ECE335 Introduction to Electronic Devices

TCAD Project # 1

Simulation of a PN Junction

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1 Introduction

PN junction serves as a building block for semiconductor devices and transistors. It can act as an emitter in the sense that it can inject hole current into N-type material, and as a rectifier, exhibiting rectifying current-voltage characteristics [4]. In this study, an N^+P one-sided abrupt junction with a heavily doped N side is given. We shall consider the behaviour of the junction analytically in each of the bias conditions outlined in the instruction document, with the aid of the Synopsys Sentaurus TCAD tool.

2 Methodology

Our approach to the problem is a holistic approach, meaning that the results and figures are explained with semiconductor physics theory and quantitative calculations. For simplicity, we shall suppose all donor and acceptor atoms are ionized. The TCAD geometric structure of the device and simulation is built on top of project 0 files that have been provided to us by the teaching team. In addition, detailed changes and add-ons to the .cmd files based on the project 0 files for subsequent questions are given in the results section, with steps outlining the changes. The rest of this section is devoted to formulation of the N^+P junction structure under practice.

3 PN junction structure/meshing/doping concentration

The PN junction structure shown in Table 1 is defined using the SDE component on the Sentaurus Workbench (SWB). Figure 1 shows the structure doping distribution and mesh definition. It is worth noting that the mesh is included to ensure observation of band bending and depletion layer expansion.

Table 1 PN junction parameters

	parameter
N+ Junction Depth	1 μm
N+ doping concentration	2×10^{18} cm^{-3}
P Junction Depth	9 μm
P substrate doping concentration	8×10^{15} cm^{-3}

Code modification steps:

Step1: Change thickness from 6µm to 10µm.

(define totalthickness 10)

Step2: Change N+ doping concentration, width, change P doping concentration.

(sdegeo:create-rectangle

(position 0.0 0.0 0.0) (position totalwidth 1 0.0) ”Silicon” ”psub”)

(sdegeo:create-rectangle

(position 0.0 1 0.0) (position totalwidth totalthickness 0.0) ”Silicon” ”nsub”)

Step3: Change Global code-meshing profile.

(sdedr:define-refinement-window ”win.PN_junction” ”Rectangle”

(position 0 0.5 0) (position totalwidth 1.5 0))

(sdedr:define-refinement-size ”RefDef.PN_junction” 0.5 0.05 0.01 0.01)

(sdedr:define-refinement-function ”RefDef.PN_junction” ”DopingConcentration” ”MaxTransDiff” 0.5)

(sdedr:define-refinement-function ”RefDef.PN_junction” ”MaxLenInt” ”Silicon” ”Oxide” 0.1 1.5 ”Doubleside”)

(sdedr:define-refinement-placement ”Place.PN_junction” ”RefDef.PN_junction” ”win.PN_junction”)

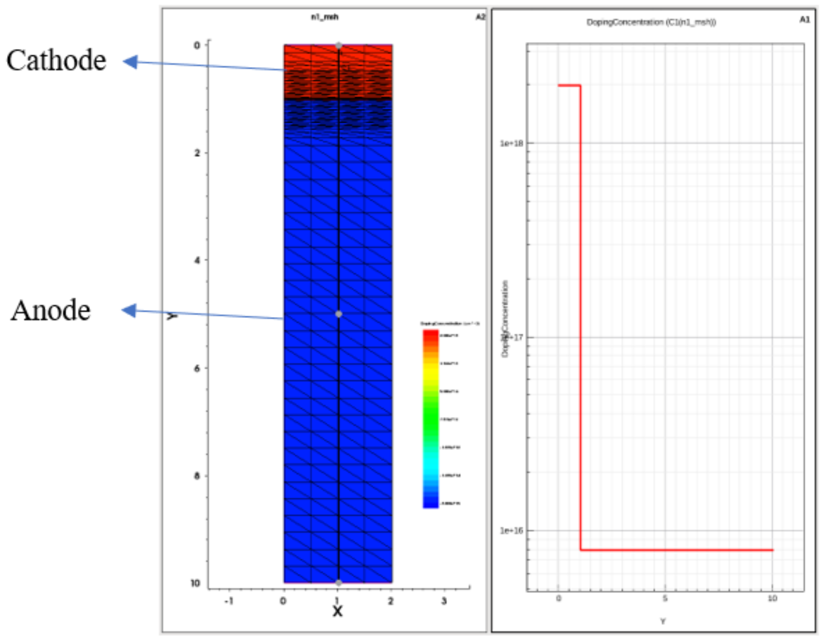

Fig. 1 1D & 2D impurity concentrations & meshing

4 Results and Discussions

Zero Bias, Uniform Doping Profiles

As shown in Fig. 1, in the PN junction structure, the electrode that contacts N+ region is a Cathode, and the electrode that contacts P region is a Anode. Refer to the given code in Project0, keep the material physics model, Plotsection and Math consistent, modify the Solve part of the code to extract the electrostatic potential and energy band distribution at PN equilibrium, as shown in Fig. 2 and Fig. 3.

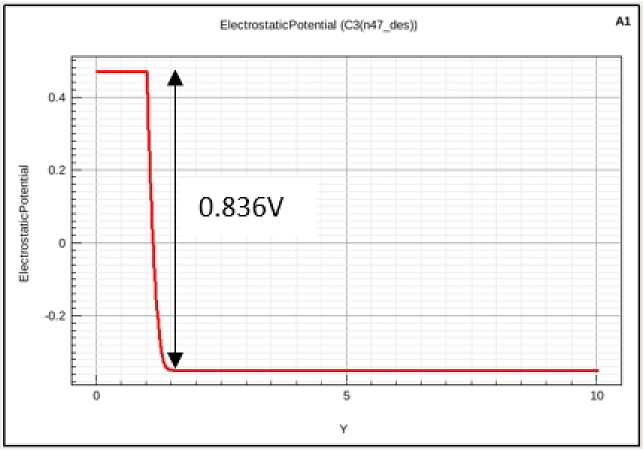

Fig. 2 1D Electrostatic potential distribution of PN junction

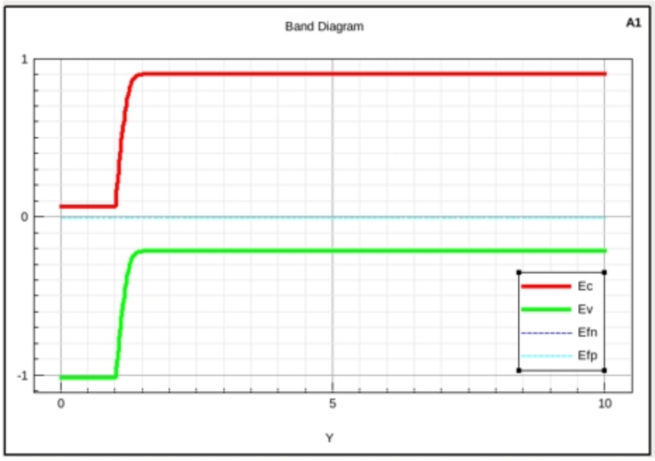

Fig. 3 Energy Band Diagram of PN junction

There is a concentration gradient on both sides of the PN junction, the built-in electric field balances out the diffusion current and drift, achieving dynamic equilibrium. From Fig. 2, the estimated built-in potential is 0.836 v. As shown in Fig. 4, the width of the depletion region is measured (white is the depletion line boundary), and the width is about 0.37um.

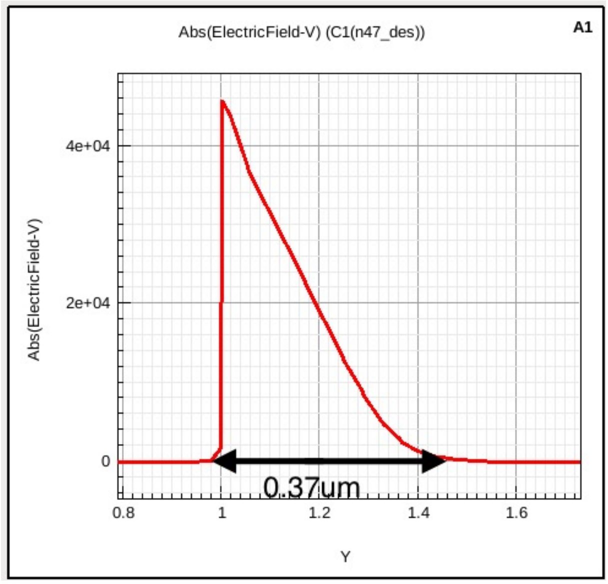

Fig. 4 Electric field distribution

$$\text{Built-in Potential: } V_D = \frac{k_0 T}{q}\left(\ln\frac{N_A N_D}{n_i^2}\right) = 0.026 \cdot \ln\frac{8\times10^{15}\times2\times10^{18}}{(1.02\times10^{10})^2} = 0.849\ \mathrm{V}$$

$$\text{Depletion region Width: } X_D = \sqrt{\frac{2\varepsilon_r\varepsilon_0 V_D}{qN_A}} = \sqrt{\frac{2\times11.7\times8.85\times10^{-14}\times0.849}{1.6\times10^{-19}\times8\times10^{15}}} = 0.37\ \mu\mathrm{m}$$

Upon comparison with the theoretical values, it is observed that the built-in voltage and depletion region width align closely with its corresponding theoretical value.

Code modification steps:

Step1: change Solveto get pn junction without bias

```
Solve {
    Poisson
    Coupled { Poisson Electron Hole }
}
```

Only leave the solve preprocessing part

Reverse Bias, Uniform Doping Profiles

The breakdown characteristic curve of the PN junction is obtained by applying bias at the PN junction Cathode. As shown in Fig. 5, the PN junction encounters avalanche breakdown when the Vbias is about 64V, and the leakage current increases greatly.

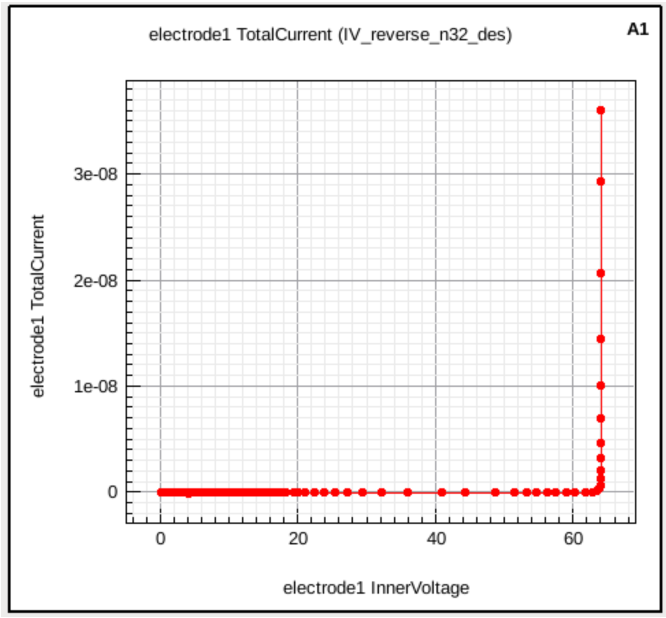

Fig. 5 IV characteristic curve- Reverse Bias

Compared to Fig. 6, when the doping concentration in the P region is 8e15, the breakdown voltage of the corresponding mutation junction is about 65V by looking up the table, which is basically consistent with the simulation results.

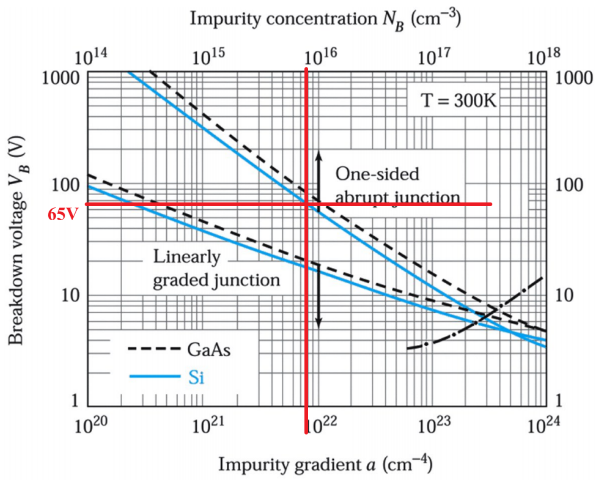

Fig. 6 Theoretical calculation of breakdown voltage [2]

Fig. 7 shows the distribution of the electric field before breakdown, and on the right it shows the distribution of the electric field in one dimension. It can be seen that the maximum electric field of the abrupt junction at this time reaches 0.4 MV/cm

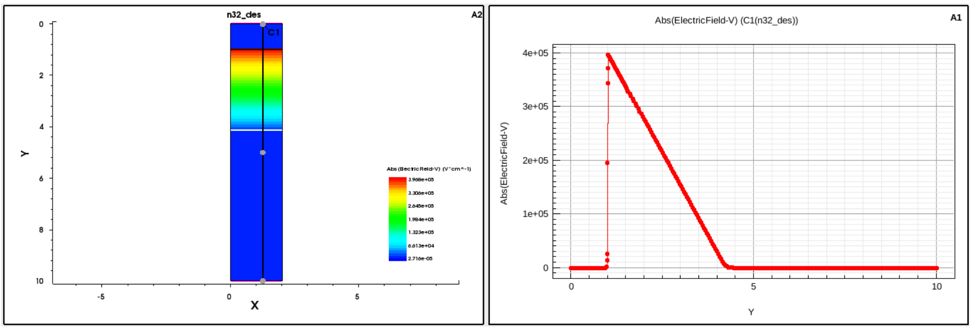

Fig. 7 Electric field distribution at breakdown

Code modification steps:

Step1: modify avalanche breakdown

```
    Physics {
        Temperature = @<temp>@
        AreaFactor = 1e3 * AreaFactor to convert current into mA
        EffectiveIntrinsicDensity(Slotboom)
        Mobility (DopingDep eHighFieldSaturation hHighFieldSaturation)
        Recombination(SRH(DopingDep) Auger Avalanche(ElectricField))
    }
```

Step2: in electrode definition section, Cathode add resistor 1e12Ohm, convenient for reverse bias

```
    Electrode {
        { Name=”electrode1” Voltage=0 resistor=1e12}
        { Name=”electrode2” Voltage= 0}
    }
```

Step3: modify Cathode simulation

```
Quasistationary (
    InitialStep=1e-5 Increment=1.5
    MinStep=1e-5 MaxStep=1e-1
    Goal { Name=electrode1 Value=100 }
){ Coupled { Poisson Electron Hole }
}
```

Forward Bias, Uniform Doping Profiles

By increasing forward bias to 1V on the Anode side, the IV curve of the PN junction is obtained, as shown in Fig. 8. As can be seen from the figure, PN is switched on when Vf>0.7V. With the increase of Vf, the PN junction conduction current increases gradually.

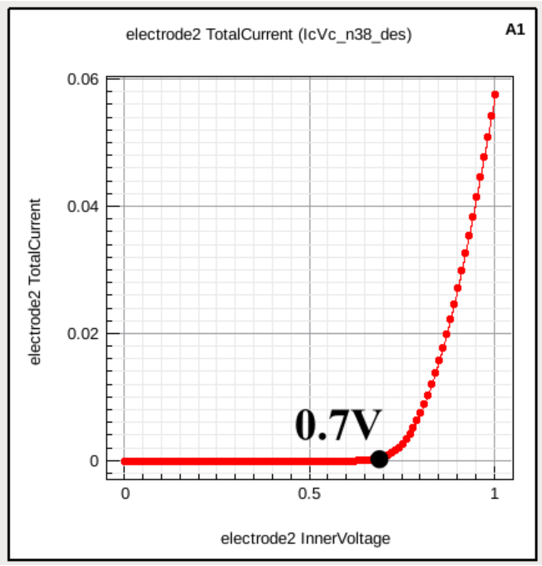

Fig. 8 PN junction iv characteristic - Forward Bias

With forward bias, the applied voltage in the opposite direction of the built-in electric field which reduces the width of the depletion layer and the barrier voltage, which makes it easier for most carriers to cross the PN junction.

Therefore, under forward bias, there will be a large forward current passing through both ends of the PN junction, which is mainly composed of the majority carriers, namely holes in the P region and electrons in the N region. When the applied voltage is greater than 0.7V, the barrier height decreases, the carrier can easily cross the barrier, and the forward current increases sharply[1]. At this time, the PN junction is in the on-state.

High Temperature, Uniform Doping Profiles

Without changing the simulation code, the 10V internal reverse bias curve of PN junction at 600°C was obtained by modifying Temp, as shown in Fig. 9. The positive bias curve within 1V at 600°C of PN junction is obtained, as shown in Fig. 10.

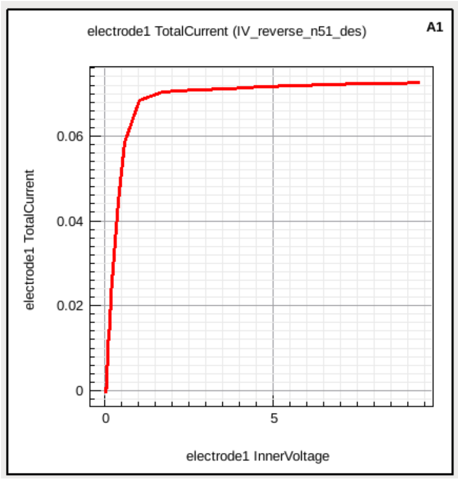

Fig. 9 IV characteristic of reverse bias 10v at 600°C

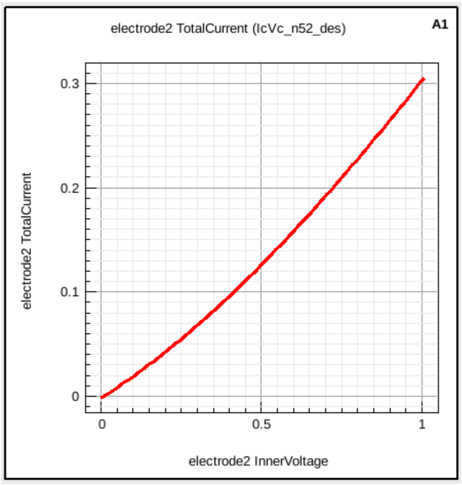

Fig. 10 IV characteristic of forward bias 1v at 600°C

When the reverse voltage is applied, according to the structural characteristics of the PN junction, the carriers in the PN junction will be driven by the electric field and drift. These carriers include minority carriers for forward bias and carriers for reverse bias. As the temperature increases, the thermal excitation of the carrier will also increase, so the reverse current will also increase. At high temperatures, the probability of carrier excitation to the conduction band or valence band increases, which increases the number of carriers and leads to the increase of the reverse current. More elections cross the forbidden energy band into the conduction band[3].
When the forward voltage is applied, the increase of temperature leads to the intensization of excitation, and it takes a smaller V for the diode to conduct current, so the higher the temperature at the same voltage, the greater the current of PN junction conduction. At this temperature, silicon starts to act like a conductor.

Gaussian n+ Doping Profiles

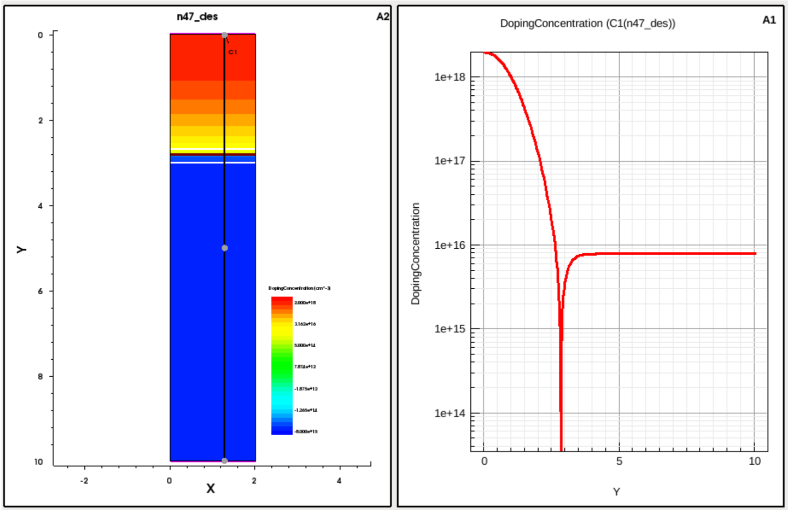

Fig. 11 Gaussian Distribution & doping concentration

Since the concentration in the n region of the slowly decreases in the form of a Gaussian distribution, the concentration distribution does not drop suddenly, a linearly graded junction.
Based on the Gaussian distribution code provided, the PN junction structure of the Gaussian distribution in the N+ region is completed by referring to the example of Gaussian doping in the SDE user manual.

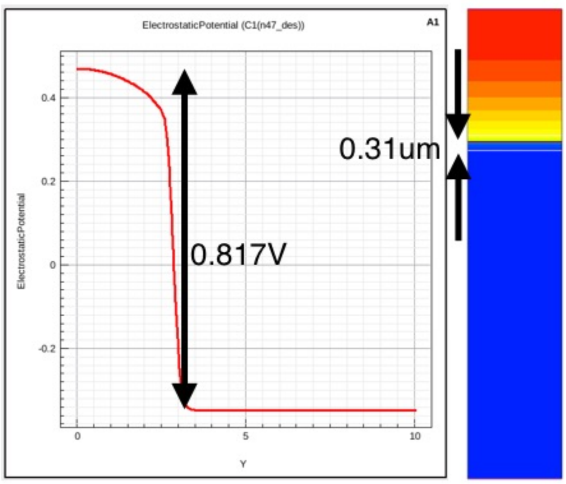

Fig. 12 1D potential + depletion width at equilibrium

Using the zero voltage bias code for uniform doping, the device structure under 0V bias is extracted to obtain the electrostatic potential distribution on 1D. As shown in Fig. 12, if the calculation starts with the surface of N+ region, the Vbi at static PN junction of Gaussian distribution is 0.817V, and the width of depletion region is 0.31um. Table 2 lists the comparison between two junctions. It can be seen that the built-in potential is smaller compared to the theoretical value and the uniformly doped diode, and depletion width is thinner.

Table 2 Built-in potential and depletion layer width of different types of PN junctions

Structure	Abrupt Junction		Linearly Graded Junction	
Parameters	V_{bi}(V)	W_{dep}(μm)	V_{bi}(V)	W_{dep}(μm)
Value	0.836	0.37	0.817	0.31

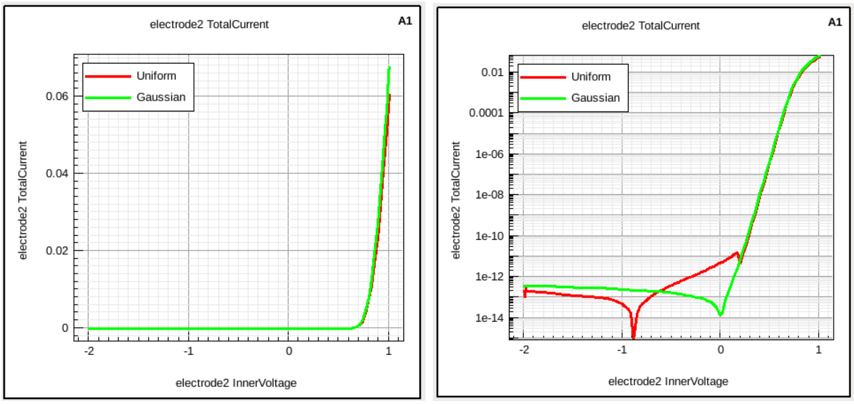

Fig. 13 Comparison of IV characteristics -2 to 1 V of two types of PN junctions

The diffusion lengths can be estimated by picking two points on the density graph and plug into the equation. The estimated LP is 0.1um and Ln is 0.02um $(p(x) = p(x_0)\, e^{-(x-x_0/L)})$.

5 Conclusions

This study showed the varying electrical characteristics of a one-sided N+P junction under bias conditions.

References

[1] C. Hu, Modern Semiconductor Devices for Integrated Circuits, Prentice Hall

[2] S. M. Sze and M. K. Lee. Semiconductor Devices: Physics and Technology (3rd ed), Wiley.

[3] D. A. Neamen. Semiconductor Physics and Devices (3rd ed), McGraw Hill

[4] Shockley W .The Theory of p-n Junctions in Semiconductors and p-n Junction Transistors