Forward bias showing applied F.B voltage.
built-in field.

Numericals: (pn junction under zero applied bias)

1. An abrupt and uniformly doped pn junction has doping levels 19 $N_a = 10^{16}\ cm^{-3}$, $N_d = 10^{15}\ cm^{-3}$ at 300K.

$[n_i = 1.5 \times 10^{10}\ cm^{-3}$, $\epsilon_{si} = \epsilon_0 \times 11.7 = 8.85\times10^{-14}\times 11.7 \approx 10^{-12}]$

Estimate a) Built-in potential
b) Space charge width
c) Peak Electric field.

Soln: 1) For abrupt pn junction,

$$V_{bi} = \frac{KT}{q} \ln\left[\frac{N_a N_d}{n_i^2}\right] \quad ; V_T = 0.0259V \approx 26mV$$

$$= V_T \ln\left[\frac{10^{16}\times10^{15}}{(1.5\times10^{10})^2}\right] = 0.0259 \ln\left[\frac{10^{16+15-20}}{2.25}\right]$$

$V_{bi} = 0.635\ V$ → Built-in voltage.

2) Space charge width (W):

$$W = \sqrt{\frac{2\epsilon_{si}}{q} V_{bi}\left[\frac{N_a+N_d}{N_a N_d}\right]}$$

$$W = \sqrt{\frac{2\times0.635}{1.6\times10^{-19}}\times10^{-12}\times\left[\frac{10^{16}+10^{15}}{10^{16+15}}\right]}$$

$$W = \sqrt{\frac{2\times0.635}{1.6}\times 1.1\times10^{\cancel{16}-12+19-\cancel{16}-15}} = \sqrt{\frac{2.2\times0.635}{1.6}\times10^{-8}}$$

$W = 0.934\times10^{-4}\ cm$

$\boxed{W \approx 0.934\ \mu m}$ → Space charge width

3) $E_m = -\frac{2V_{bi}}{W} = \frac{-2\times0.635}{0.934\times10^{-4}} = -13.597\times10^{3}\ V/cm$

$\boxed{E_m = -13.6\ \frac{KV}{cm}}$ → Peak Electric field

Forward voltage (V)
$V_F \to$ applied F.B voltage.
... Forward bias showing applied built-in field.

2. Calculate V_{bi}, W, x_n, x_p, E_m for a Si abrupt pn junction at 300K with $N_a = 10^{18}\,cm^{-3}$, $N_d = 10^{15}\,cm^{-3}$ 20
$[n_i = 1.5\times10^{10}\,cm^{-3}$, $\epsilon_s = 8.85\times10^{-14}\times 11.7]$

Sol^n: i) $V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right] = 0.0259\times \ln\left[\frac{10^{18}\times10^{15}}{(1.5\times10^{10})^2}\right] = \underline{0.754\ V}$

ii) $W = \sqrt{\frac{2\epsilon_s V_{bi}}{q}\left[\frac{N_a+N_d}{N_a \times N_d}\right]} = \sqrt{\frac{2\times11.7\times8.854\times10^{-14}\times0.754}{1.6\times10^{-19}}\left[\frac{10^{18}+10^{15}}{10^{18}\times10^{15}}\right]}$

$W = 9.88\times10^{-5}\ cm \approx \underline{0.988\ \mu m}$

iii) $|x_n| = \left(\frac{N_a}{N_a+N_d}\right)W = \underline{98.70\times10^{-6}\ cm}$

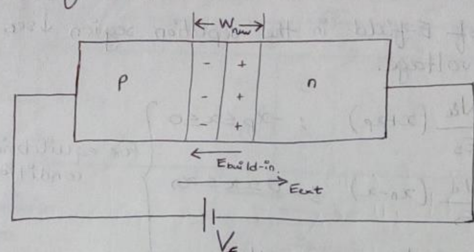
$|x_p| = \left(\frac{N_d}{N_a+N_d}\right)W = \underline{9.87\times10^{-8}\,cm}$

iv) $E_m = -\frac{2V_{bi}}{W} = \underline{-15.26\times10^3\ V/cm}$

3. An abrupt Si pN junction at zero bias is doped uniformly with $10^{16}\,cm^{-3}$ atoms of Boron on pside (N_a) and $10^{15}\,cm^{-3}$ atoms of Phosphorus on nside (N_d). at $T=300K$.
a) Calculate the Fermi level on each side of the junction w.r.t intrinsic Fermi level.
b) Sketch the equilibrium energy-band diagram for the junction and determine V_{bi} from the diagram and the results of part (a).
c) Calculate V_{bi}, and compare the results to part (b).
d) Determine x_n, x_p and the peak electric field for this junction.

—x—

01. Analysis of pn junction under Forward bias. 20/7/14



$E_{build-in}$ → Build-in E-field

E_{ext} → Externally applied E-field due to applied Forward voltge (V)

V_F → applied F.B voltage.

fig 1: A pn junction under Forward bias showing applied E-field and internal built-in field.

- Under forward-bias, 1) a pn junction is not in thermal equilibrium.
  2) Depletion region width reduces. (W ↓ses)
  3) Equilibrium Fermi energy level changes.
  4) Net Electric field reduces (since applied E-field opposes the built-in E field).

- The Energy bands at forward bias condition shift due to applied voltage ⇒ The Fermi level on n side E_{Fn} moves upwards and above E_{Fp} due to energy of applied voltage.

⇒ ∴ Total barrier potential reduces:-

$$V_{total} = V_{bi} - V_F \quad — ①$$

- Space charge width (W) reduces with ↑se in V_F:

$$\boxed{W_{nw} = \sqrt{\frac{2\epsilon_s (V_{bi} - V_F)}{q}\left[\frac{N_a + N_d}{N_a N_d}\right]}} \quad — ②$$

why?

↳ As net E-field is lowered below thermal equilibrium value due to applied F.B 'V_F', ⇒ thus depletion space charge width (W) decreases. ∴ W ↓ses with an ↑sing applied Forward bias V_F

· Electric field for pn junction under Forward bias →

· The magnitude of E-field in the depletion region ↓ses with an applied forward bias voltage.

The equations

1) $E = -\frac{qN_a}{\epsilon_s}(x+x_p)$; $-x_p \le x \le 0$

2) $E = -\frac{qN_d}{\epsilon_s}(x_n-x)$; $0 \le x \le x_n$

3) $E_{max} = -\frac{qN_a}{\epsilon_s} \cdot x_p = \frac{-qN_d}{\epsilon_s} x_n$

For equilibrium conditions

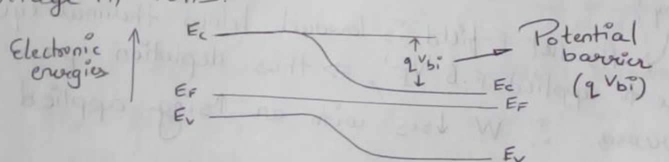
Equations (1),(2),(3) are valid and are linear functions of distance through space-charge region.

· Since x_n and x_p reduce with forward bias voltage and Maximum E-field due to applied F.B occurs at junction (ie $x=0$)

$$\therefore \boxed{E_m = -\frac{2}{W}(V_{bi} - V_F)} \quad - (3)$$

Note (R):

. When external bias is applied to the junction, the potential barrier is raised or lowered from the value of the built-in or contact potential, and the Fermi levels on either side of the junction are shifted w.r.t to each other by an energy in eV numerically equal to the applied voltage in volts.



EBD of pn junction under equilibrium.

24/7/14

Analysis of pn junction under forward bias contd...

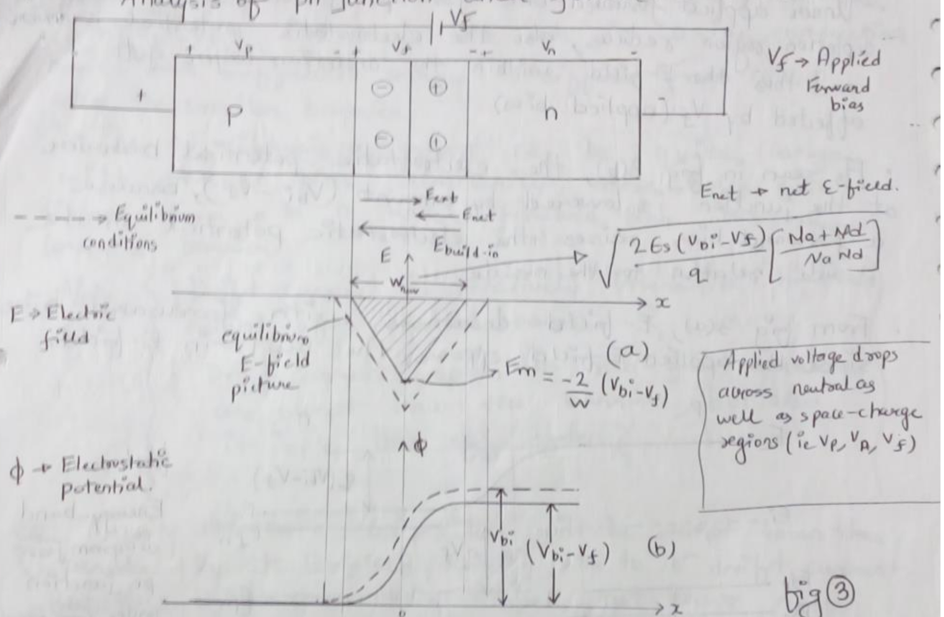


fig ③

- Analysis steps:

Assumptions:
1) Boundary between space-charge and neutral regions is abrupt.
2) pn junction is abrupt
3) p and n regions are uniformly doped.

Additional assumptions:
1) Applied bias is small (ie quasi-equilibrium approximation)
2) p and n region → Quasi-neutral regions
3) Entire applied voltage (V_f) drop's across the Depletion / Space-charge region (ie V_p & V_n << V_{bi} so that $\boxed{V_{bi} \approx V_f \text{(applied voltage)}}$)

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04.

- Under applied forward bias for pn junction, width of depletion region reduces, also the electrostatic potential barrier and thus the E-field within the depletion layer gets affected by V_f (applied bias).

- As seen in fig 3(b), the electrostatic potential barrier at the junction is lowered by amount $(V_{bi} - V_f)$, because a forward bias raises the electrostatic potential on the p-side relative to the n-side.

- From fig 3(a), E-field decreases with forward bias, since the applied E-field opposes the built-in E-field.

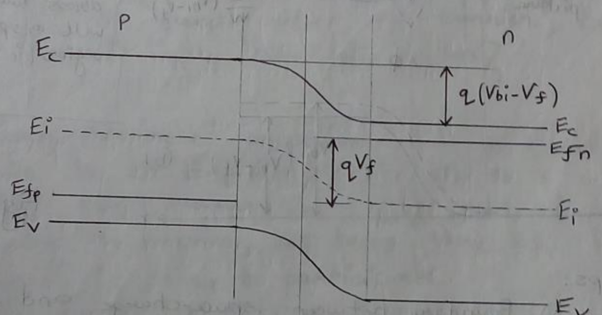


fig4: Energy-band diagram for pn junction under forward bias.

- The separation of energy bands is a direct function of the electrostatic potential barrier at the junction.
- The height of electron energy barrier is $q(V_{bi}-V_f)$ for forward bias conditions. Thus the energy bands are separated less $[q(V_{bi}-V_f)]$ under forward bias than at equilibrium.
- Under forward bias, the Fermi level on the n-side E_{fn} is above E_{fp} by energy 'qV_f'.

NOTE: On EBD, we show electronic energies going up, since more negative regions will be shown with higher energies, ie why E_{fn} is above E_{fp}

- Under forward bias, the potential barrier is lowered to $(V_{bi} - V_f)$, and many more e^-s in n side conduction band have sufficient energy to diffuse from n to p over the smaller barrier.

∴ The e^- diffusion current can be quite large with forward bias. Similarily, more holes can diffuse from p to n under forward bias becoz of lowered barrier.

- Note: { Drift current is relatively insensitive to the height of potential barrier }
  { Drift current implies → how fast carriers are swept down the barrier, but also it imply how ~~off~~ often }

eg: Minority carriers e^- on p side will be swept down the barrier by the E-field, giving rise to e^- drift current. But this drift current is small not becoz of the size of the barrier, but becoz there are very few minority e^-s in p side to participate.

∴ Diffusion currents dominate over drift in a forward bias.

Under forward bias in summary, there is smaller potential barrier, reduced E-field, diffusion of majority carriers and drift due to minority carriers.

Note: The injection of holes into the n-region means that these holes are minority carriers. Similarily, the injection of e^-s into p-region means that these e^- are minority carriers.

—x—

Analysis of pn junction under reverse-bias

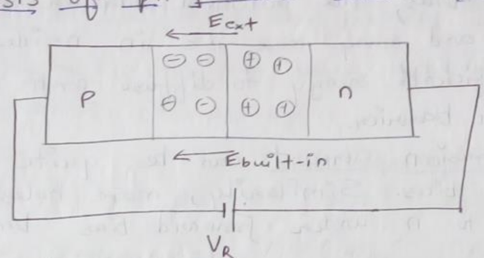


fig 5: A pn junction under reverse bias showing applied E-field and internal built-in E-field.

Under Reverse bias
1) pn junction – no longer in equilibrium
2) Depletion region width increases (W ↑ses)
3) Equilibrium Fermi energy level changes
4) Net Electric field increases

- Effect on Fermi levels ⇒ Fermi level on the p-side E_{Fp} is above the fermi-level on the n side ie E_{Fn}.
- The difference between the two fermi-levels is equal to the applied reverse voltage in units of energy.

⇒ ∴ Total potential barrier :-

$$\boxed{V_{total} = V_{bi} + V_R} \quad — (1).$$

where V_{bi} → Built-in potential in thermal equilibrium.

$$\frac{KT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

07.

· Space-charge width (w) and E-field under Reverse Bias:-

· Magnitude of E-field ↑ses above equilibrium value for applied reverse bias voltage.

· E-field ↑ses ⇒ that the number of +ve & -ve charges ↑se if E-Field ↑ses. and this is possible if W ↑ses.

· ∴ Space-charge width W ↑ses, with an ↑sing V_R.

$$\boxed{W_{new} = \sqrt{\frac{2\epsilon_s (V_{bi}+V_R)}{q}\left[\frac{N_a+N_d}{N_a N_d}\right]}} \quad — ②$$

Also, the maximum E-field for a pn junction under reverse-bias is

$$\boxed{E_m = \frac{-2(V_{bi}+V_R)}{W}} \quad — ③$$

Note: (Rep)

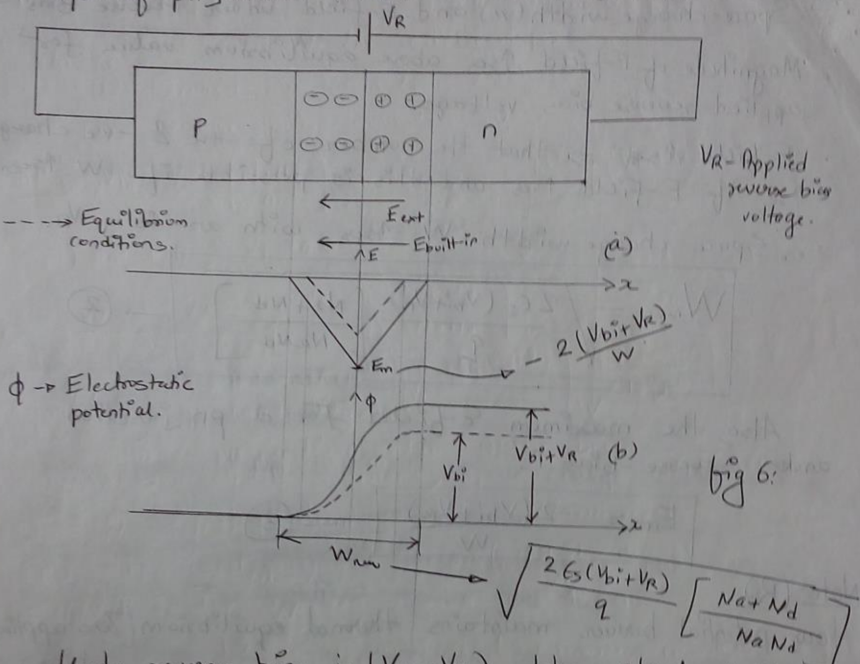
How potential barrier maintains thermal equilibrium (Zero applied bias)

· The potential barrier seen by the e's, for example, holds back the large concentration of e's in the n-region and keeps them from flowing into the p-region.

· Similarly, the potential barrier seen by the holes holds back the large concentration of holes in the p region and keeps them from flowing into the n-region.

Thus, potential barrier in a pn junction under zero applied bias maintains thermal equilibrium

Analysis of pn junction under reverse bias contd --- 08.



- Under reverse bias ie $(V = -V_R)$ the electrostatic potential of the p-side is depressed relative to the n-side and the potential barrier at the junction becomes larger $(V_{bi}+V_R)$. (from 6 (b))
- With reverse bias, the Electric field at the junction is increased by the applied field, which is in the same direction as the equilibrium Field. (from 6(a))
- Under reverse bias, the energy bands are separated by more than $q(V_{bi}+V_R)$, whereas E_{fp} is 'qV_R' ~~times~~ joules higher than E_{fn}.

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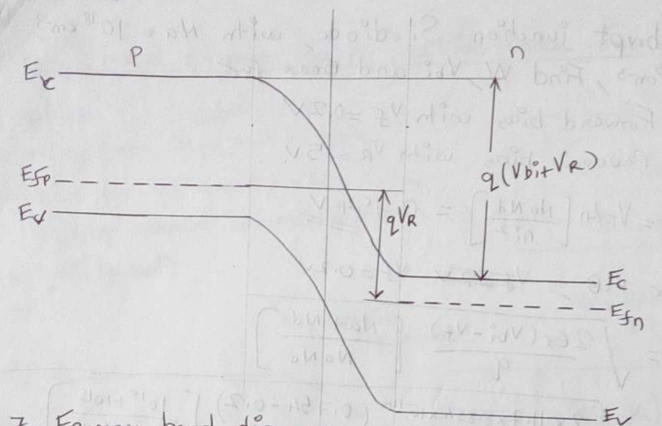


fig 7: Energy band diagram for a pn junction under reverse bias.

- Under reverse bias conditions, space-charge width W ↑ses, also the total potential barrier has increased.
- Thus, the ↑sed potential barrier means that the E-field in the depletion region has ↑sed.
- For reverse bias, the potential barrier becomes so large ie $(V_{bi}+V_R)$ that virtually no e^- in the n side CB or holes in the p side V.B have enough energy to surmount it.

Therefore, the diffusion current is usually negligible for reverse bias pn junction.

- The only current which flows is due to drift mechanism of minority charge carriers.

So, under Reverse bias, drift current dominates diffusion current.

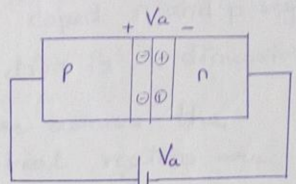
—x—

01 30/07/14

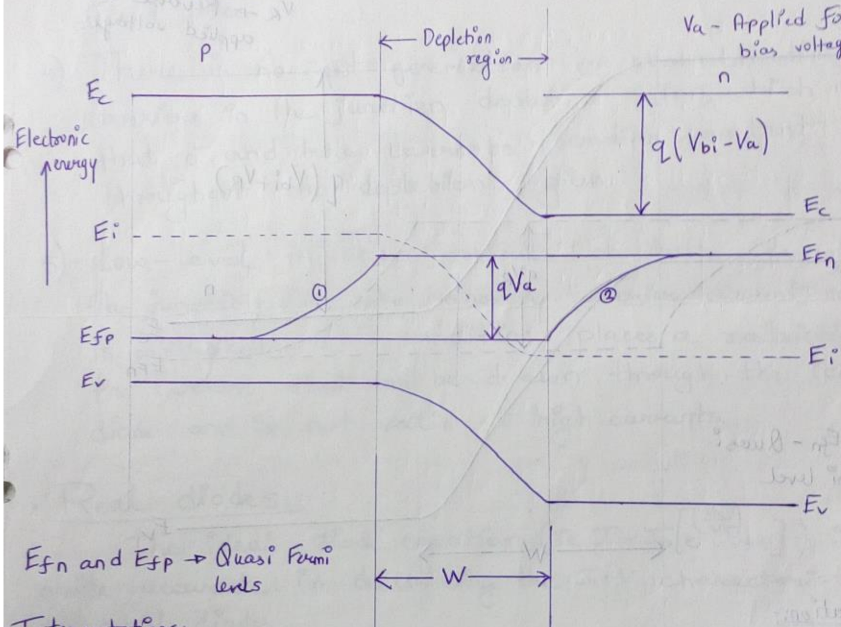
Energy band diagram of pn junction under forward bias:-

Assumptions:

1) No voltage drops in neutral p and n regions
2) Injection level in n and p sides is low;
ie (majority carrier concentration is not disturbed).



Va - Applied Forward bias voltage



E_{Fn} and E_{Fp} → Quasi Fermi levels

Interpretations:

① and ② ⇒ Indicates the presences of excess carriers

- $E_{Fn} - E_{Fp} = qV_a$
- E_{Fn} and E_{Fp} remains constant in the depletion region.
- Splitting of quasi fermi level in the neutral n and p regions indicates the presences of excess carriers in these regions.

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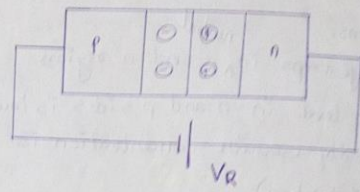
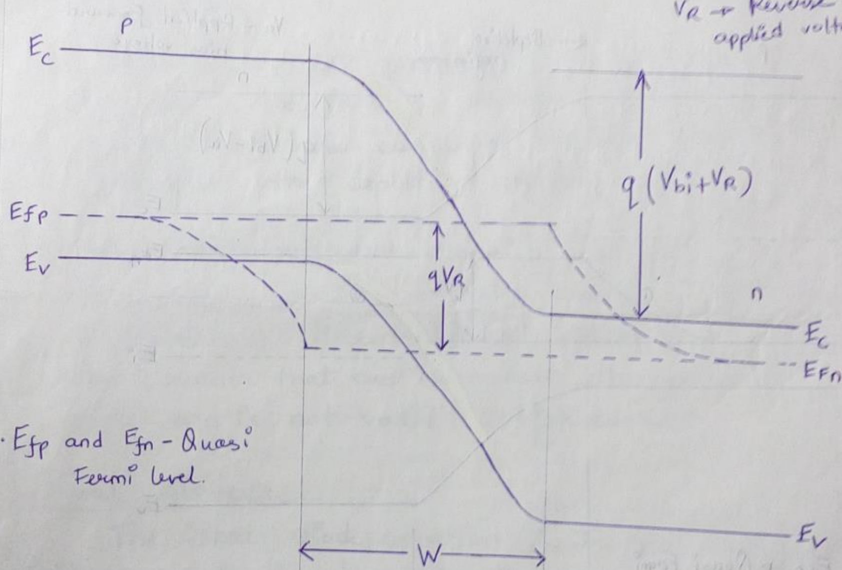
Energy band diagram of a pn junction under Reverse Bias. 02



$V_R \rightarrow$ Reverse applied voltage.



· E_{Fp} and E_{Fn} - Quasi Fermi level.

· Interpretation:-

- E_{Fn} in n-region is displaced from E_{Fp} in neutral p-region by qV_R.
- E_{Fn} and E_{Fp} are constant throughout the depletion region.
- Splitting of quasi-Fermi level in the neutral n and p regions indicates the extraction of minority carriers from these regions.