Engineering breakdown voltage in a pn-junction diode

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***Abstract*—For this lab, the goal is to design a one-sided abrupt silicon pn-junction diode. This diode must have a breakdown voltage of at least 60V with a forward-bias current of 50mA when applying 0.625V. We know that the minority carrier lifetimes are $\tau_0 = 2 \times 10^{-7} s$. The parameters to engineer are doping density and cross-sectional area.**

Introduction

For this pn-junction experiment, the *PN Junction Lab* from nanoHUB.org was used [1].

Part I: Analytical Design

Since we are using silicon, $\mu_n = 1350$ cm^2/Vs and $\mu_p = 480$ cm^2/Vs. And, I assume $T = 300$ K.

Using the Shockley diode equation, we can back-solve for the reverse saturation current I_s in our diode:

$$\begin{aligned} I_D &= I_s(e^{V_D/V_{th}} - 1) \\ \implies I_s &= I_D(e^{V_D/V_{th}} - 1)^{-1} \\ &= (0.050)(e^{0.625/0.0259} - 1)^{-1} \\ &= 1.655 \times 10^{-12} \text{ A} \end{aligned}$$

We will use this quantity to match the reverse saturation current density J_s with doping densities and the device cross-sectional area.

A one-sided abrupt pn-junction will have either $N_d >> N_a$ or vice-versa, so choosing the former, a n^+p-junction will be made. This means the doping density in the low-doped region of the one-sided junction $N_B = N_a$. So, rearranging Equation (7.61) from the textbook:

$$\begin{aligned} N_a &= \frac{\epsilon_s E_{crit}^2}{2qV_B} \\ &= \frac{11.7(8.854 \times 10^{-14})(4 \times 10^5)^2}{2(1.6 \times 10^{-19})(60)} \\ &\boxed{N_a = 8.633 \times 10^{15} \text{ cm}^{-3}} \end{aligned}$$

Here, I assumed the critical electric field of silicon is 4×10^5V/cm.

Then, since this is a n^+p-junction, I will just choose N_d to be some value larger than N_a. I found graphically, when solving for the donor doping density using the equation for J_s, the function was asymptotic, so it is somewhat arbitrary when choosing the donor doping density. However, it would not make sense to make this value arbitrarily large, since larger and larger doping densities will not affect the device performance after enough doping. The donor doping density I chose was:

$$\boxed{N_d = 1 \times 10^{19} \text{ cm}^{-3}}$$

From here, we can calculate for the reverse saturation current density J_s using a form of Equation (8.27) from the textbook:

$$J_s = qn_i^2 \left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}} \right)$$

Using the Einstein Relation, $D/\mu = kT/q$, the equation can be rearranged:

$$\begin{aligned} J_s &= n_i^2 \sqrt{qkT} \left(\frac{1}{N_a}\sqrt{\frac{\mu_n}{\tau_0}} + \frac{1}{N_d}\sqrt{\frac{\mu_p}{\tau_0}} \right) \\ &= (1.5 \times 10^{10})\sqrt{6.624 \times 10^{-40}} \left(\frac{1}{8.633 \times 10^{15}}\sqrt{\frac{1350}{2 \times 10^{-7}}} \right. \\ &\left. + \frac{1}{1 \times 10^{19}}\sqrt{\frac{480}{2 \times 10^{-7}}} \right) \end{aligned}$$

$$\boxed{J_s = 5.514 \times 10^{-11} \text{ A/cm}^2}$$

Now, we can find the cross-sectional area A, since $I_s = AJ_s$.

$$\begin{aligned} A &= I_s/J_s \\ &= (1.655 \times 10^{-12})/(5.514 \times 10^{-11}) \\ &\boxed{A = 0.03 \text{ cm}^2} \end{aligned}$$

Part II: Verification using nanoHUB simulations

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== STRUCTURE ==
  P-region:  11um (60 nodes) at 8.633e+15/cm3
  I-region:  0um (0 nodes)
  N-region:  7um (120 nodes) at 1e+19/cm3

== MATERIALS ==
  Material: silicon
  taun = 2e-07s
  taup = 2e-07s

== ENVIRONMENT ==
  Temperature: 300K
  V bias: 0.625V (20 points)
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Fig. 1. Input Parameters in Simulator

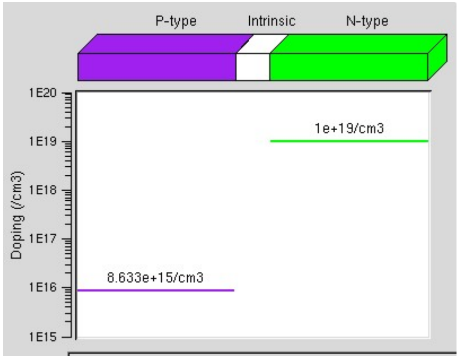

Fig. 2. Doping Profile in Simulator

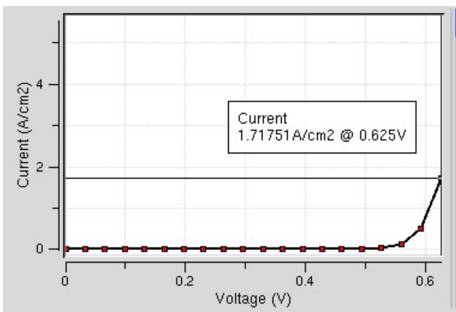

Fig. 3. IV-Characteristics in Simulator

ANSWERS TO QUESTIONS

REFERENCES

[1] e. a. Vasileska, Dragica, "Pn junction lab," https://nanohub.org/resources/pntoy, 2014.