EEA Assignment 1: 1D Device Simulation

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January 8, 2026

1 STEP DOPED RESISTOR

For this project, I simulated a 1D bar of Silicon ($50\mu m$ long) using the DEVSIM software. I created a Step Doping profile to see how electrons behave when the concentration changes abruptly. My device has two regions:

- Left Side ($0 - 25\mu m$): High Doping (10^{17})
- Right Side ($25 - 50\mu m$): Low Doping (10^{16})

I ran the simulation for two cases: first for equilibrium (0V) and then for a 0.3V bias to analyse the results in both the situations.

1.1 Theoretical Background

Before running the simulation, I studied the fundamental equations that govern how semiconductor devices work. The DEVSIM software solves those differential equations but knowing the physics behind them helped me understand the results.

1.1.1 Poisson's Equation

The electrostatic potential (ϕ) inside the device is determined by the distribution of charges. This relationship is given by Poisson's Equation:

$$\frac{d^2\phi}{dx^2} = -\frac{q}{\epsilon_{si}}(p - n + N_D - N_A) \tag{1}$$

Where:

- N_D and N_A are the doping concentrations I defined.
- n and p are the electron and hole concentrations.
- ϵ_{si} is the permittivity of Silicon.

In the Zero Bias case of my project, the software solved this equation alone to find the equilibrium potential.

1.1.2 Drift-Diffusion Model

When I applied a bias (0.3V), current began to flow.
The current in a semiconductor is of two types the drift and the diffusion current.

The total current density (J_n) is the sum of these two components:

$$J_n = \underbrace{q\mu_n n E}_{\text{Drift}} + \underbrace{qD_n \frac{dn}{dx}}_{\text{Diffusion}} \tag{2}$$

My simulation solved this equation along with Poisson's equation to generate the potential graph under 0.3V bias and calculate the current flowing through the resistor.

1.2 Observations

1.2.1 Zero Bias (Equilibrium)

When I solved for 0V, I observed a sharp potential step at the junction ($25\mu m$).

- **Potential Drop:** The potential is higher on the left side ($\approx$ 0.42V) and lower on the right ($\approx$ 0.36V). This behavior is governed by the **Boltzmann Relation**, which states that in equilibrium, the potential must scale logarithmically with the carrier concentration:

$$\phi = V_T \ln\left(\frac{N_D}{n_i}\right) \implies \phi \propto \ln(N_D)$$

  Since the left side has higher doping (10^{17}) than the right (10^{16}), it must have a higher electrostatic potential to maintain equilibrium.

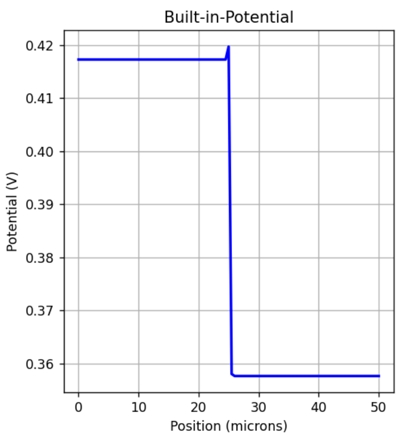

Figure 1: Potential at 0V.

- **Spillover (Excess Carriers):** As seen in Figure 2, there is a spike of electrons entering the low-doped region. This is due to diffusion. Electrons naturally move from the high-concentration region to the low-concentration region. This flow creates a small spillover zone until the internal electric field pushes back enough to stop them.

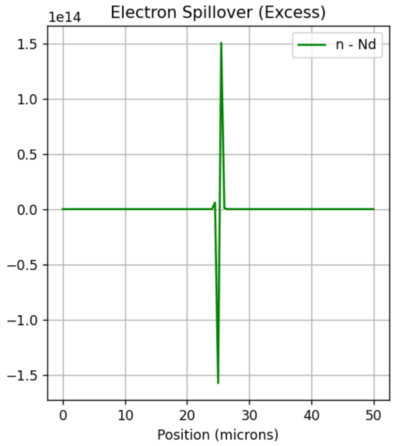

Figure 2: Spillover.

1.2.2 With 0.3V Bias

When I applied 0.3V, the potential graph changed from a flat step to a continuous slope as seen in Figure 3. This slope represents the Electric Field ($E = -d\phi/dx$) driving the drift current.

- **Change in Slope:** I noticed the slope is not constant.
  - The left side ($0 - 25\mu m$) is flatter.
  - The right side ($25 - 50\mu m$) is steeper.
  - This confirms Ohm's Law ($J = \sigma E$). The left side has high doping, meaning high conductivity ($\sigma = q\mu_n n$). To maintain the same current, it needs only a small electric field (flat slope). The right side has low doping (low σ), so it requires a large electric field (steep slope) to push the same amount of current through.
- **Steepness at the Junction:** At the junction ($25\mu m$), the potential drop is extremely steep, appearing almost vertical.
  - This is due to the abrupt change in doping concentration, which creates a huge diffusion force.
  - To balance this strong diffusion, a very strong Internal Electric Field is generated in that region.
  - Since the Electric Field is defined as the gradient of the potential ($E = -d\phi/dx$), a large field magnitude means a very steep slope on the potential graph.

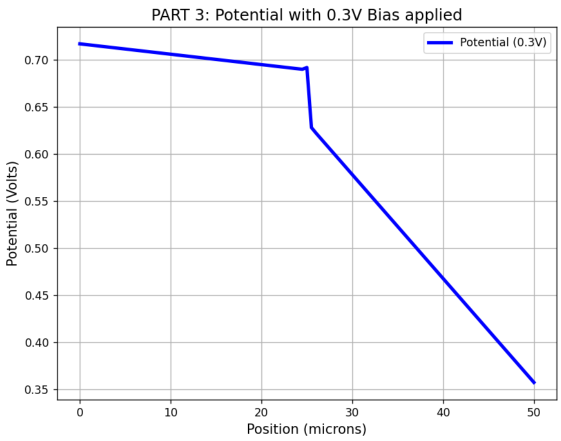

Figure 3: Potential at 0.3V.

2 Part 2: PN Junction Diode

2.1 Device Configuration

In this part, I set up a PN junction diode to observe how it behaves differently from the resistor in Part 1. The device structure is defined as follows:

- **Length:** The total length of the silicon bar is $50\,\mu$m.
- **Doping:** Instead of uniform doping, the device is split into two halves:
  - **P-Side ($0 - 25\,\mu$m):** Doped with Acceptors ($N_A = 10^{17}\,\text{cm}^{-3}$).
  - **N-Side ($25 - 50\,\mu$m):** Doped with Donors ($N_D = 10^{17}\,\text{cm}^{-3}$).
- **Mesh:** A finer mesh was used near the center ($25\,\mu$m) to accurately capture the sharp changes in carrier concentration at the junction.

2.2 Physics and Theory

The main difference between this diode and the resistor is the formation of a **Depletion Region** at the center.

2.2.1 Built-in Potential (Zero Bias)

At equilibrium (0V), holes from the left and electrons from the right diffuse across the junction. This creates a built-in electric field that stops further flow. The theoretical barrier height is calculated by:

$$\phi_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) \tag{3}$$

Using the simulation parameters, this value is approximately 0.8 V. This barrier effectively blocks current when no voltage is applied.

2.2.2 Forward Bias Operation

When we apply a positive voltage to the P-side, it pushes carriers towards the junction and lowers the potential barrier. This allows current to flow easily. The current (I) and voltage (V) relationship follows the standard diode equation:

$$I = I_S \left(e^{\frac{V}{nV_T}} - 1 \right) \tag{4}$$

2.3 Conclusion

From the theoretical analysis, we expect the following behavior:

1. Unlike the resistor, the I-V graph will not be a straight line.
2. There should be almost zero current until the voltage exceeds the knee voltage (around 0.6 V - 0.7 V).
3. After the knee voltage, the current should increase exponentially, confirming that the diode only conducts current in one direction.