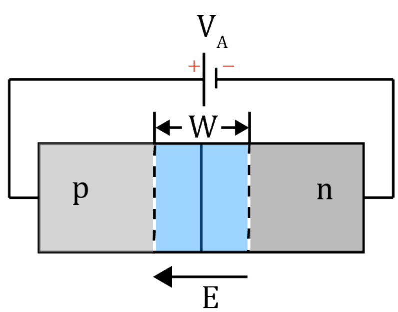
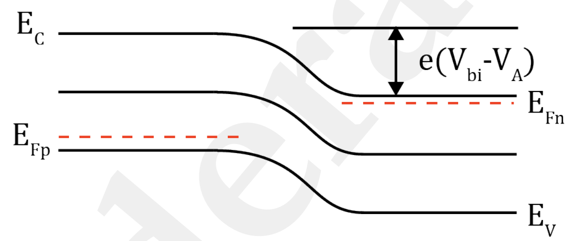
A quick recap of the material covered in lectures

This week was devoted to modelling the steady state response of a *pn* junction diode. A qualitative description of the diode operation using the band diagram was given, and various parameters characterizing the forward and reverse bias for an ideal diode were derived. Non-idealities (resulting from approximations used to derive the diode characteristics) were described and attention was given to the different processes and their impact on diode parameters. Finally, the temperature dependence of the diode parameters is mentioned, along with its impact on the threshold voltage (V_t), reverse saturation current (J_S), and reverse breakdown voltage (V_{BD}). A summary of the same is given below.

Forward biased *pn* Junction

Forward biasing of the *pn* junction lowers the potential hill between the two sides of the diode and enhances majority carrier injection across the junction and into the opposite-side quasi neutral region.





- The minority carrier concentration at the edge of the depletion regions in forward bias is given by -

$$\boxed{n_p(-x_p) = n_{p0}\exp\left(qV_a/kT\right)} \quad \boxed{p_n(x_n) = p_{n0}\exp\left(qV_a/kT\right)} \tag{1}$$

- The law of the junctions is the np product, which is valid all across the junction.

$$\boxed{np = n_i^2\exp\left(qV_a/kT\right)} \tag{2}$$

- The variation (diffusion) of minority carrier concentration from the edge of the depletion region in forward bias is given by -

$$\boxed{\delta p_n(x) = p_n(x) - p_{n0} = p_{n0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(-\frac{x - x_n}{L_p}\right)} \tag{3}$$

$$\boxed{\delta n_p(x) = n_p(x) - n_{p0} = n_{p0}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]\exp\left(\frac{x_p + x}{L_n}\right)} \tag{4}$$

- The total diffusion current in the forward bias is thus given by

$$\boxed{J_{total} = eD_n\frac{d\delta n}{dx} - eD_p\frac{d\delta p}{dx}} \tag{5}$$

$$\boxed{J_{total} = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]} \tag{6}$$

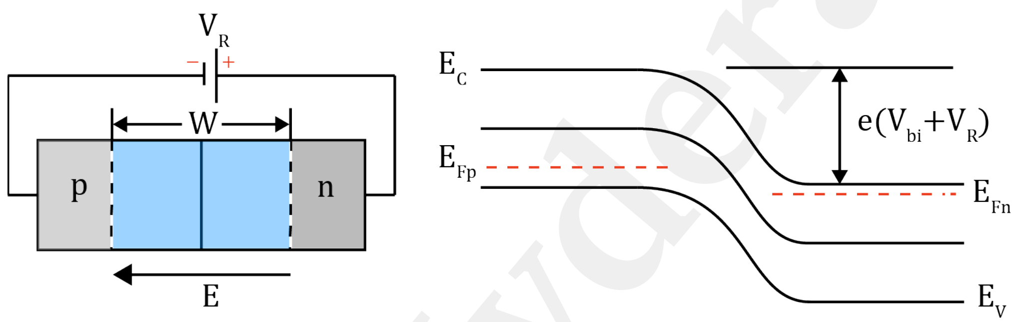
where,

$$\boxed{J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]} \tag{7}$$

is the reverse saturation current.

Reverse biased *pn* Junction

The reverse bias current in an ideal diode is associated with minority carriers moving into the depletion region and being accelerated to the opposite side of the junction (drift) due to the applied bias.



- The width of the depletion region in reverse bias is given by -

$$\boxed{W = \sqrt{\frac{2\epsilon_{si}}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)(V_R + V_{bi})}} \tag{8}$$

- The maximum electric field in the reverse bias can be written as

$$\boxed{E_{max} = \frac{-2(V_{bi} + V_R)}{W}} \tag{9}$$

Since we have a separation of positive and negative charges in the depletion region due to the reverse bias, a capacitance is associated with the pn junction. Consider an abrupt pn junction and it is biased with reverse bias voltage V_R. The depletion width across the junction increases and forms a capacitance known as depletion or junction capacitance $C_{dep} = C_j$ (typically in $pF/cm^2 - nF/cm^2$).

- The junction or the depletion capacitance is given by,

$$\boxed{C_j = \frac{\epsilon_{si}}{W} = \sqrt{\frac{q\epsilon_{si}N_aN_d}{2(N_a+N_d)(V_R+V_{bi})}}} \tag{10}$$

- Hence, for an abrupt junction, the capacitance varies inversely with the square root of the total voltage drop across the depletion region.

$$\boxed{C_j \propto \sqrt{\frac{1}{V_R+V_{bi}}}} \tag{11}$$

- Whereas, for a linearly graded junction, the capacitance varies inversely with the cubed root of the total voltage drop across the depletion region.

$$\boxed{C_j \propto \sqrt[3]{\frac{1}{V_R+V_{bi}}}} \tag{12}$$

- The x-intercept of the $1/|C^2|\ vs\ V_R$ gives the built-in voltage, and the slope (m) of the graph is

$$\boxed{m = \frac{2}{e\epsilon_s N_d}} \tag{13}$$

- The reverse saturation current almost doubles for every 10^oC rise in temperature.

$$\boxed{I_{02} \simeq I_{01}2^{\frac{\Delta T}{10}}} \tag{14}$$

Solve the following questions. There are 14 questions, for a total of 25 marks.

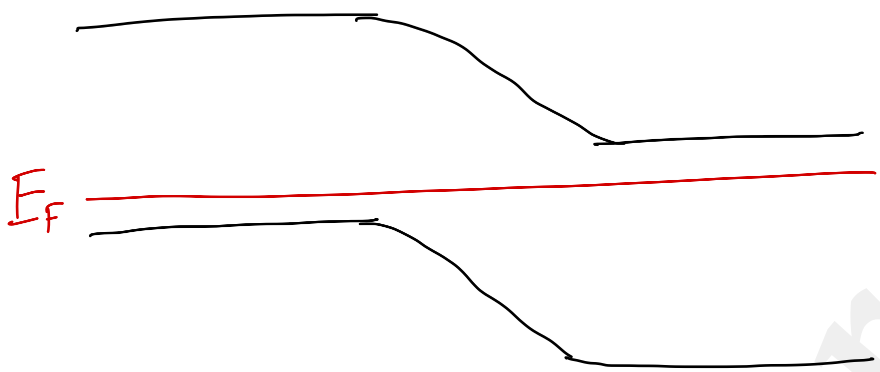
1. (1 mark) Taking the Fermi level on P-side as a reference (E_{FP}), the Fermi level on N-side of PN Junction (E_{FN}) -

   A. Moves down when a negative voltage is applied to the N side

   B. Moves up when a negative voltage is applied to the N side

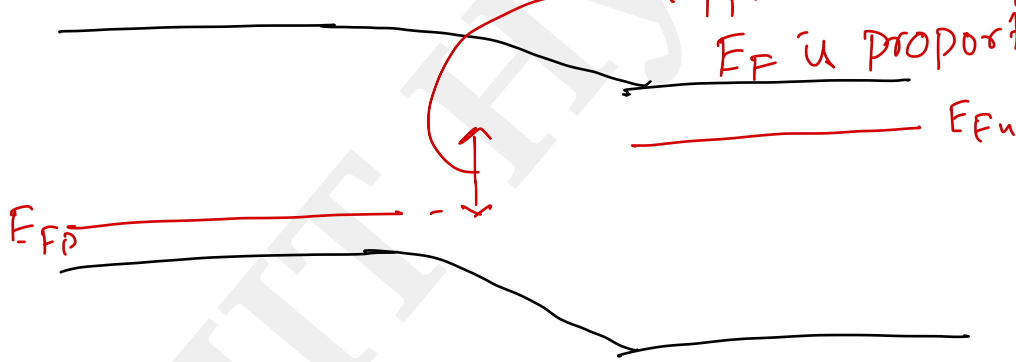
   C. Moves up when a positive voltage is applied to the N side

   D. Remains stationary when a positive voltage is applied to the N side



when a negative bias is applied to N side (relative to p side) the band diagram becomes

Applied voltage. Splitting in E_F is proportional to applied voltage.



2. (3 marks) The plot below shows the carrier concentrations in a PN junction at room temperature. Only the quasi-neutral N-side of the junction is shown in figure 1. Answer the following questions - (Use $kT = 0.0259\ eV$)

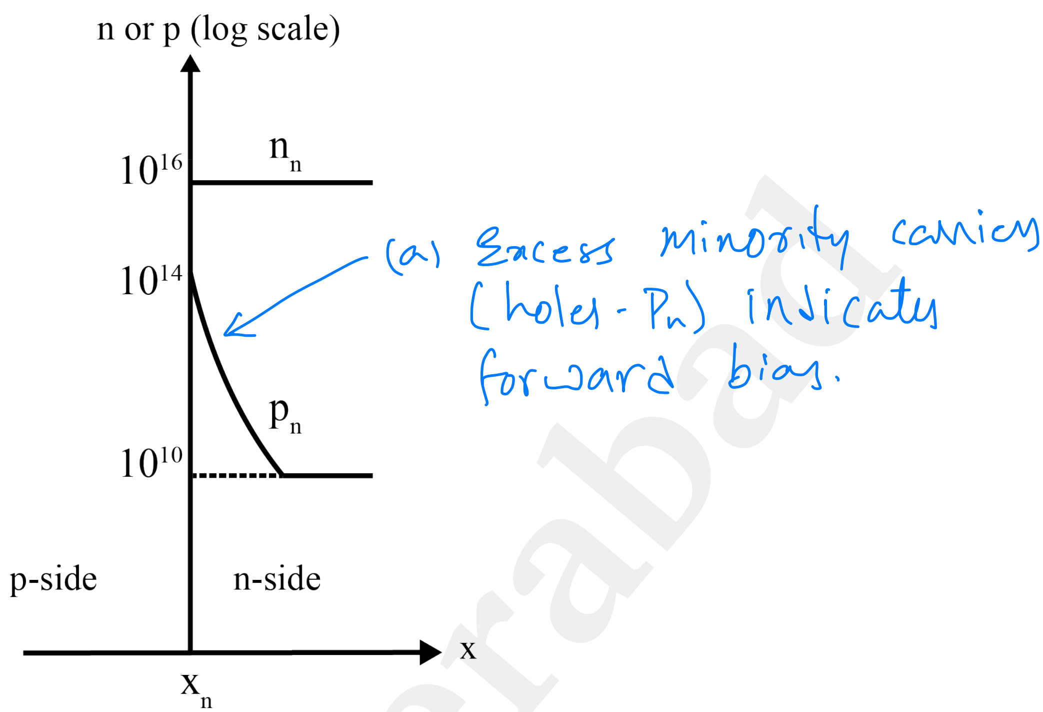


Figure 1: Carrier concentration - Problem 2

(a) (*1 mark*) The diode is in ______

A. *Forward bias*, as there are excess electrons on the N-side

B. *Reverse bias*, as there are excess holes on the N-side

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

D. Forward bias, as there are excess holes on the N-side

E. *Forward bias*, as there are excess electrons available in the quasi-neutral regions.

F. *Equilibrium condition*, as the electrons and holes are constant at any given position in the quasi-neutral region

(b) (*1 mark*) The intrinsic carrier concentration (n_i) in cm^{-3} is ______

A. 1×10^{10}

B. 1.5×10^{10}

C. 1.5×10^{13}

D. 1×10^{16}

Under equilibrium $n_n = 10^{16}$

$p_n = 10^{10}$

$n_i^2 = n_n p_n = 10^{26}$

$n_i = 1 \times 10^{13}\ cm^{-3}$

E. 1×10^{13}

F. 1.5×10^{11}

(c) (*1 mark*) The magnitude of the applied voltage (V_A) is ______ (*Hint:* Use law of the junctions, calculate n_i in the quasi-neutral region)

A. $2.385\ V$

B. $2.385\ mV$

C. $0.02385\ V$

D. $0.2385\ V$

E. $260\ mV$

F. $0.1192\ V$

law of junction is

$$P_n(x_n) = P_{no} \exp\left(\frac{qV_a}{KT}\right)$$

$$P_n(x_n) \to 10^{14} \qquad P_{no} \to 10^{10}$$

$$V_a = \frac{KT}{q} \ln(10^4)$$

$$= 0.0259 \times \ln(10^4) = 0.2385\ V$$

3. (2 marks) A silicon pn junction has impurity doping concentrations of $N_d = 2 \times 10^{15}\ cm^{-3}$ and $N_a = 8 \times 10^{15}\ cm^{-3}$. The minority carrier concentrations at the edges of the depletion region for an applied bias of $V_a = 0.55\ V$ are ______ (use $kT/q = 25.9\ mV,\ n_i = 1.5 \times 10^{10}\ cm^{-3}$)

   A. $p_n = 1.878 \times 10^{14}\ cm^{-3}$, $n_p = 4.69 \times 10^{14}\ cm^{-3}$

   B. $p_n = 4.69 \times 10^{13}\ cm^{-3}$, $n_p = 1.878 \times 10^{13}\ cm^{-3}$

   C. $p_n = 1.878 \times 10^{13}\ cm^{-3}$, $n_p = 4.69 \times 10^{14}\ cm^{-3}$

   D. $p_n = 4.69 \times 10^{14}\ cm^{-3}$, $n_p = 1.878 \times 10^{13}\ cm^{-3}$

   E. $p_n = 4.69 \times 10^{13}\ cm^{-3}$, $n_p = 1.878 \times 10^{14}\ cm^{-3}$

   F. $p_n = 1.878 \times 10^{14}\ cm^{-3}$, $n_p = 4.69 \times 10^{13}\ cm^{-3}$

   G. $p_n = 4.69 \times 10^{14}\ cm^{-3}$, $n_p = 1.878 \times 10^{14}\ cm^{-3}$

N side

$$P_{no} = \frac{n_i^2}{N_D} = \frac{2.25 \times 10^{20}}{2 \times 10^{15}}$$

$$= 1.125 \times 10^{5}\ cm^{-3}$$

$$P_n(x_n) = P_{no} \exp\left(\frac{qV_a}{kT}\right)$$

$$= 1.125 \times 10^{5} \times \exp\left(\frac{0.55}{0.0259}\right)$$

$$= 1.88 \times 10^{14}\ cm^{-3}$$

P side

$$n_{po} = \frac{n_i^2}{N_a} = \frac{2.25 \times 10^{20}}{8 \times 10^{15}}$$

$$= 2.8125 \times 10^{4}$$

$$n_p(-x_p) = 4.69 \times 10^{13}\ cm^{-3}$$

Note that for a particular applied voltage higher doping density gives fewer minority carriers.

4. (2 marks) A silicon pn junction with cross-sectional area of $10^{-4}\ cm^2$ has the following properties at $T = 300\ K$. (Use $n_i = 1.5 \times 10^{10}\ cm^{-3}$)

Recall
$L_n = \sqrt{D_n \tau_n}$
$L_p = \sqrt{D_p \tau_p}$
$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = \frac{kT}{q}$

n region	**p region**
$N_d = 10^{17}\ cm^{-3}$	$N_a = 5 \times 10^{15}\ cm^{-3}$
$\tau_{p0} = 10^{-7}\ s$	$\tau_{n0} = 10^{-6}\ s$
$\mu_n = 850\ cm^2(V-s)^{-1}$	$\mu_n = 1250\ cm^2(V-s)^{-1}$
$\mu_p = 320\ cm^2(V-s)^{-1}$	$\mu_p = 420\ cm^2(V-s)^{-1}$

$D_p = 0.0259 \times 320 = 8.288\ \frac{cm^2}{s}$

$D_n = 0.0259 \times 1250 = 32.375\ \frac{cm^2}{s}$

(a) (*1 mark*) The forward bias current at an applied voltage of $V_b = 0.5\ V$ is ______

A. $1.07\ \mu A$

B. $1.07\ mA$

C. $10.7\ mA$

D. $10.7\ A$

E. $1.07\ A$

F. $10.7\ \mu A$

$J = J_s \left[\exp\left(\frac{qV_A}{kT}\right) - 1 \right]$

$J_s = \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right)$

Substituting $J_{hole} = 7.936 \times 10^{-4}\ A/cm^2$

$J_{electron} = 9.919 \times 10^{-3}\ A/cm^2$

(b) (*1 mark*) The ratio of hole current (I_h) to total current (I_{total}) at the space charge region edge x_n is ______

A. 0.074%

B. 0.74%

C. 8.85%

D. 92.6%

E. 7.4%

F. 91.15%

$J_{total} = J_{hole} + J_{electron}$
$= 1.07 \times 10^{-2}\ A/cm^2$

$I = J_{total} \times Area$
$= 1.07\ \mu A$

$\frac{I_h}{I_{total}} = \frac{7.936 \times 10^{-4}}{1.07 \times 10^{-2}} = 0.0742 = 7.4\%$

5. (2 marks) Consider a uniformly doped GaAs pn junction at $T = 300\ K$. The ratio of the junction capacitance at zero bias '$C_j(0)$' and the junction capacitance with at $10\ V$ reverse-biased voltage '$C_j(10)$' is 3.13. Under reverse bias, the depletion region width on the p-side is 20% of the total space charge width. (use $n_i = 2 \times 10^6\ cm^{-3}$)

   (a) (*1 mark*) The built in voltage V_{bi} is ______ V.

      A. 0.725

      B. 0.67

      C. 1.136

      D. 1.52

Eq 11 is $C_j \propto \frac{1}{\sqrt{V_{bi} + V_R}}$

$\frac{C_j(0)}{C_j(10)} = \frac{\sqrt{10 + V_{bi}}}{\sqrt{V_{bi}}} = 3.13$

$\Rightarrow V_{bi} = 1.136\ V$

   (b) (*1 mark*) The doping concentrations (N_a and N_d) in cm^{-3} are ______ respectively.

      A. $3 \times 10^{15},\ 12 \times 10^{15}$

      B. $12 \times 10^{15},\ 3 \times 10^{15}$

      C. $2 \times 10^{15},\ 8 \times 10^{15}$

      D. $8 \times 10^{15},\ 2 \times 10^{15}$

$x_p = 0.2W \quad x_n = 0.8W$

$x_p N_a = x_n N_d \Rightarrow N_a = 4N_d$

$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.0259 \times \ln\left(\frac{4N_d^2}{(2\times10^6)^2}\right)$

$\Rightarrow N_d = 3.34 \times 10^{15}\ cm^{-3}$

$N_a = 4N_d = 12.56 \times 10^{15}\ cm^{-3}$

Choose the closest answer.

6. (2 marks) Choose the correct statement(s) for a forward biased pn junction -

   A. Majority carrier diffusion current is dominant in the quasi neutral regions whereas minority carrier drift current is dominant at the edges of depletion region

   B. Majority carrier drift current is dominant in the quasi neutral regions whereas minority carrier diffusion current is dominant at the edges of depletion region

   C. Diffusion current is dominant in the quasi neutral regions whereas drift current is negligibly small for a forward bias

   D. Minority carrier diffusion current is dominant in the quasi neutral regions whereas majority carrier drift current is dominant at the edges of depletion region

   E. Diffusion current is dominant near the depletion region whereas drift current is negligibly small for a forward bias

   F. Minority carrier drift current is dominant in the quasi neutral regions whereas majority carrier diffusion current is dominant at the edges of depletion region

In forward bias minority carriers are introduced into the adjacent regions (holes in n-type and electrons into p type). The excess carrier concentration decays away from the junction reaching equilibrium concentration after few diffusion lengths. In quasi-neutral regions only majority carrier drift current is present.

Drift current is negligible near depletion region in forward bias.

Please analyze why the other options are wrong! Also review the various current contributions in lecture slides. The distribution of various components changes with position but the total current remains same as it should be.

7. (4 marks) Consider a uniformly doped silicon pn junction with doping concentrations $N_a = 2 \times 10^{17}\ cm^{-3}$ and $N_d = 4 \times 10^{16}\ cm^{-3}$. The cross-sectional area of the junction is $2 \times 10^{-4}\ cm^2$, and the applied reverse bias is $V_R = 2.5\ V$. (use $n_i = 1.5 \times 10^{10}\ cm^{-3}$, $\epsilon_0 = 8.85 \times 10^{-14}\ F/cm$, $\epsilon_{si} = 11.9$, $kT = 0.0259\ eV$)

(a) (*1 mark*) The built-in voltage of the pn junction is ______ V.

A. 0.75
B. 0.78
C. 0.81
D. 0.84
E. 0.87
F. 0.90

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.0259 \times \ln\left(\frac{2 \times 4 \times 10^{33}}{2.25 \times 10^{20}}\right)$$
$$= 0.81\ V$$

(b) (*1 mark*) The width of the depletion region is ______ μm.

A. 0.36
B. 2.98
C. 3.6
D. 0.47
E. 0.298
F. 0.33

$$W = \sqrt{\frac{2\epsilon_{si}}{q} \times \frac{N_a + N_d}{N_a N_d} (V_R + V_{bi})}$$
$$= 0.36 \times 10^{-4}\ cm = 0.36\ \mu m$$

(c) (*1 mark*) The maximum electric field in the depletion region $|E_{max}|$ is ______ $V cm^{-1}$.

A. 2.22×10^5
B. 1.84×10^5
C. 1.84×10^4
D. 3.2×10^4
E. 3.2×10^5
F. 2.22×10^4

Refer Eq 9. $\mathcal{E}_{max} = -\frac{2(V_{bi} + V_R)}{W}$
$$= -\frac{2(2.5 + 0.81)}{0.36 \times 10^{-4}} = 1.84\ V/cm$$

(d) (*1 marks*) The junction capacitance is ______ pF.

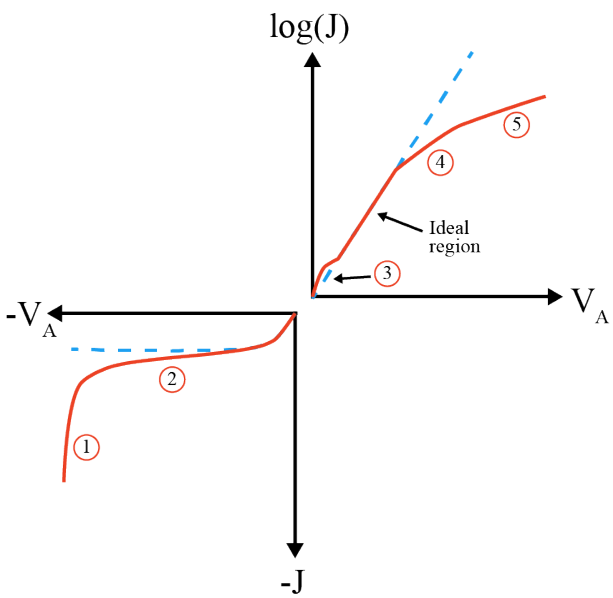
A. 1.94
B. 5.85
C. 2.64
D. 4.97

Review eq. 10. $C_j = \frac{\epsilon_{si}}{W} A$
$$= \frac{11.9 \times 8.85 \times 10^{-14}}{0.36 \times 10^{-4}} \times 2 \times 10^{-4}$$
$$= 5.85\ pF$$

E. 6.96

F. 3.88

8. (2 marks) Match the non-idealities in the diode IV characteristics to the corresponding regions given in figure 2.



A	Photogeneration
B	Thermal recombination in depletion region
C	Avalanche and/or Zener process
D	Low level injection
E	Depletion approximation
F	Thermal generation in depletion region
G	Band bending
H	Series resistance
I	$V_A > V_{bi}$
J	High level injection

Figure 2: Junction Characteristics - Problem 8

A. $1 \to J$, $2 \to A$, $3 \to B$, $4 \to H$, $5 \to I$

B. $1 \to F$, $2 \to J$, $3 \to E$, $4 \to B$, $5 \to C$

C. $1 \to C$, $2 \to F$, $3 \to B$, $4 \to J$, $5 \to H$

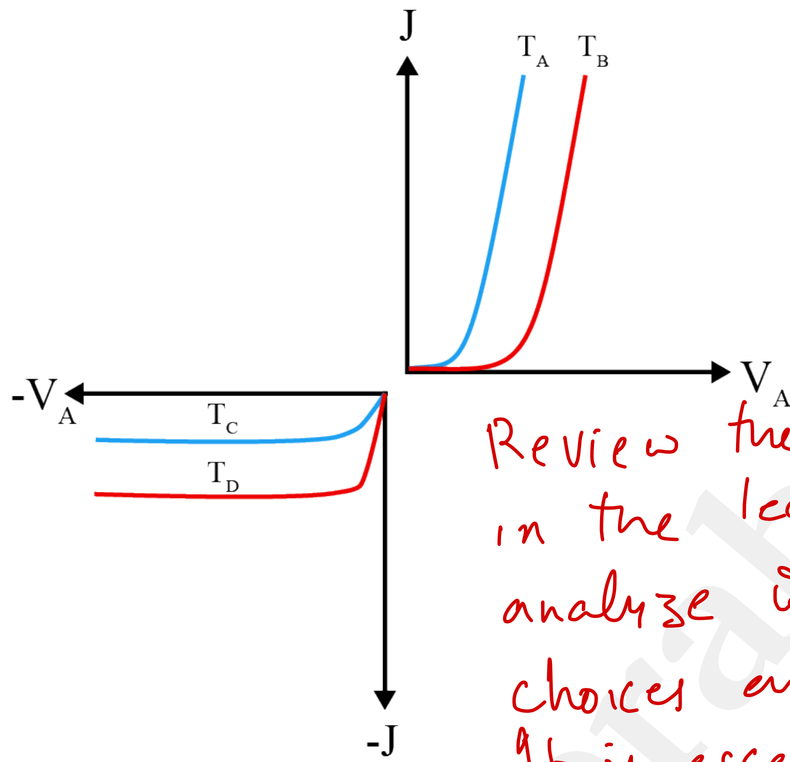
D. $1 \to C$, $2 \to B$, $3 \to F$, $4 \to J$, $5 \to H$

E. $1 \to F$, $2 \to C$, $3 \to I$, $4 \to J$, $5 \to G$

F. $1 \to C$, $2 \to F$, $3 \to G$, $4 \to J$, $5 \to H$

Review lecture video and slides!
Analyze why other choices are incorrect.

9. (2 marks) An p^+n diode is subjected to varying temperatures, and the corresponding $I - V$ characteristics are plotted in the figure 3. Based on the given data, answer the following questions



Review the discussion in the lecture and analyze why other choices are incorrect. It is essential to get the reasoning right.

Figure 3: I-V Characteristics - Problem 9

(a) (*1 mark*) In the *forward bias*, a change in temperature results in a shift in the threshold voltage. Choose the correct temperature dependence of the $I - V$ characteristics along with the reason.

A. $T_A > T_B$, as $T \uparrow$, energy of carriers $\uparrow$, and hence $V_t \downarrow$.

B. $T_B > T_A$, as $T \uparrow$, scattering of carriers $\uparrow$, and hence $V_t \uparrow$.

C. $T_A > T_B$, as $T \uparrow$, energy of carriers $\downarrow$, and hence $V_t \downarrow$.

D. $T_B > T_A$, as $T \uparrow$, energy of carriers $\uparrow$, and hence $V_t \uparrow$.

E. $T_A > T_B$, as $T \uparrow$, scattering of carriers $\downarrow$, and hence $V_t \downarrow$.

(b) (*1 mark*) In the *reverse bias*, a change in temperature results in a shift in the reverse saturation current, J_s. Choose correct temperature dependence of the reverse saturation current along with the reason.

A. $T_C > T_D$, as $T \uparrow$ n_i $\uparrow$, and $J_s \propto 1/n_i^2$

B. $T_C < T_D$, as $T \uparrow$ n_i $\uparrow$, and $J_s \propto n_i^2$

C. $T_C < T_D$, as $T \uparrow$ n_i $\downarrow$, and $J_s \propto 1/n_i^2$

D. $T_D > T_C$, as $T \uparrow$ n_i $\uparrow$, and $J_s \propto n_i$

E. $T_D < T_C$, as $T \uparrow \ n_i \ \downarrow$, and $J_s \propto n_i$

F. $T_C > T_D$ as $T \uparrow, \ n_i \ \downarrow$, and $J_s \propto \sqrt{n_i}$

Gate Previous Year Questions

10. (1 mark) **(EC-GATE 2018)** A p-n step junction diode with a contact potential of $0.65\ V$ has a depletion width of $1\ \mu m$ at equilibrium. The forward voltage (in V) at which this width reduces to $0.6\ \mu m$ is ______

A. 0.72

B. 0.62

C. 0.42

D. 1.02

$$W = \sqrt{\frac{2\epsilon_{si}}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)(V_{bi} - V_{FB})}$$

with $V_{FB} = 0$ $W = W_0 = 1\,\mu m$

$$\frac{W_{FB}}{W_0} = \sqrt{\frac{V_{bi} - V_{FB}}{V_{bi}}}$$

$$\Rightarrow \frac{0.6\,\mu m}{1\,\mu m} = \sqrt{\frac{0.65 - V_{FB}}{0.65}}$$

$$\Rightarrow 0.36 \times 0.65 = 0.65 - V_{FB}$$

$$\Rightarrow V_{FB} = 0.416\,V$$

11. (1 mark) **(EC-GATE 2017)** As shown in figure 4, two Silicon (Si) abrupt p-n junction diodes are fabricated with uniform donor doping concentration of $N_{d1} = 10^{14}\ cm^{-3}$ and $N_{d2} = 10^{16}\ cm^{-3}$ in the n-regions of the diodes, and uniform acceptor doping concentrations of $N_{a1} = 10^{14}\ cm^{-3}$ and $N_{a2} = 10^{16}\ cm^{-3}$ in the p-regions of the diodes, respectively. Assuming $V_R >> V_{bi}$, the ratio $\frac{C_2}{C_1}$ of their reverse bias capacitance for the same applied reverse bias, is _______

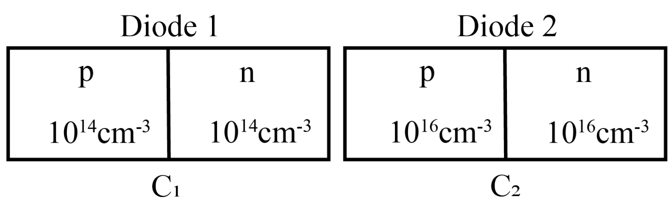


Figure 4: PN diodes - Problem 11

A. 2

B. 5

C. 10

D. 1

$$C_1 = \frac{\epsilon_{Si}}{W}\ F/cm^2$$

$$W \propto \sqrt{\frac{N_a + N_d}{N_a N_d}}$$

$$\frac{C_2}{C_1} = \frac{W_1}{W_2} = \left(\frac{N_{a_1} + N_{d_1}}{N_{a_1} N_{d_1}} \Big/ \frac{N_{a_2} + N_{d_2}}{N_{a_2} N_{d_2}} \right)^{1/2}$$

$$= \left(\frac{\cancel{2\times 10^{14}}}{10^{\cancel{28}\,14}} \Big/ \frac{\cancel{2\times 10^{16}}}{10^{\cancel{32}\,16}} \right)^{1/2} = \sqrt{10^2}$$

$$= 10$$

12. (1 mark) **(EC-GATE 2013)** In a forward biased pn junction diode, the sequence of events that best describes the mechanism of current flow is

    A. injection, and subsequent diffusion and recombination of minority carriers

    B. injection, and subsequent drift and generation of minority carriers

    C. extraction, and subsequent diffusion and generation of minority carriers

    D. extraction, and subsequent drift and recombination of minority carriers

Review lecture videos and slides.
Analyze why other options are wrong.

13. (1 mark) **(EC-GATE 2021)** A silicon P-N junction is shown in the figure 5. The doping in the P region is $5 \times 10^{16}\ cm^{-3}$ and doping in the N region is $10 \times 10^{16}\ cm^{-3}$. The parameters given are

- $Built - in\ voltage\ (\Phi_{bi}) = 0.8\ V$
- $\epsilon_{Si} = 12$

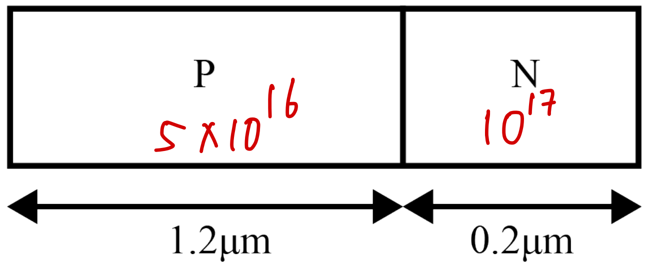


Figure 5: PN Junction - Problem 13

The magnitude of reverse bias voltage that would completely deplete one of the two regions (P or N) prior to the other (*rounded off to one decimal place is*) ______ V

Ans: $8.2\ V$

Range: $8.17\ V - 8.24\ V$

$x_p N_a = x_n N_d \Rightarrow x_p = 2 x_n$

$\therefore$ N region will be fully depleted before P region. W_{dep} when N region is fully depleted is $W = x_p + x_n = 0.4\,\mu m + 0.2\,\mu m = 0.6\,\mu m$

$$0.6 \times 10^{-4} = \sqrt{\frac{2\epsilon_{Si}}{q}\left(\frac{10^{17} + 5\times10^{16}}{10^{17}\times 5\times 10^{16}}\right)(0.8 + V_R)}$$

$$V_R + 0.8 = \frac{0.36\times10^{-8} \times q}{2\times12\times8.85\times10^{-14}} \times \frac{5\times10^{33}}{1.5\times10^{17}} = 9.05$$

$\therefore V_R = 8.25\ V$

14. (1 mark) **(EC-GATE 2019)** In an ideal pn junction with an ideality factor of 1 at $T = 300\ K$, the magnitude of the reverse-bias voltage required to reach 75% of its reverse saturation current (*rounded off to 2 decimal places*) is ______ mV (Use $kT/q = 0.0259\ V$)

Ans: $14.49\ mV$

Range: $14.46\ mV - 14.52\ mV$

Recall $I = I_s\left(e^{qV_a/KT} - 1\right)$

$$0.75\, I_s = I_s\left(\exp\left(\frac{qV_R}{KT}\right) - 1\right)$$

$$V_R = \frac{KT}{q}\ln(1.75)$$

$$= 14.49\ mV$$