

Test 1 - EE 5340/4329 (print last name) key (print first name) _____
 Thursday, September 27, 2001, 8:00 AM
 80 minutes allowed (last four digits of your student #) _____ (e-mail if new) _____

Instructions: [1] Do your own work. [2] Open book (including text, class handouts, and your class notes). [3] Calculator allowed. [4] Do not use previously solved problems. [5] Explicitly state definitions and assumptions that you use. [6] Where possible, calculate parameters rather than read them from a graph. [7] Do all work on this paper. [8] Show all calculations, making numerical substitutions and giving numerical results where possible. [9] Write answers in space given. [10] Unless stated otherwise, $T = 300\text{K}$ and $V_i = 25.852\text{ mV}$. [11] Each part is worth [x] points.

1. A Silicon wafer has a uniform impurity distribution of $5 \times 10^{16}/\text{cm}^3$ phosphorous atoms and $1 \times 10^{17}/\text{cm}^3$ boron atoms.

a) Calculate the majority carrier concentration.

$$N_D = 5 \times 10^{16} \quad N_A = 1 \times 10^{17}$$

$$n = N_D - N_A = -5 \times 10^{16} \Rightarrow \text{p type, holes are majority carriers}$$

Answer a) [6] $p = \underline{5 \times 10^{16} \text{ cm}^{-3}}$.

b) Calculate the minority carrier concentration.

$$n = \frac{n_i^2}{p} = \frac{(1 \times 10^{10})^2}{5 \times 10^{16}} = 2 \times 10^3 / \text{cm}^3$$

Answer b) [6] $n = \underline{2 \times 10^3 \text{ cm}^{-3}}$.

c) Next, calculate $E_v - E_f$.

$$E_v - E_f = kT \ln \left(\frac{p}{N_v} \right) = 0.025852 \times \ln \left(\frac{5 \times 10^{16}}{3.08 \times 10^{19}} \right) = -0.17 \text{ eV}$$

text P41, $N_v = 3.08 \times 10^{19}$

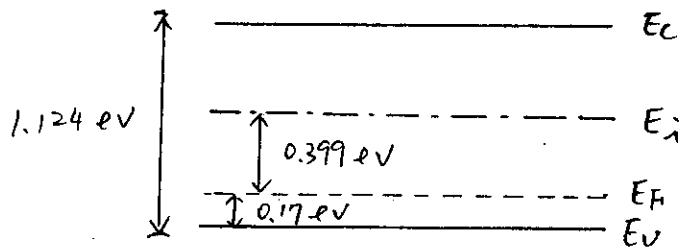
Answer c) [6] $E_v - E_f = \underline{-0.17 \text{ eV}}$.

d) Next, calculate $E_f - E_i$.

$$E_f - E_i = kT \ln \left(\frac{p}{n_i} \right) = 0.025852 \times \ln \left(\frac{5 \times 10^{16}}{1 \times 10^{10}} \right) = -0.399 \text{ eV}$$

Answer d) [6] $E_f - E_i = \underline{-0.399 \text{ eV}}$.

e) [7] Next, draw the energy band diagram showing E_c , E_f , E_i , E_v for this material.



f) Next, calculate the energy gap for this material at $T = 375$ K. Assume that the effective masses for electrons and holes are temperature independent.

$$(2.72) \quad E_g(T) = 1.17 - 4.73 \times 10^{-4} \times \left(\frac{T^2}{T + 636} \right)$$

$$= 1.17 - 4.73 \times 10^{-4} \times \left(\frac{375^2}{375 + 636} \right) = 1.104 \text{ eV}$$

f [7] $E_g = \underline{1.104 \text{ eV}}$

2. For the same material shown in problem 1.

a) Calculate the hole mobility.

$$(3.11) \quad \mu_p = \frac{468 - 49.7}{1 + \left(\frac{N_1}{1.6 \times 10^{17}} \right)^{0.7}} + 49.7 = 263.5 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$N_1 = N_D + N_A = 1.5 \times 10^{17}$$

Answer a) [6] $\mu_p = \underline{263.5 \text{ cm}^2/\text{V}\cdot\text{s}}$

b) Next, calculate the resistivity of this material.

$$\rho = \frac{1}{q \mu_p p} = \frac{1}{1.6 \times 10^{-19} \times 263.5 \times 5 \times 10^6} = 0.47 \text{ ohm}\cdot\text{cm}$$

Answer b) [6] $\rho = \underline{0.47 \text{ ohm}\cdot\text{cm}}$

c) Next, calculate the minority carrier diffusion length using the minority carrier lifetime model equation.

(Lab. slide 9) $\tau_{\min} = \frac{45 \mu\text{s}}{1 + (7.7 \times 10^{-18}) N_2 + (4.5 \times 10^{-36}) N_1^2} = 2 \times 10^{-5} \text{ s}$ $N_2 = 1.5 \times 10^{17}$

$$(3.10) \quad \mu_n = \frac{1360 - 92}{1 + (1.3 \times 10^{17})^{0.91}} + 92 = 684 \text{ cm}^2/\text{V}\cdot\text{s} \quad D_n = \frac{kT}{q} \mu_n = 0.025852 \times 684 = 17.7 \text{ cm}^2/\text{s}$$

Answer c) [7] $L_n = \underline{1.88 \times 10^{-2} \text{ cm}}$

$$L_n = \sqrt{D_n \tau_n} = \sqrt{17.7 \times 2 \times 10^{-5}} = 1.88 \times 10^{-2}$$

3. For a Si abrupt p-n junction with $p = N_A^- = 3E16/cm^3$ and $n = N_D^+ = 8E15/cm^3$.

a) Calculate the total built-in potential.

$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right) = 0.025852 \times \ln \left(\frac{3 \times 10^{16} \times 8 \times 10^{15}}{1 \times 10^{20}} \right) = 0.737 \text{ V}$$

Answer a) [6] $V_{bi} = 0.737 \text{ V}$

b) Next, calculate the depletion width in the n-type side when $V_a = 0V$.

$$x_n = \sqrt{\frac{2 \epsilon_s V_{bi} N_A}{q N_D (N_A + N_D)}} = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} \times 0.737 \times 3 \times 10^{16}}{1.6 \times 10^{-19} \times 8 \times 10^{15} \times (3.8 \times 10^{16})}} = 3.07 \times 10^{-5} \text{ cm}$$

Answer b) [6] $x_n(0) = 3.07 \times 10^{-5} \text{ cm}$

c) Calculate the minority carrier lifetime in the p-type side.

$$\tau_n = \tau_{min} = \frac{45 \mu s}{1 + (7.7 \times 10^{-18} \times 3 \times 10^{16}) + (4.5 \times 10^{-36} \times (3 \times 10^{16})^2)} = 3.64 \times 10^{-5} \text{ s}$$

Answer c) [6] $\tau_n = 3.64 \times 10^{-5} \text{ s}$

d) Next, calculate the junction capacitance per unit area when $V_a = -3V$.

$$N_{eff} = \frac{N_A N_D}{N_A + N_D} = 6.3 \times 10^{15}$$

$$C_j'(-3) = C_j'(0) \left[\frac{V_{bi}}{V_{bi} - V_a} \right]^{0.5} = 1.2 \times 10^{-8} \text{ F/cm}^2$$

$$C_j'(0) = \sqrt{\frac{\epsilon_s \epsilon_0 N_{eff}}{2 V_{bi}}} = \sqrt{\frac{11.7 \times 8.85 \times 10^{-14} \times 1.6 \times 10^{-19} \times 6.3 \times 10^{15}}{2 \times 0.737}} = 2.7 \times 10^{-8} \text{ F/cm}^2$$

Answer d) [6] $C_j'(-3) = 1.2 \times 10^{-8} \text{ F/cm}^2$

e) Next, calculate the total depletion width when $V_a = -3V$.

$$W(-3) = \sqrt{\frac{2 \epsilon_s (V_{bi} - V_a)}{q N_{eff}}} = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} \times (3.737)}{1.6 \times 10^{-19} \times 6.3 \times 10^{15}}} = 8.76 \times 10^{-5} \text{ cm}$$

Answer e) [6] $W(-3) = 8.76 \times 10^{-5} \text{ cm}$

f) Next, calculate the Debye length of the n-type side.

$$L_{D,n} = \sqrt{\frac{\epsilon V_t}{q N_D}} = \sqrt{\frac{11.7 \times 8.85 \times 10^{-14} \times 0.025852}{1.6 \times 10^{-19} \times 8 \times 10^{15}}} = 4.57 \times 10^{-6} \text{ cm}$$

Answer f) [6] $L_{D,n} = 4.57 \times 10^{-6} \text{ cm}$

g) Next, calculate the electron concentration at the depletion boundary of the p-type side, $-x_p'$, when $V_a = 0.6\text{V}$.

$$n_{p0}(-x_p') = \frac{n_i^2}{3 \times 10^{16}} = 3.33 \times 10^3$$

$$(4.85) \quad n_p(-x_p') = n_{p0}(-x_p') \exp\left(\frac{V_a}{V_t}\right) = 3.33 \times 10^3 \times \exp\left(\frac{0.6}{0.025852}\right) = 4 \times 10^{13}$$

Answer g) [6] $n_p(-x_p') = 4 \times 10^{13} \text{ cm}^{-3}$

h) Next, calculate the maximum electric field in the depletion region when $V_a = -3\text{V}$

$$E_{\max} = \frac{2(V_{bi} - V_a)}{W(-3)} = \frac{2 \times 3.737}{8.76 \times 10^{-5}} = 8.53 \times 10^4$$

Answer h) [7] $E_{\max} = 8.53 \times 10^4 \text{ V/cm}$