Objective: Explore the PN Junction Simulation Tool in order to understand depletion, carrier modeling, and PN junction device physics. 116 pts

Effect of Doping on the Depletion Region

Use the PN Junction Tool on nanoHUB to simulate a PN junction with $N_A = 2 \times 10^{15}/cm^3$ for p-side and $N_D = 10^{15}/cm^3$ for the n-side. Use all default parameters for this simulation with the exception of the applied voltage. Click on the **Environment tab** and set the **applied voltage** (Va) to zero.

A. Select the **Net Charge Density (at equilibrium)** tab on the **Result** window and use your cursor to measure the depletion width on each side of the junction. Make sure to measure the absolute value on each side. Use the green model and include units in your solution. Copy and paste this plot in the space below. [2 pts]

Depletion Width on p-side (x_p): ______________________ [2 pts]

Depletion Width on n-side (x_n): ______________________ [2 pts]

B. From the **Net Charge Density (at equilibrium)** plot, identify the type of charges in each depletion region (positive or negative) and explain where these charges come from.

Type of Charges on p-side (x_p): ______________________ [2 pts]

Explanation: [2 pts]

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Type of Charges on n-side (x_n): ______________________ [2 pts]

Explanation: [2 pts]

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C. Select the **Electric Field (at equilibrium)** tab on the **Result** window and use your cursor to determine the maximum electric field at the junction (peak value). Use the green model and include units in your solution. Make sure to use the appropriate sign. Copy and paste this plot in the space below. [2 pts]

Maximum Electric Field Value: ______________________ [2 pts]

D. Increase the doping on the p-side from $N_A = 2 \times 10^{15}/cm^3$ to $N_A = 2 \times 10^{16}/cm^3$ and repeat steps A and C. (Change the doping value by placing the cursor over the doping value on the diagram and click on the value.) Copy and paste the charge density and electric field plots in the space below. [4 pts]

Depletion Width on p-side (x_p): __________________ [2 pts]

Depletion Width on n-side (x_n): __________________ [2 pts]

Maximum Electric Field Value: __________________ [2 pts]

Location of Maximum Electric Field along x axis (check one): [2 pts]

☐ p-side ☐ n-side ☒ junction

Explain the effect of doping on the depletion widths for each side and on the maximum electric field. You can toggle back and forth between the two simulations by clicking on the two lines in the **All** window at the bottom of the simulation results.

Effect of Doping on overall depletion width ($x_p + x_n$): [2 pts] ________________

Effect of Doping on the electric field: [2 pts] ________________

Explain your results: [2 pts]

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Effect of Doping on Carrier Concentration

A. For the first simulation in which $N_A = 2 \times 10^{15}/cm^3$ for p-side and $N_D = 10^{15}/cm^3$ for the n-side, calculate the p and n concentrations on **each side** using the equilibrium equations below. Note that if you click on the Environment tab on the input side, the default temperature is 300 K. Recall that kT = 0.0259 eV at 300K. Show all your calculations and units in the space provided below.

$$p = n_i e^{\left(\frac{Ei-Ef}{kT}\right)}$$

$$n = n_i e^{\left(\frac{Ef-Ei}{kT}\right)}$$

$$n_i = np$$

p-side calculations:

p concentration: ____________________ [2 pts]

n concentration: ____________________ [2 pts]

n-side calculations:

n concentration: ______________________ [2 pts]

p concentration: ______________________ [2 pts]

B. How do these values change when the doping on the p-side is increased? Show your values only.

p-side calculations: [4 pts]

p concentration: ______________________

n concentration: ______________________

n-side calculations: [4 pts]

n concentration: ______________________

p concentration: ______________________

Effect of Bias on Energy Band Diagram

For the first simulation in which $N_A = 2 \times 10^{15}/cm^3$ for p-side and $N_D = 10^{15}/cm^3$ for the n-side, change the **applied voltage** from zero to +0.4 V and run the simulation. CLEAR ALL SIMULATIONS BEFORE RUNNING THIS SIMULATION.

A. From the **Results** tab, select **Energy Band Diagram (at applied bias).** Click the ▶ button to allow the simulation to model the change in the energy band diagram as a function of applied voltage from Va = 0 to Va = +0.4. Describe what is happening to the following barriers (recall that energy increases in the upward direction in the conduction band ↑, and increases in the downward direction ↓ in the valence band):

Barrier for electrons on n-side (Increases or Decreases): ______________________ [2 pts]

Barrier for holes on p-side (Increases or Decreases): ______________________ [2 pts]

Print the initial and final energy band diagram plots in the space below [4 pts]:

B. If the barrier is a function of – dV, and the electric field is represented by

$$E = -\frac{dV}{dx}$$

what should happen to the maximum electric field at the junction as a result of a forward bias of 0.4V? [2 pts]

☐ increase ☐ decrease

C. From the **Results** tab, select **electric field (at applied bias)**. Click the ▶ button to allow the simulation to model the change in the electric field as a function of applied voltage from Va = 0 to Va = +0.4. Notice what happens to the electric field and how it changes (pay particular attention to the slope) and record the maximum electric field at final bias (make sure to use the appropriate sign):

Maximum electric field value at final bias: ______________________________ [2 pts]

Print the initial and final electric field plots in the space below [4 pts]:

D. Repeat steps A - C, using Va = -0.4 V and describe what is happening to the barriers on each side of the junction.

Barrier for electrons on n-side (Increases or Decreases): ______________________ [2 pts]

Barrier for holes on p-side (Increases or Decreases): ______________________ [2 pts]

and what should happen to the maximum electric field at the junction as a result of a reverse bias of -0.4V? [2 pts]

☐ increase ☐ decrease

What is the maximum **electric field (at applied bias)**? (notice how the electric field changes, including any changes in the slope? __________________________ [2 pts]

Print the initial and final plots in the space below [4 pts]:

E. From the **Results** tab, select **Net Charge Density (at applied bias)**. Click the ▶ button to allow the simulation to model the change in charge density as a function of applied voltage from Va = 0 V to Va = 0.4 V. Describe what is happening in terms of the net charge density on each side (value on y axis) and the depletion widths on each side. In other words, does the maximum charge density value change with applied bias? Do the depletion widths change with applied bias? Answer these questions below.

Maximum net charge density on each side (Increase/Decrease/Stay the same):

______________________ [2 pts]

Depletion widths on each side (Increase/Decrease/Stay the same: ______________________ [2 pts]

Print the initial and final plots in the space below [4 pts]:

Repeat for Va = -0.4V

Maximum net charge density on each side (Increase/Decrease/Stay the same):

______________________ [2 pts]

Depletion widths on each side (Increase/Decrease/Stay the same: ______________________ [2 pts]

Print the initial and final plots in the space below [4 pts]:

Explain what you observe regarding the net charge density values and the depletion width values as a function of forward or reverse bias in terms of

(i) what needs to happen to the maximum electric field from part B for forward and reverse bias,

(ii) how does the slope of the electric field change in parts C and D $\rho \propto \frac{dE}{dx}$, and

(iii) how do you connect the observations from (i) and (ii) to part E.
[20 pts]