

Instructions:

1. Do your own work. DO NOT REMOVE THE STAPLE ON THIS EXAM.
2. You may use either a legal copy of the text OR reference text OR ONE sheet of hand-written notes. You may NOT pass a book or note sheet to another student. You may NOT use class notes. Do not use previously solved problems.
3. Calculator allowed. You may NOT share a calculator with another student.
4. Use values given on this cover sheet. If a value is not given, explicitly state definitions and assumptions that you use.
5. Where possible, calculate parameters rather than read them from a graph.
6. Do all work in the spaces provided on this exam paper. If you write on the back of a sheet, make the notation "PTO" in your solution in order to assure that material written on the back of the page is evaluated for a grade. AN EXTRA BLANK SHEET IS ATTACHED AT THE BACK OF THE EXAM.
7. Show all calculations, making numerical substitutions and giving numerical results where possible.
8. Write answers in space given.
9. Unless stated otherwise,

$$T = 300\text{K}, \quad V_t = 25.852 \text{ mV}$$

10. Unless otherwise stated, the material is silicon with

$n_i = 1.07\text{E}10 \text{ cm}^{-3}$	$N_c = 2.84\text{E}19 \text{ cm}^{-3}$	$q\chi_{\text{Si}} = 4.05 \text{ eV}$
$E_{g,\text{Si}} = 1.125 \text{ eV}$	$N_v = 3.08\text{E}19 \text{ cm}^{-3}$	

11. For the work function of poly silicon, use

$$\phi_{n+} = \chi_{\text{Si}} = 4.05 \text{ V}$$

$$\phi_{p+} = \chi_{\text{Si}} + E_{g,\text{Si}}/q = 5.175 \text{ V}.$$

12. For minority carrier (either electrons or holes) lifetime in silicon, use the relationship

$$\tau_{\text{min}} = (45\text{E}-6 \text{ sec}) / (1 + 7.7\text{E}-18 * N_{\text{imp}} + 4.5\text{E}-36 * N_{\text{imp}}^2),$$

where N_i = the total impurity concentration

13. For holes in silicon, assume

$$\mu_p = \{418.3 \div [1 + (N_i \div 1.6\text{E}17)^{0.7}] + 49.7, \text{ in cm}^2/\text{V-sec}$$

(where N_i = the total impurity concentration in n- or p-type material, compensated or not).

14. For electrons in silicon, assume

$$\mu_n = \{1268 \div [1 + (N_i \div 1.3\text{E}17)^{0.91}] + 92, \text{ in cm}^2/\text{V-sec}$$

(where N_i = the total impurity concentration in n- or p-type material, compensated or not).

15. Metal gate work functions should be assumed to be

$$\phi_{\text{Au}} = 4.75 \text{ V}, \quad \phi_{\text{Al}} = 4.1 \text{ V}.$$

16. The electron affinity of SiO_2 is $\chi_{\text{SiO}_2} = 0.95 \text{ V}$.

17. Planck constant $h = 6.62618 \times 10^{-34} \text{ J-s} = 4.1354 \times 10^{-15} \text{ eV-s}$, $1 \text{ eV} = 1.60218 \times 10^{-19} \text{ Joule}$

18. free electron mass $m_o = 9.1095 \times 10^{-28} \text{ g}$.

19. Boltzmann constant, $k = 1.38066 \times 10^{-23} \text{ J/K}$

20. Electron charge, $q = 1.60218 \times 10^{-19} \text{ Coulomb}$

21. Permittivity of free space, $\epsilon_o = 8.85418 \times 10^{-14} \text{ Fd/cm}$

22. Relative permittivity of silicon, $\epsilon_r = 11.7$

23. The breakdown voltage of an abrupt (step) junction (assymetrical or one-sided) diode with doping on the lightly doped side of N_B is $V_B = 60(E_g/1.1)^{3/2} (10^{16}/N_B)^{3/4} \text{ V}$.

24. Each part is worth [x] points, as given in the problem.

1. For this problem, consider a **hypothetical** semiconductor material with $n_i = 8.00E+10/cm^3$ and a relative permittivity of 16. Consider the charge neutral region width to be the same as at $V_a = 0$, unless otherwise stated.

- The anode (p-type) region has $|N| = 5.00E+18/cm^3$ (no compensation), $D_{min} = 8 cm^2/sec$ and $\tau_{min} = 3E-8$ sec, and is $1E-4$ cm wide from junction to contact.

The cathode (n-type) region has $|N| = 3E15/cm^3$ (no compensation), $D_{min} = 35 cm^2/sec$ and $\tau_{min} = 6E-6$ sec, and is $400E-4$ cm wide from junction to contact.

$V_{a1} = 0$	$\epsilon_r = 16$
$N_{a1} = 5.00E+18 \quad cm^{-3}$	$N_{d1} = 3.00E+15 \quad cm^{-3}$
$D_{n1a} = 8 \quad cm^2/sec$	$D_{p1a} = 35 \quad cm^2/sec$
$TAU_{n1} = 3.00E-08 \quad sec$	$TAU_{p1} = 6.00E-06 \quad sec$
$x_{p1} = 1.00E-04 \quad cm$	$x_{n1} = 4.00E-02 \quad cm$

- a. Calculate the built-in voltage, V_{bi} .

$$V_{bi} = V_t \ln(N_{a1} N_{d1} / n_i^2)$$

$$V_{bi} = 0.736 \text{ V}$$

Answer a[5]: $V_{bi} = \underline{\hspace{2cm}}$ V.

- b. Calculate the depletion region width, W .

$$W = \text{SQRT}(2 * \epsilon_r * \epsilon_0 * (V_{bi} - V_{a1}) / (q * N_{a1} * N_{d1} / (N_{a1} + N_{d1})))$$

$$W = 6.59E-05 \quad cm$$

Answer b[5]: $W = \underline{\hspace{2cm}}$ cm.

- c. Calculate (to 2 significant figures) the charge neutral region width on the n-side, $W_{n,CNR}$.

$$W_{n,CNR} = x_{n1} - W / (1 + N_{d1} / N_{a1})$$

$$W_{n,CNR} = 4.0E-02 \quad cm$$

since $x_n \sim W * 500 / 503 < 10\%$ of 4 micron.

Answer c[5]: $W_{n,CNR} = \underline{\hspace{2cm}}$ cm.

- d. Calculate (to 2 significant figures) the charge neutral region width on the p-side, $W_{p,CNR}$.

$$W_{p,CNR} = x_{p1} - W / (1 + N_{a1} / N_{d1})$$

$$W_{p,CNR} = 1.0E-04 \quad cm$$

since $x_p \sim W * 3 / 503 < 10\%$ of 1 micron

Answer d[5]: $W_{p,CNR} = \underline{\hspace{2cm}}$ cm.

- e. Calculate the minority carrier diffusion length, L_p .

$$L_p = \text{SQRT}(D_{p1a} * TAUp1)$$

$$L_p = 1.45E-02 \quad cm$$

Answer e[5]: $L_p = \underline{\hspace{2cm}}$ cm.

2. Continue to consider the same **hypothetical** semiconductor material as in Problem 1. Continue to consider the charge neutral region width to be the same as at $V_a = 0$, unless otherwise stated.

a. Calculate the minority carrier diffusion length, L_n .

$$L_n = \text{SQRT}(D_n I_a / q n_i^2)$$

$$L_n = 4.90E-04 \text{ cm}$$

Answer a[5]: $L_n =$ _____ cm.

b.[4] The anode is best represented as a **SHORT** LONG (circle one) diode region because:

$$W_p, \text{CNR} < L_n, \text{ so SHORT}$$

$$W_p, \text{CNR} = 1.0E-04 \text{ cm}$$

$$L_n = 4.90E-04 \text{ cm}$$

c.[4] The cathode is best represented as a SHORT **LONG** (circle one) diode region because:

$$L_p < W_n, \text{CNR}, \text{ so LONG}$$

$$W_n, \text{CNR} = 4.0E-02 \text{ cm}$$

$$L_p = 1.45E-02 \text{ cm}$$

d. For $V_a = 500$ mV (in the low-level injection range, and ignoring recombination currents), calculate the largest component of the forward diffusion current density at the appropriate depletion region boundary (either $J_p(x_n)$ or $J_n(-x_p)$ in functional notation).

$$V_a = 0.5 \text{ V}$$

$$J_p = q n_i^2 D_p / (N_d L_p) (\exp(V_a / V_t) - 1)$$

$$J_p = 2.07E-01 \text{ A/cm}^2$$

Answer d[7]: $J(500 \text{ mV}) =$ _____ A/cm^2 .

e. For $V_a = 500$ mV the depletion capacitance per unit area (assume a perfectly abrupt junction) is:

$$C_j' = (e r \epsilon_0 / W) (1 - V_a / V_{bi})^{1/2}$$

$$C_j' = 3.35E-08 \text{ Fd/cm}^2$$

Answer e[6]: $C_j'(500 \text{ mV}) =$ _____ Fd/cm^2 .

3. a. [Use the parameters given for problems 1 and 2.] When a diode (ideality factor = 1) conducts with a current of 3 mA, the diffusion conductance is:

$$i_D = 0.003 \text{ A}, N = 1$$

$$g_d = i_D / (N \cdot V_t)$$

$$g_d = 1.16E-01 \text{ ohm}^{-1}$$

Answer a[5]: $g_d(3 \text{ mA}) = \underline{\hspace{2cm}}$ ohm^{-1} .

b. When this diode (ideality factor = 1) conducts with a current of 3 mA, the diffusion capacitance is:

The characteristic time will be
 $\tau_{diff} = \tau_{up1}$ on the lightly doped n-side (since LONG)
 $C_{diff} = \tau_{up1} \cdot g_d$
 $C_{diff} = 6.96E-07 \text{ Fd}$
 If silicon TAU is used, $\tau_{up1} = 4.40E-05 \text{ sec}$
 $C_{diff} = 5.10E-06 \text{ Fd}$, either answer OK

Answer b[5]: $C_d(3 \text{ mA}) = \underline{\hspace{2cm}}$ Fd.

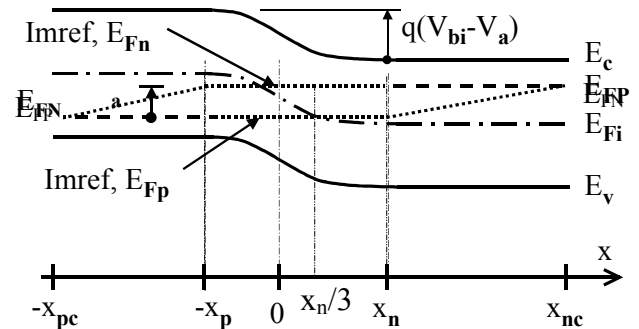
4. A silicon p-n diode under forward bias has the energy level diagram (including non-equilibrium Fermi levels, E_{Fn} and E_{Fp} , in the depletion region) as shown.

a. At $x \approx x_n/3$, estimate the value of p_n .

At $x_n/3$, $E_{fp} \sim E_{fi}$, so $p_n \sim n_i = 1.07E10 \text{ cm}^{-3}$

Answer a[4]: $p_n \approx \underline{\hspace{2cm}}$ cm^{-3} .

b.[4] Justify the reason for the answer you gave in part a.



The E_{fp} relative to the intrinsic Fermi level, E_{fi} is given by

$$E_{fi} - E_{fp} = (kT/q) \cdot \ln(p/n_i)$$

$$p = n_i \cdot \exp(q \cdot (E_{fi} - E_{fp}) / (kT)), E_{fi} = E_{fp} \text{ at } x_n/3, \text{ so}$$

$$p = n_i, \text{ at } x_n/3$$

5. Using the same coordinate system as in Problem 4, consider an abrupt junction with doping on the n-side of $1E15 \text{ cm}^{-3}$ phosphorous and on the p-side of $5E17 \text{ cm}^{-3}$ boron.

$$\begin{aligned} N_a &= 5.00E+17 & \text{cm}^{-3} \\ N_d &= 1.00E+15 & \text{cm}^{-3} \\ V_a &= 0.6 & \text{V} \end{aligned}$$

a. For $V_a = 0.6$ volts, calculate the excess hole population at x_n .

$$\begin{aligned} \text{at } x_n, \text{dnp} &= (n_i^2/N_d) * \text{EXP}(V_a/V_t) \\ \text{dnp}(x_n) &= 1.38E+15 & \text{cm}^{-3} \end{aligned}$$

Answer a[5]: $\delta p_n(x=x_n, V_a=0.6) = \underline{\hspace{2cm}} \text{ cm}^{-3}$.

b. Calculate the minority carrier diffusion length in the n-side of this diode

$$\begin{aligned} D_p &= V_t * ((418.3 / (1 + (n_i / 1.6e17)^{0.7})) + 49.7) \\ D_p &= 12.1 & \text{cm}^2/\text{sec} \\ \text{TAUp} &= (45E-6) / (1 + 7.7E-18 * N_d + 4.5E-36 * N_d^2), \\ \text{TAUp} &= 4.47E-05 & \text{sec} \\ L_p &= \text{sqrt}(D_p * \text{TAUp}) \\ L_p &= 2.32E-02 & \text{cm} \end{aligned}$$

Answer b[9]: $L_{\min} = \underline{\hspace{2cm}} \text{ cm}$.

c. Consider that the n-side is "long". For the same condition in part c, calculate the excess hole population at $x = x_n + 2.2E-3 \text{ cm}$.

$$\begin{aligned} x &= x_n + 2.20E-03 & \text{cm} \\ \text{dnp} &= \text{dnp}(x_n) * \exp(-(x-x_n)/L_p) \\ \text{dnp} &= 1.25E+15 & \text{cm}^{-3} \end{aligned}$$

Answer c[5]: $\delta p_n(x=x_n+2.2E-4, V_a=0.6) = \underline{\hspace{2cm}} \text{ cm}^{-3}$.

d. Consider that the p-side is "short". For the same condition in part c, calculate the excess electron population at $x = -(x_{pc} + x_p)/2$, i.e. midway between x_{pc} and x_p .

$$\begin{aligned} \text{for the short diode at this point, dnp} &= \text{dnp}(x_p)/2 \\ \text{dnp} &= 0.5 * (n_i^2/N_a) * \text{EXP}(V_a/V_t) \\ \text{dnp} &= 1.38E+12 & \text{cm}^{-3} \end{aligned}$$

Answer d[5]: $\delta n_p(x=-(x_{pc} + x_p)/2, V_a=0.6) = \underline{\hspace{2cm}} \text{ cm}^{-3}$.

e. Calculate the breakdown voltage $V_B = BV$ for this diode, assuming a planar junction.

$$\begin{aligned} BV &= 60 * (E_{gSi}/1.1)^{3/2} * (1e16/N_d)^{3/4} \\ BV &= 349 & \text{V} \end{aligned}$$

Answer e[7]: $BV = \underline{\hspace{2cm}} \text{ V}$.