

1. (a) The breakdown voltage is

$$V_B = \frac{\epsilon_s E_{crit}^2}{2eN_B}$$

so the semiconductor doping in the low-doped region of the one-sided junction

$$N_B = \frac{\epsilon_s E_{crit}^2}{2eV_B}$$

$$N_B = \frac{11.7 \epsilon_0 \times (4 \times 10^5)^2}{2e \times 40} = 1.293 \times 10^{16} \text{ cm}^{-3}$$

(b) The maximum p-type doping concentration such that the breakdown voltage is 20V is

$$N_B = \frac{11.7 \epsilon_0 \times 4.0 \times (4 \times 10^5)^2}{2e \times 20} = 2.586 \times 10^{16} \text{ cm}^{-3}$$

$$\begin{aligned} 2. (a) V_{bi} &= \frac{kT}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right) = V_t \ln\left(\frac{N_A N_D}{n_i^2}\right) \\ &= \frac{300k}{e} \ln \frac{2 \times 10^{17} \times 2 \times 10^{15}}{(1.5 \times 10^{10})^2} \\ &= 0.7292 \text{ V} \end{aligned}$$

(b) (i) The cross-sectional area  $A = 10^{-5} \text{ cm}^2$

$$C = C' A = A \sqrt{\frac{e \epsilon_s N_A N_D}{2(V_{bi} + V_R)(N_A + N_D)}}$$

$$C = 10^{-5} \sqrt{\frac{11.7 \epsilon_0 \times 2 \times 10^{17} \times 2 \times 10^{15}}{2(0.7292 + 1)(2 \times 10^{17} + 2 \times 10^{15})}} = 9.749 \times 10^{-14} \text{ F}$$

(ii) The junction capacitance

$$C = 10^{-5} \sqrt{\frac{11.7 \epsilon_0 \times 2 \times 10^{17} \times 2 \times 10^{15}}{2(0.7292 + 3)(2 \times 10^{17} + 2 \times 10^{15})}} = 6.638 \times 10^{-14} \text{ F}$$

$$\text{Uii) } C = 10^{-5} \sqrt{\frac{11.7 \epsilon_0 \times 2 \times 10^{17} \times 2 \times 10^{15}}{2(0.7292 + 5)(2 \times 10^{17} + 2 \times 10^{15})}} = 5.356 \times 10^{-14} \text{ F}$$

(c) The graph see attached pages.

From the graph we can find that as  $N_A \gg N_D$ , the junction capacitance of the p-n junction can be reduced to

$C \approx \sqrt{\frac{e \epsilon_s N_D}{2(V_{bi} + V_R)}}$  or  $\left(\frac{1}{C}\right)^2 = \frac{2(V_{bi} + V_R)}{e \epsilon_s N_D}$ , so the slope of  $V_C - V_R$  curve is  $\frac{2}{e \epsilon_s N_D}$  is related to  $N_D$  and the intercept at the voltage axis is  $-V_{bi}$  that is related to  $V_{bi}$  (absolute value is  $V_{bi}$ )



3. (a) The ideal reverse-saturation current density is given by

$$J_s = \frac{e D_p p_{n0}}{L_p} + \frac{e D_n n_{p0}}{L_n} = e n_i^2 \left( \frac{1}{N_A} \sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_A} \sqrt{\frac{D_p}{\tau_{p0}}} \right)$$

$$J_s = (1.5 \times 10^{10})^2 e \left( \frac{1}{8 \times 10^{15}} \sqrt{\frac{10}{8 \times 10^{-8}}} + \frac{1}{5 \times 10^{17}} \sqrt{\frac{25}{10^{-7}}} \right)$$

$$= 5.152 \times 10^{-11} \text{ A/cm}^2$$

The reverse-biased saturation current

$$I_s = J_s A = 1.030 \times 10^{-14} \text{ A}$$

(b) (i) The forward-biased current at  $V_a = 0.45 \text{ V}$

$$I = I_s \exp\left(\frac{e V_a}{k T}\right)$$

$$= I_s \exp\left(\frac{0.45 e}{300 k}\right)$$

$$= 3.738 \times 10^{-7} \text{ A}$$

(ii)  $I = I_s \exp\left(\frac{0.55 e}{300 k}\right) = 1.789 \times 10^{-5} \text{ A}$

(iii)  $I = I_s \exp\left(\frac{0.65 e}{300 k}\right) = 8.561 \times 10^{-4} \text{ A}$

4. (a) Denote the current in the depletion region due to the flow of electrons as  $I_n$  and the corresponding current density as  $J_n$ .  
Denote the current in the depletion region due to the flow of holes as  $I_p$  and the corresponding current density as  $J_p$ .

then we have  $\frac{I_n}{I_n + I_p} = 90\% = 0.9 = \frac{J_n}{J_n + J_p}$

$$J_n = e n_i^2 \frac{1}{N_A} \sqrt{\frac{D_n}{\tau_{n0}}} \quad J_p = e n_i^2 \frac{1}{N_A} \sqrt{\frac{D_p}{\tau_{p0}}}$$

so  $\frac{1}{1 + \frac{N_A}{N_A} \sqrt{\frac{D_p \tau_{n0}}{D_n \tau_{p0}}}} = 0.9$

The ratio of  $\frac{N_d}{N_A} = \frac{\frac{1}{0.9} - 1}{\sqrt{\frac{D_p \tau_{n0}}{D_n \tau_{p0}}}} = \frac{\frac{1}{0.9} - 1}{\sqrt{\frac{10 \times 5 \times 10^{-7}}{25 \times 10^{-7}}}} = 0.07857$

(b) The ratio of  $\frac{N_d}{N_A} = \frac{\frac{1}{0.2} - 1}{\sqrt{\frac{10 \times 5 \times 10^{-7}}{25 \times 10^{-7}}}} = 2.828$





5. The ratio of hole current to the total current crossing the space charge region

$$\frac{J_p}{I} = \frac{J_p}{J_n + J_p} = \frac{1}{1 + \frac{N_A}{N_D} \sqrt{\frac{D_n \tau_{p0}}{D_p \tau_{n0}}}} \quad (\text{using result from 4})$$

$$\frac{D_n}{D_p} = \frac{25}{10} = \frac{5}{2}$$

$$\frac{J_p}{I} = \frac{1}{1 + \frac{10^{16}}{N_A} \sqrt{\frac{5}{2} \times \frac{10^{-7}}{10^{-6}}}} = \frac{1}{1 + \frac{5 \times 10^{16}}{N_A}}$$

The graph plotted by Mathematica LogLinear plot function is attached at last

6. (a) The ideal reverse-saturation current density

$$J_s = e n_i^2 \left( \frac{1}{N_A} \sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau_{p0}}} \right)$$

the ideal reverse-saturation current

$$I_s = J_s A = A e n_i^2 \left( \frac{1}{N_A} \sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau_{p0}}} \right)$$

$$= 10^{-4} e \times (1.5 \times 10^{10})^2 \times \frac{1}{4 \times 10^{16}} \left( \sqrt{\frac{25}{10^{-7}}} + \sqrt{\frac{10}{10^{-7}}} \right)$$

$$= 2326 \times 10^{-15} \text{ A}$$

(b) The built-in potential across the semiconductor device

$$V_{bi} = \frac{kT}{e} \ln \left( \frac{N_A N_D}{n_i^2} \right) = V_T \ln \left( \frac{N_A N_D}{n_i^2} \right) = 0.765 \text{ V}$$

The depletion width when applied a reverse-biased voltage

$$W = \sqrt{\frac{2 \epsilon_s (V_{bi} + V_r)}{e} \frac{N_A + N_D}{N_A N_D}}$$

The reverse biased generation current

$$I_{gen} = -J_{gen} A = \frac{e n_i W A}{\tau_{n0}} = \frac{A n_i}{\tau_{n0}} \sqrt{\frac{2 \epsilon_s (V_{bi} + V_r)}{2 N_A N_D}} = 7.336 \times 10^{-11} \text{ A}$$

(c) The ratio of the generation current to ideal saturation current

$$\frac{I_{gen}}{I_s} = 3.154 \times 10^4$$

7. (i) Since the question description gives the data of mobility  $\mu_n$  and  $\mu_p$ , calculate  $D_n$  and  $D_p$  on our own with the given data

$$D_n = \frac{kT}{e} \mu_n = \mu_n V_e = 142.2 \text{ cm}^2/\text{s}$$

$$D_p = \frac{kT}{e} \mu_p = \mu_p V_e = 5.687 \text{ cm}^2/\text{s}$$

The ideal reverse-saturation current

$$I_s = J_s A = A e n_i^2 \left( \frac{1}{N_A} \sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau_{p0}}} \right) = 1.50 \times 10^{-22} \text{ A}$$



The ideal diode current

$$I_D = -I_S \left( \exp\left(\frac{eV_A}{kT}\right) - 1 \right) = 1.501 \times 10^{-12} \text{ A}$$

$$\text{Cii)} I_D = I_S \left( \exp\left(\frac{eV_A}{kT}\right) - 1 \right) = 1.802 \times 10^{-12} \text{ A}$$

$$\text{Ciii)} I_D = I_S \left( \exp\left(\frac{eV_A}{kT}\right) - 1 \right) = 4.128 \times 10^{-9} \text{ A}$$

$$\text{Civ)} I_D = I_S \exp\left(\frac{eV_A}{kT}\right) = 9.452 \times 10^{-6} \text{ A}$$

If we use  $D_n = 205 \text{ cm}^2/\text{s}$ ,  $D_p = 9.8 \text{ cm}^2/\text{s}$  compare with our previous results.

$$I_S = 1.830 \times 10^{-12} \text{ A}$$

$$\text{Ci)} I_D = 1.830 \times 10^{-12} \text{ A} \quad \text{Cii)} I_D = 2.198 \times 10^{-11} \text{ A}$$

$$\text{Ciii)} I_D = 5.033 \times 10^{-9} \text{ A} \quad \text{Civ)} I_D = 1.153 \times 10^{-5} \text{ A}$$

8. Using Einstein relation,  $D_n = \frac{kT}{e} \mu_n = 90.48 \text{ cm}^2/\text{s}$   
 $D_p = \frac{kT}{e} \mu_p = 5.697 \text{ cm}^2/\text{s}$

$$I_S = A e n_i^2 \left( \frac{1}{N_A} \sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_D} \sqrt{\frac{D_n}{\tau_n}} \right) = 3.088 \times 10^{-11} \text{ A}$$

$$I = I_S \left( \exp\left(\frac{eV_D}{kT}\right) - 1 \right)$$

$$I_{rec} = \frac{e n_i W_A}{2\tau_0} e^{-\frac{V_A}{2V_D}} = \frac{e n_i A}{2\tau_0} e^{-\frac{V_A}{2V_D}} \sqrt{\frac{2q_s(V_{bi}-V_D)}{e} \frac{N_A + N_D}{N_A N_D}} \quad \text{where } V_{bi} = \frac{kT}{e} \ln \frac{N_A N_D}{n_i^2}$$

$$I_{net} = I + I_{rec}$$

$$= 3.088 \times 10^{-11} \left( \exp(38.68 V_D) - 1 \right) + 1.228 \times 10^{-12} e^{-\frac{V_A}{2V_D}}$$

$$\text{for an ideal diode } I = 3.088 \times 10^{-11} \left( e^{38.68 V_D} - 1 \right) \exp(19.34 V_D) \sqrt{1.279 - V_D}$$

Graphs see attached pages.



# VE320

## Intro to Semiconductor Devices

HOMEWORK 5 ATTACHED PAGES

October 30, 2020

Yihua Liu 518021910998

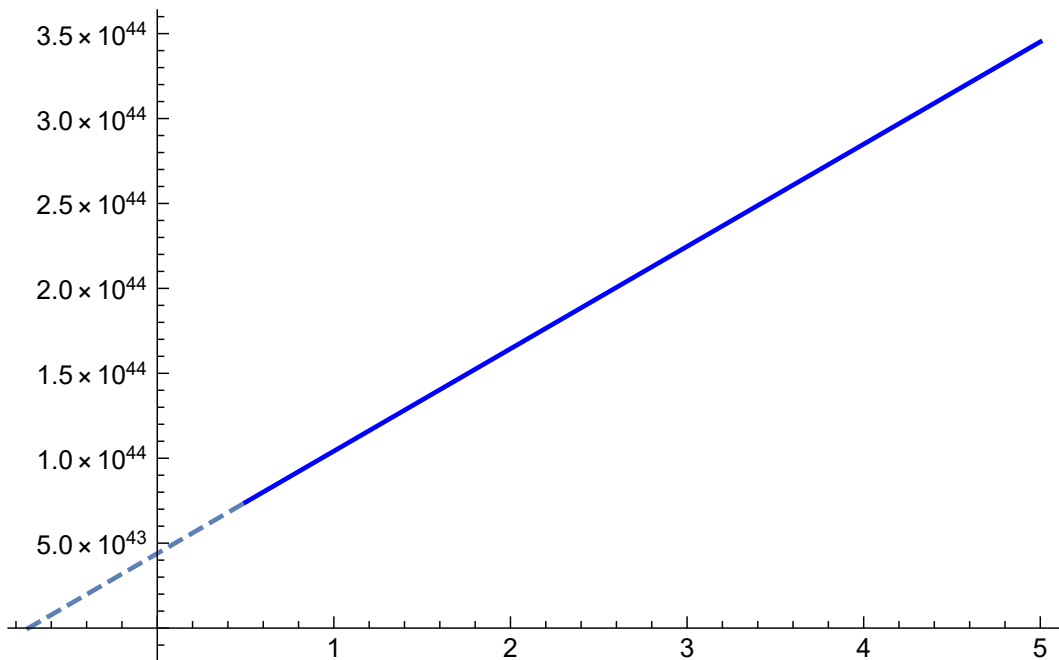


Figure 1: 2(c).

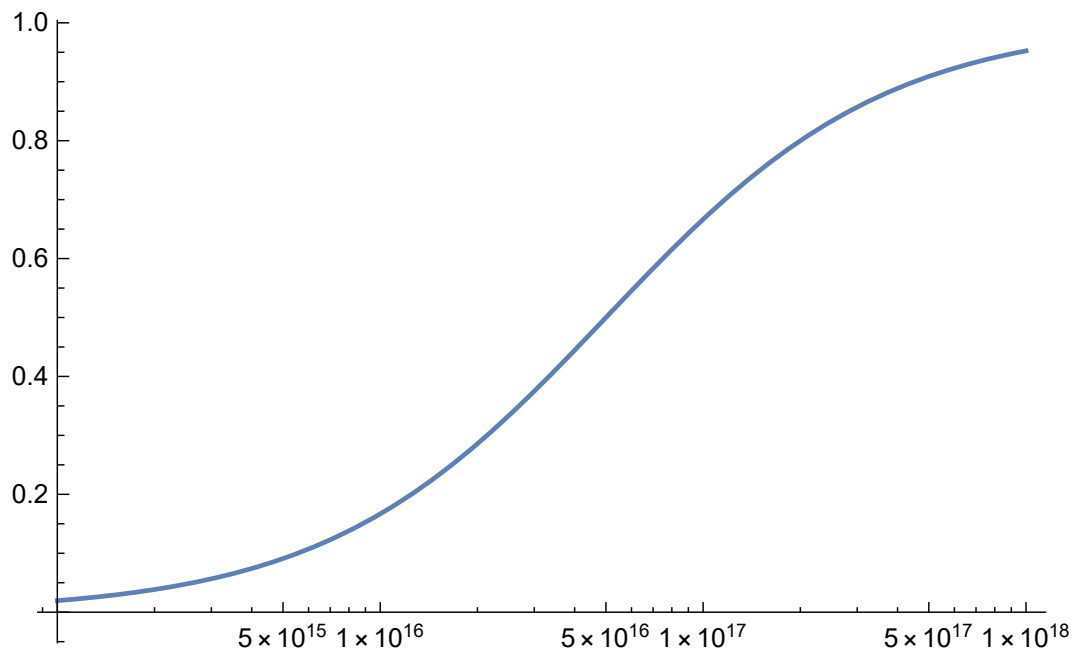


Figure 2: 5

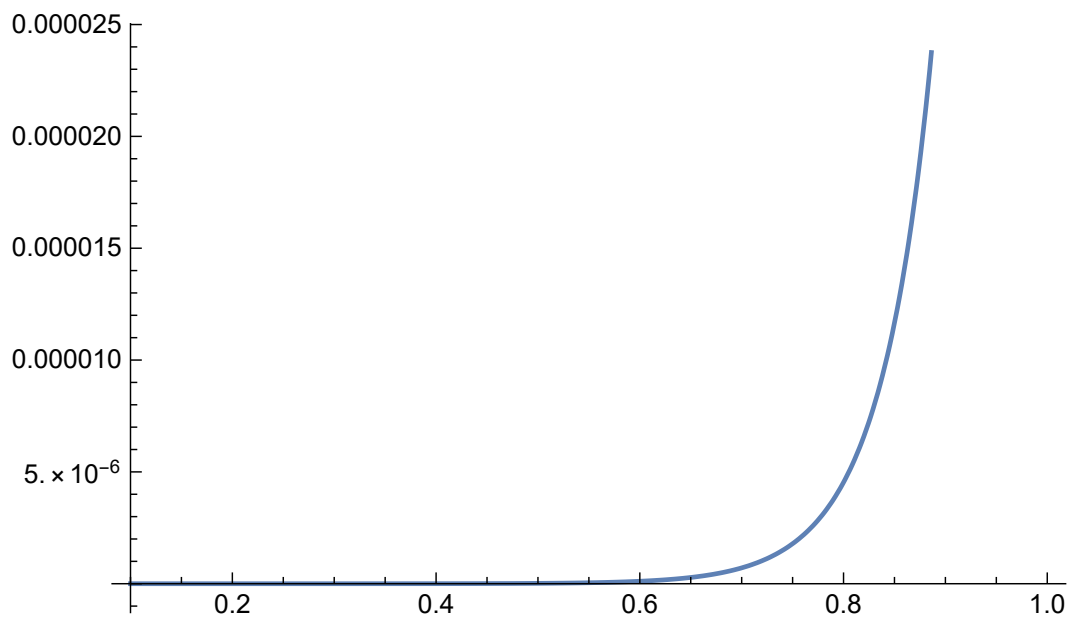


Figure 3: 8 - the diode forward-bias current include including recombination current.

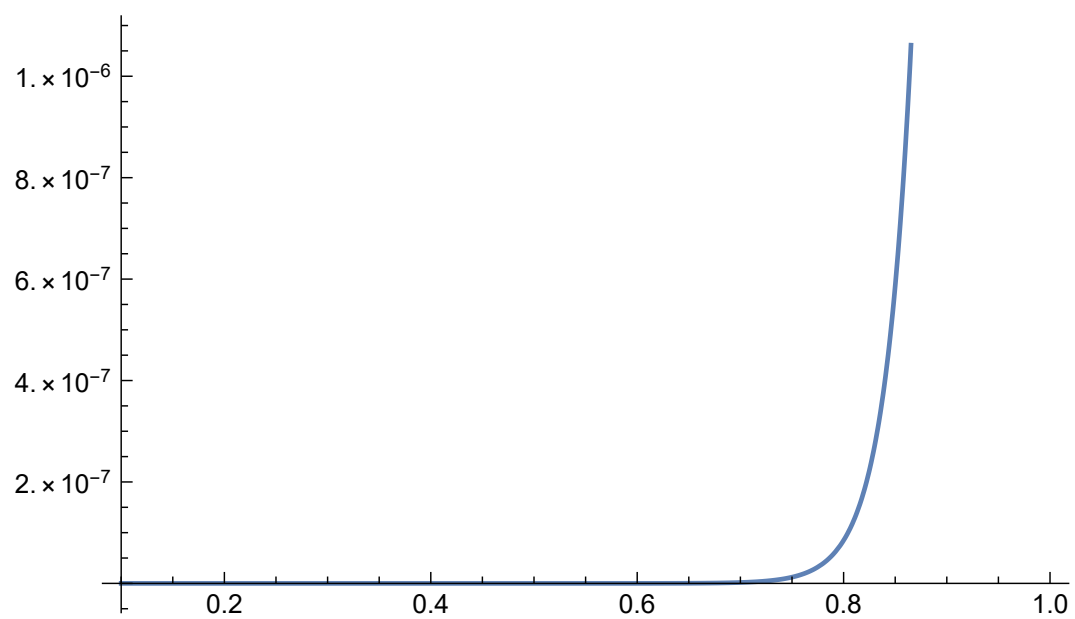


Figure 4: 8 - an ideal diode.