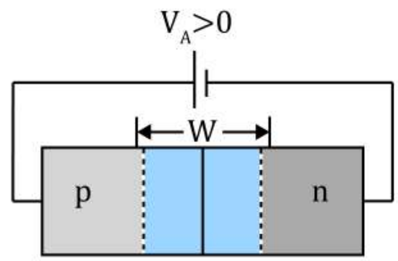
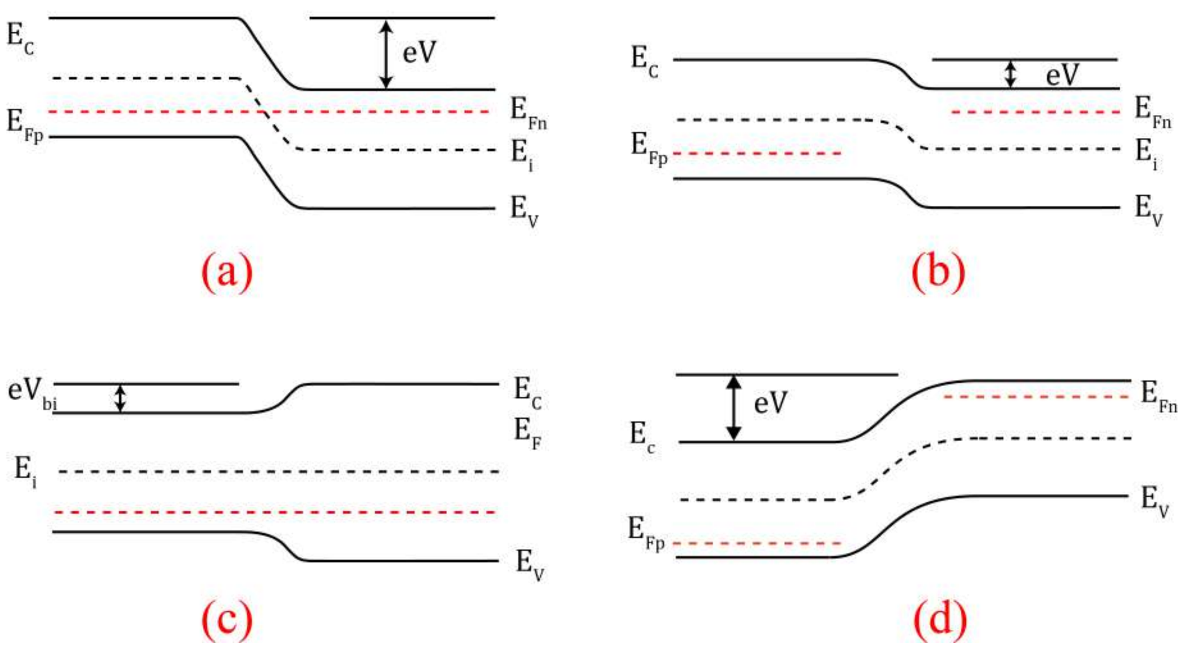
ISD 2023 - Week 5 Assignment

There are 10 questions for a total of 20 marks.

For Q1-Q2: With respect to biasing of the pn junctions, answer the following questions.

1. (2 marks) For a forward-biased pn junction given below, choose the associated band diagram from the given options.





A. a

B. b

C. c

D. d

> **Reflect and remember:** The bandgap of the material has to remain constant while drawing the band diagram, as it is a material property.

2. (2 marks) In a forward-biased pn junction -

   A. the barrier across the junction reduces proportional to the applied voltage, resulting in the drift of majority carriers across the barrier.

   B. the barrier across the junction increases proportional to the applied voltage, resulting in the drift of majority carriers across the barrier.

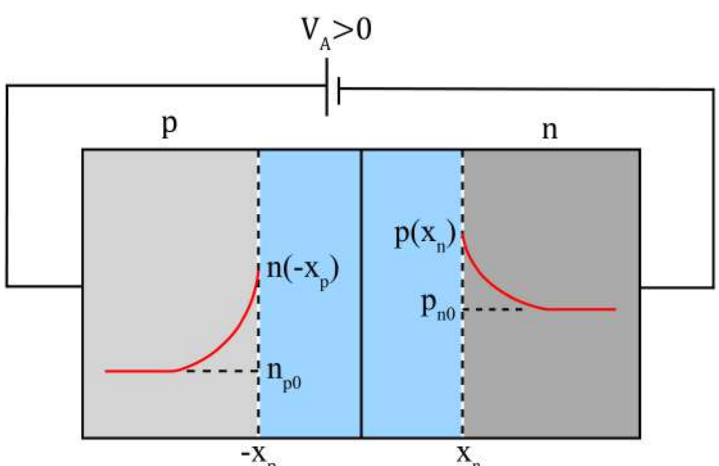
   C. the barrier across the junction reduces proportional to the applied voltage, resulting in the diffusion of majority carriers across the barrier.

   D. the barrier across the junction reduces proportional to the applied voltage, resulting in the diffusion of minority carriers across the barrier.

   E. the barrier across the junction increases proportional to the applied voltage, resulting in the diffusion of majority carriers across the barrier.

> **Reflect and remember:** In the forward biased pn junction, what is the contribution of the drift current to the total current density? Please think about it.

For Q3-Q5 The figure below shows the carrier profile across a silicon pn junction.The impurity doping concentrations are $N_d = 2 \times 10^{15}\ cm^3$ and $N_a = 8 \times 10^{15}\ cm^3$, and a voltage of V_A is applied across the junction. Based on the given data, answer the following questions.



3. (2 marks) The diode is in ______

   A. Forward bias, as there are excess minority carriers available at the edge of the depletion region.

   B. Equilibrium condition, as there is no movement of carriers through the depletion region.

C. Reverse bias, as there are excess minority carriers available in the quasi-neutral regions.

D. Forward bias, as there are excess majority carriers available at the edge of the depletion region.

E. Reverse bias, as there are negligible minority carriers available at the edge of the depletion region.

F. Equilibrium condition, as the carrier concentrations are constant at any given position in the quasi-neutral region

4. (2 marks) The steady-state minority concentration (in cm^{-3}) in $p-$side (n_{p0}) and $n-$side (p_{n0}) is ______, respectively.

(*Hint:* Use mass action law to determine the steady-state minority carrier concentrations in the bulk. Take $kT/q = 26\ mV,\ n_i = 1 \times 10^{10}\ cm^{-3}$).

A. $n_{p0} = 2 \times 10^{12}$, $p_{n0} = 5 \times 10^4$

B. $n_{p0} = 1.25 \times 10^4$, $p_{n0} = 5 \times 10^4$

C. $n_{p0} = 5 \times 10^4$, $p_{n0} = 1.25 \times 10^4$

D. $n_{p0} = 1.25 \times 10^4$, $p_{n0} = 2 \times 10^{12}$

E. $n_{p0} = 1.25 \times 10^{14}$, $p_{n0} = 5 \times 10^{14}$

$n_{p0} = \frac{n_i^2}{N_A} = \frac{10^{20}}{8\times10^{15}} = \underline{1.25\times10^{4}/cm^3}$

$p_{n0} = \frac{n_i^2}{N_D} = \frac{(10^{10})^2}{2\times10^{15}} = \underline{5\times10^{4}/cm^3}$

5. (2 marks) The minority carrier concentration (in cm^{-3}) at the edge of the depletion region [$n(-x_p)$ and $p(x_n)$], for an applied forward bias $V_A = 0.6\ V$, is ______.

(*Hint:* Use the law of the junctions to determine the carrier concentrations at the edge of the depletion region.)

A. $n(-x_p) = 1.25 \times 10^4$, $p(x_n) = 5 \times 10^4$

B. $n(-x_p) = 1.315 \times 10^{14}$, $p(x_n) = 5.26 \times 10^{14}$

C. $n(-x_p) = 3 \times 10^{12}$, $p(x_n) = 5 \times 10^{12}$

D. $n(-x_p) = 1.315 \times 10^4$, $p(x_n) = 5.26 \times 10^4$

E. $n(-x_p) = 1 \times 10^{10}$, $p(x_n) = 1 \times 10^{12}$

$n(-x_p) = n_{p0} e^{qV_A/kT}$

$= 1.25\times10^{4} \times e^{0.6/0.026}$

$\therefore \underline{n(-x_p) = 1.315\times10^{14}/cm^3}$

$p(x_n) = p_{n0} e^{qV_A/kT} = 5\times10^{4} \times e^{0.6/0.026}$

$= \underline{5.26\times10^{14}/cm^3}$

Reflect and remember: The injected minority carriers are significant as compared to the equilibrium minority carrier density. The injection of such a large number of carriers results in high current densities in the forward bias, which grows exponentially with applied voltage.

For Q6-Q7: A silicon pn junction at $T = 300\ K$ with applied reverse bias $V_R = 5\ V$ has doping concentrations $N_a = 2 \times 10^{17}\ cm^{-3}$ and $N_d = 1 \times 10^{16}\ cm^{-3}$.

(Take $n_i = 1 \times 10^{10}\ cm^{-3}$ and $kT/q = 26\ mV$).

6. (2 marks) The total potential across the pn junction at $V_R = 5\ V$ is ______ V.

   A. 0.79

   B. -4.28

   C. 5.79

   D. -0.79

   E. -5.79

$V_{total} = V_{bi} + V_R$ $\quad$ $V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$

$\therefore V_{bi} = 0.026 \ln\left(\frac{2\times10^{17} \times 1\times10^{16}}{10^{20}}\right) = 0.796\,V$

$\therefore V_{total} = 0.796 + 5 = \underline{\underline{5.796\,V}}$

Reflect and remember: The total potential across a pn junction, in reverse bias, is the built-in potential plus the additional drop in the voltage across the junction due to the applied voltage.

7. (2 marks) The ratio of depletion widths with and without applied reverse bias $(W_{V=V_R}/W_{V=0})$ is ______

   A. 0.38

   B. 0.038

   C. 27

   D. 2.7

   E. 0.828

$W \propto \sqrt{V_b}$ $\quad \therefore \frac{W_{V=V_R}}{W_{V=0}} = \sqrt{\frac{V_{bi}+V_R}{V_{bi}}}$

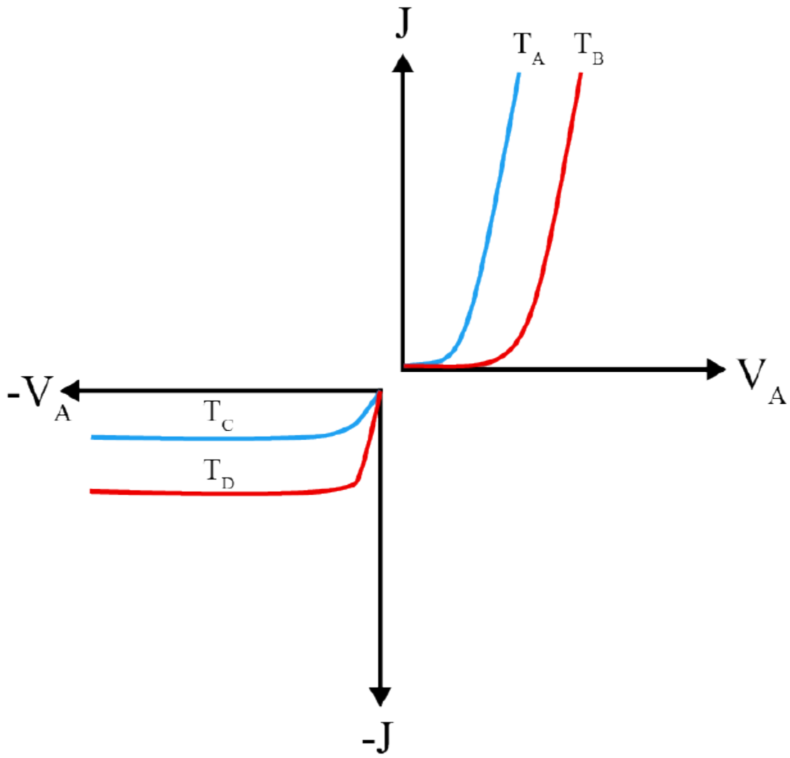
$= \sqrt{\frac{5.79}{0.796}} \simeq \underline{\underline{2.7}}$

Reflect and remember: Note the significant difference between the depletion widths of the pn junction with and without applied reverse bias. The reverse bias uncovers additional space charge region by depleting the free carriers, thereby increasing the depletion width. Another point to note is that an increased depletion width implies a larger peak electric field, but the reverse bias current saturates beyond an increase in the depletion width. This is because the current depends on the availability of the minority charge carriers, which are depleted due to the reverse bias.

For Q8-Q9: An p^+n diode is subjected to varying temperatures, and the corresponding $I-V$ characteristics are plotted in the figure below. Based on the given data, answer the following questions

8. (2 marks) In the forward bias, a change in temperature results in a shift in the threshold voltage. Choose the correct temperature relation along with the reason.

   A. As the temperature increases, scattering of carriers increases, and hence V_t increases. Therefore, $T_B > T_A$.



B. As the temperature increases, energy of carriers decreases, and hence V_t decreases. Therefore, $T_A > T_B$.

C. As the temperature increases, energy of carriers increases, and hence V_t increases. Therefore, $T_B > T_A$.

D. As the temperature increases, energy of carriers increases, and hence V_t decreases. Therefore, $T_A > T_B$.

E. As the temperature increases, scattering of carriers decreases, and hence V_t decreases. Therefore, $T_A > T_B$.

9. (2 marks) In the reverse bias, a change in temperature results in a shift in the reverse saturation current, J_s. Choose the correct temperature relation along with the reason.

A. $T_C > T_D$ as $J_s \propto 1/n_i^2$

B. $T_C < T_D$ as $J_s \propto 1/n_i^2$

C. $T_D > T_C$ as $J_s \propto n_i$

D. $T_D < T_C$ as $J_s \propto n_i$

E. $T_C < T_D$ as $J_s \propto n_i^2$

F. $T_C > T_D$ as $J_s \propto \sqrt{n_i}$

10. (2 marks) **(EC-GATE 2015)** The built-in potential of an abrupt pn junction is $0.75\ V$. If its junction capacitance C_J at a reverse bias V_R of $1.25\ V$ is $5\ pF$, the value of C_J (in pF) when $V_R = 7.25\ V$ is ______.

    A. 5

    B. 2.5

    C. 10

    D. 1

    E. 0.5

$V_{bi} = 0.75V$

$C_j = \frac{\varepsilon_{Si}}{W} \Rightarrow C_j \propto \frac{1}{\sqrt{V_{bi}+V_R}}$

$\therefore \frac{C_{j1}}{C_{j2}} = \sqrt{\frac{V_{bi}+V_{R2}}{V_{bi}+V_{R1}}}$

$\Rightarrow \frac{5pF}{C_{j2}} = \sqrt{\frac{0.75+7.25}{0.75+1.25}}$

$\therefore C_{j2} = 5pF \times \sqrt{\frac{2}{8}} = \underline{2.5pF}$