different operating temperatures for i1=i2=60nm.

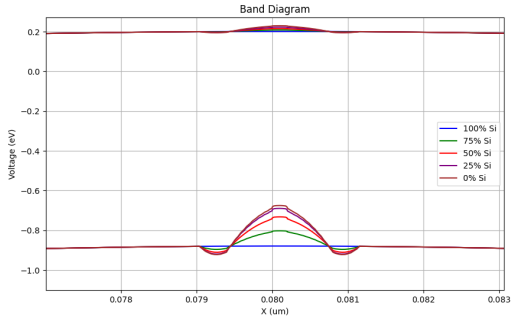

Fig. 14. Band diagrams for different proportions of Silicon and Germanium doping in the p-region.

V. Appndix - Code

A. SDE Command File

```
;;NIPIN Expt ans Sim IV match with higher doping Gradient than SIMS data ;;

(define nm 1e-3)
(define n1_thick (* 20 nm))
(define n2_thick (* @n2_thickness@ nm))
(define p_thick (* @P_thickness_1@ nm))
(define i1_thick (* (+ @i_thickness_1@ @offset_1@ ) nm))
(define i2_thick (* (- @i_thickness_1@ @offset_1@ ) nm))

(define xminn1 0)
(define yminn1 0)
(define xmaxn1 (+ xminn1 n1_thick))
(define ymaxn1 (* @width@ nm))

(define xmini1 xmaxn1)
(define ymini1 0)
(define xmaxi1 (+ xmini1  i1_thick ))
(define ymaxi1 (* @width@ nm))

(define xminp xmaxi1 )
(define yminp 0)
(define xmaxp (+ xminp p_thick))
(define ymaxp (* @width@ nm))

(define xmini2 xmaxp  )
(define ymini2 0)
(define xmaxi2 (+ xmini2 i2_thick))
(define ymaxi2 (* @width@ nm))

(define xminn2 xmaxi2)
(define yminn2 0)
(define xmaxn2 (+ xminn2 n2_thick))
(define ymaxn2 (* @width@ nm))

(define xmeshmin (+ xminn1 (* 15 nm)))
(define xmeshmax (- xmaxn2 (* 15 nm)))
(define PdopingGauss (/ @Pdoping_1@ 10))

;

(sdegeo:create-rectangle
        (position xminn1 yminn1 0) (position xmaxn1 ymaxn1 0)
        "Silicon" "n1"
)

(sdegeo:create-rectangle
        (position xminn2 yminn2 0) (position xmaxn2 ymaxn2 0)
        "Silicon" "n2"
)

(sdegeo:create-rectangle
        (position xmini1 ymini1 0) (position xmaxi1 ymaxi1 0)
        "Silicon" "i1"
)

(sdegeo:create-rectangle
        (position xmini2 ymini2 0) (position xmaxi2 ymaxi2 0)
        "Silicon" "i2"
)

(sdegeo:create-rectangle
        (position xminp yminp 0) (position xmaxp ymaxp 0)
        "Silicon" "p"
)

(sdegeo:define-contact-set "n1contact"     4.0 ( color:rgb 1.0 0.0 0.0 ) "%%" )
(sdegeo:define-contact-set "n2contact"     4.0 ( color:rgb 1.0 0.0 0.0 ) "||" )

(sdegeo:define-2d-contact (find-edge-id (position xminn1 (/ (+ yminn1 ymaxn1) 2) 0 )) "n1contact")
(sdegeo:define-2d-contact (find-edge-id (position xmaxn2 (/ (+ yminn2 ymaxn2) 2) 0 )) "n2contact")

;;; **************Defining the regions ***************** ;;;
; n1 layer
;(sdegeo:create-rectangle (position xSilow ySilow 0)  (position xSihigh ySihigh 0)  "Silicon" "CentreGe")
;(sdegeo:create-rectangle (position xSilow ySilow 0)  (position xSihigh ySihigh 0)  "Silicon" "CentreGe")



; P and N region doping

;(sdedr:define-constant-profile "Const.P" "BoronActiveConcentration" @Pdoping@)
;(sdedr:define-constant-profile-region "PlaceCD.P" "Const.P" "p")

;(sdedr:define-constant-profile "Const.N1" "ArsenicActiveConcentration" @ndoping@)
;(sdedr:define-constant-profile-region "PlaceCD.N1" "Const.N1" "n1")

;(sdedr:define-constant-profile "Const.N2" "ArsenicActiveConcentration" @ndoping@)
;(sdedr:define-constant-profile-region "PlaceCD.N2" "Const.N2" "n2")


;(sdedr:define-constant-profile "Const.I1" "BoronActiveConcentration" @i1doping@)
;(sdedr:define-constant-profile-region "PlaceCD.I1" "Const.I1" "i1")

;(sdedr:define-constant-profile "Const.I2" "BoronActiveConcentration" @i2doping@)
;(sdedr:define-constant-profile-region "PlaceCD.I2" "Const.I2" "i2")

(sdedr:define-gaussian-profile "Gauss.N" "ArsenicActiveConcentration"
#"PeakPos" 0 "PeakVal" 1e20 "ValueAtDepth" 1e19 "Depth" 0.003 "Gauss" "Factor" 1.0)
"PeakPos" 0 "PeakVal" 1e20 "ValueAtDepth" 1e19 "Depth" @ngrad@"Gauss" "Factor" 1.0)

(sdedr:define-gaussian-profile "Gauss.P" "BoronActiveConcentration"
#"PeakPos" 0 "PeakVal" @Pdoping@ "ValueAtDepth" PdopingGauss "Depth" 0.002 "Gauss" "Factor" 1.0)
"PeakPos" 0 "PeakVal" @Pdoping_1@ "ValueAtDepth" PdopingGauss "Depth" @pgrad@ "Gauss" "Factor" 1.0)


;;*************constant profile in the undoped n-region below source ***********************************
;(sdedr:define-constant-profile "Ssideldd" DSD Na)
```

```
;(sdedr:define-refeval-window "Ssideldd_window" "Rectangle" (position xhdlow (- (- param Wfin_s_d) (* nmperdec decades)) 0) (position xoxidelow (+ width_hd Wfin_ld) 0))
;(sdedr:define-constant-profile "Ssideldd_Def" "Ssideldd" "Ssideldd_window")


;*************constant profile in the undoped i1-region *********************************
(sdedr:define-constant-profile "Const_I1" "BoronActiveConcentration" @i1doping@)
(sdedr:define-refeval-window "Const_I1_window" "Rectangle" (position xmini1 ymini1 0) (position (- xmaxi1 0.00015) ymaxi1  0))
(sdedr:define-constant-profile-placement "Const_I1_Def" "Const_I1" "Const_I1_window")

;*************constant profile in the undoped i2-region *********************************
(sdedr:define-constant-profile "Const_I2" "BoronActiveConcentration" @i2doping@)
(sdedr:define-refeval-window "Const_I2_window" "Rectangle" (position (+ xmini2 0.00015) ymini2 0) (position  xmaxi2  ymaxi2  0))
(sdedr:define-constant-profile-placement "Const_I2_Def" "Const_I2" "Const_I2_window")

;(sdedr:define-gaussian-profile "Gauss.I1" "BoronActiveConcentration"
;"PeakPos" 0 "PeakVal" @i1doping@ "ValueAtDepth" PdopingGauss "Depth" 0.0001 "Gauss" "Factor" 1.0)

;(sdedr:define-gaussian-profile "Gauss.I2" "BoronActiveConcentration"
;"PeakPos" 0 "PeakVal" @i2doping@ "ValueAtDepth" PdopingGauss "Depth" 0.0001 "Gauss" "Factor" 1.0)

(sdedr:define-refinement-window "RefWinN1" "Rectangle"   (position xminn1 yminn1 0) (position  xmaxn1 ymaxn1  0))

(sdedr:define-refinement-window "RefWinN2" "Rectangle"   (position xminn2 yminn2 0) (position  xmaxn2 ymaxn2  0))

(sdedr:define-refinement-window "RefWinI1" "Rectangle"   (position xmini1 ymini1 0) (position  xmaxi1 ymaxi1  0))



(sdedr:define-refinement-window "RefWinI2" "Rectangle"   (position xmini2 ymini2 0) (position  xmaxi2 ymaxi2  0))

(sdedr:define-refinement-window "RefWinP" "Rectangle"   (position xminp yminp 0) (position  xmaxp ymaxp  0))


(sdedr:define-analytical-profile-placement "PlaceGD.N1" "Gauss.N" "RefWinN1" "Positive" "NoReplace" "Eval")
(sdedr:define-analytical-profile-placement "PlaceGD.N2" "Gauss.N" "RefWinN2" "Negative" "NoReplace" "Eval")
(sdedr:define-analytical-profile-placement "PlaceGD.P" "Gauss.P" "RefWinP" "Both" "NoReplace" "Eval")

; Meshing
;
(sdedr:define-refinement-window "RefWin.general" "Rectangle"   (position xmeshmin yminn1 0) (position  xmeshmax ymaxn2  0))
(sdedr:define-refinement-size "RefDef.general" 0.0001   @width_fac@   0.005  @width_fac@)

 #0.00005   @width_fac@
 # 0.00001  @width_fac@)

#    0.0001   0.05
# 0.0005   0.05 )
(sdedr:define-refinement-placement "Place.general" "RefDef.general" "RefWin.general" )


(sde:build-mesh "snmesh" "" "n@node@_msh")
```

B. SDevice Command File

```
##;;NIPIN Expt ans Sim IV match with matched SIMS data with out II ;;

    File {
   grid    = "@tdr@"
    doping = "@tdr@"
    current = "@plot@"
    output = "@log@"
    plot    = "@tdrdat@"
    save    = "new_nipin_expSim_@node@"
   Parameters = "pp10_des.par"
}
Plot { eDensity hDensity eCurrent/Vector hCurrent
    equasiFermi hquasiFermi
   Potential SpaceCharge ElectricField/Vector
   eMobility hMobility eVelocity hVelocity
   Doping DonorConcentration AcceptorConcentration
    Bandgap ConductionBandEnergy ValenceBandEnergy
   eAvalancheGeneration hAvalancheGeneration
    SRHRecombination TotalRecombination
   eQuasiFermiPotential  hQuasiFermiPotential
    eAlphaAvalanche hAlphaAvalanche
   #eBarrierTunneling
    #NonLocal
}
Electrode {
   { Name="n1contact" Voltage=0.0}
  { Name="n2contact"  Voltage=0.0  }
}


Physics {
   #HeteroInterface
   #MoleFraction( RegionName = ["p"]
   #xFraction = 1.00)
   AreaFactor = @areafac@
   EffectiveIntrinsicDensity( Slotboom )
   #Hydrodynamic( eTemperature )
   Mobility (
      DopingDependence
    HighFieldSaturation Enormal
    #  eHighFieldsat(CarrierTempDrive)

   )
   Recombination (
    #eAvalanche(CarrierTempDrive)
    eAvalanche
     #hAvalanche(Eparallel)
    hAvalanche
     # eBarrierTunneling "Tun"
     SRH(DopingDependence) )
     Temperature= @T@
    #  eBarrierTunneling "Tun"
}

#Math{ NonLocal "Tun" (regionInterface="n1/i1"
    Length=115e-7 Permeable Permeation=7e-7)}

Math {
   -CheckUndefinedModels
   method=blocked
   submethod=pardiso
   wallclock
   Extrapolate
   Derivatives
   RelErrControl
   Digits=4
   ErRef(electron)=1.e20
   ErRef(hole)=1.e20
   Notdamped=50
   Iterations=30
   Number_of_Threads = 2
}
Solve {
   Poisson
   coupled {poisson electron hole}
   #Coupled { Poisson Electron Hole eTemperature }
   Save (FilePrefix="Hydro_@node@")

   plot(FilePrefix="0v_@node@_des.plt")
   Quasistationary(
       InitialStep=1e-3 Increment=1
                                      #InitialStep=1e-3Increment=2
      MinStep=1e-10 MaxStep=0.001
       Goal{ Name="n1contact" Voltage=@V3@}
           ){ Coupled{ Poisson Electron Hole  }
     CurrentPlot(Time=(Range=(0 1) Intervals=60))
    }
}
```