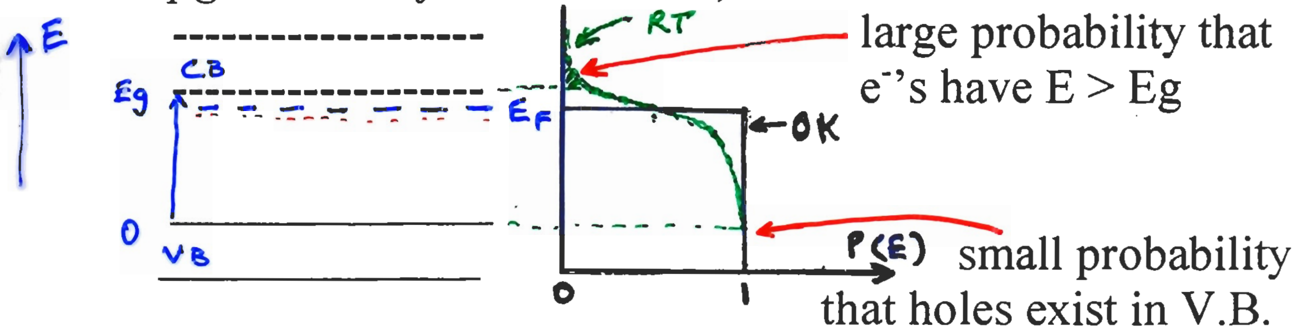
Position of Fermi Level E_F in Doped Semiconductors

i) intrinsic – mid-gap, $E_g/2$

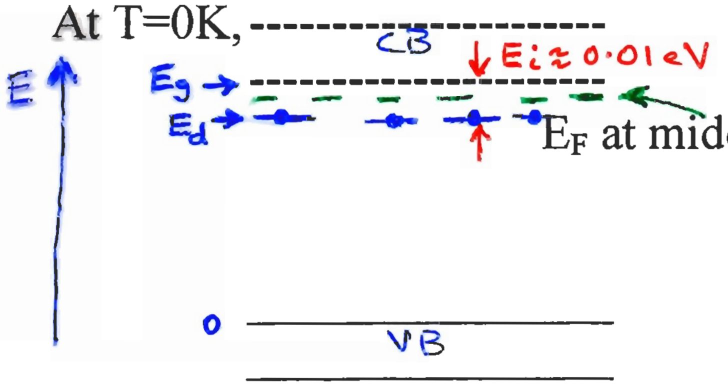
ii) **n-type** : characterised by $n(C.B.) >> p(V.B.)$
($10^{22}\ m^{-3}$) ($10^{10} m^{-3}$)

Accounted for by E_F moving up to bottom of C.B. (*see JA pg. 124-127 for more detail*)



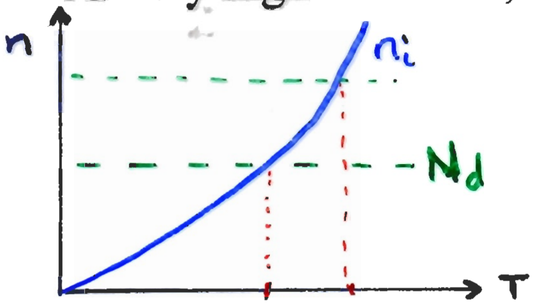
At usual temperatures, the picture above holds true.

At T=0K,



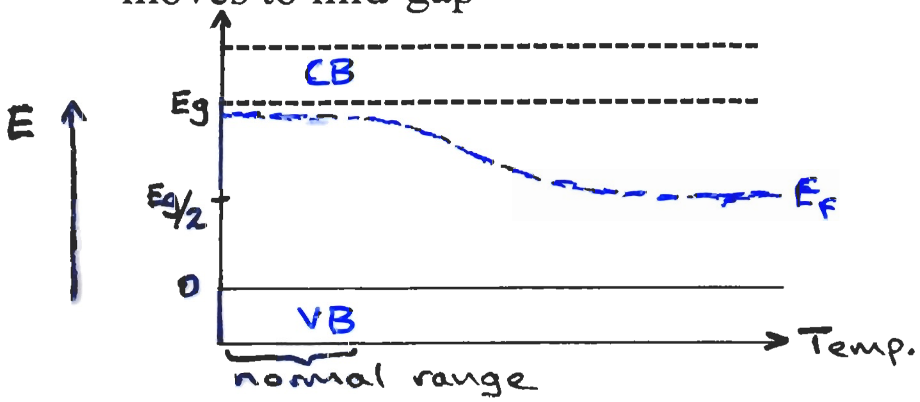
Possibility of V.B. electron crossing E_g is negligible. As T ↑ from 0K, first electrons to reach C.B. come from donor levels, - so behaves like intrinsic semiconductor with gap reduced to E_i and E_F located at the middle of this gap.

At very high T>300°C,

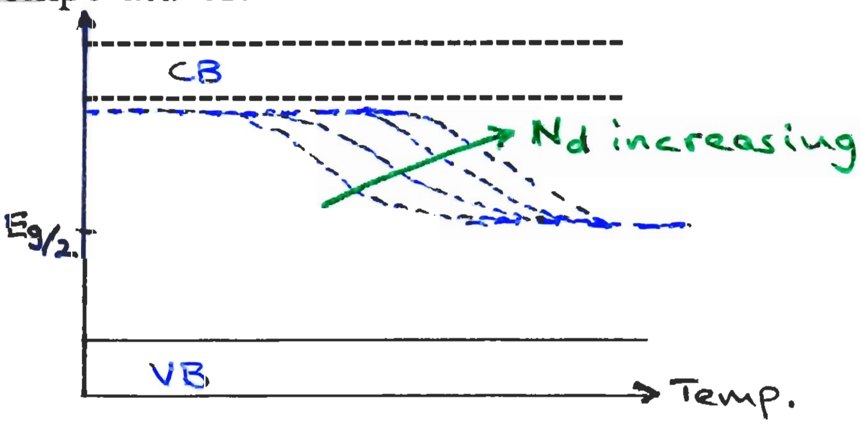


All donors ionised
$n = N_d +$ 'intrinsic'
electrons from V.B.
Latter significant when $kT >> E_g$

As 'intrinsic' carriers become more dominant, as T ↑ E_F moves to mid-gap



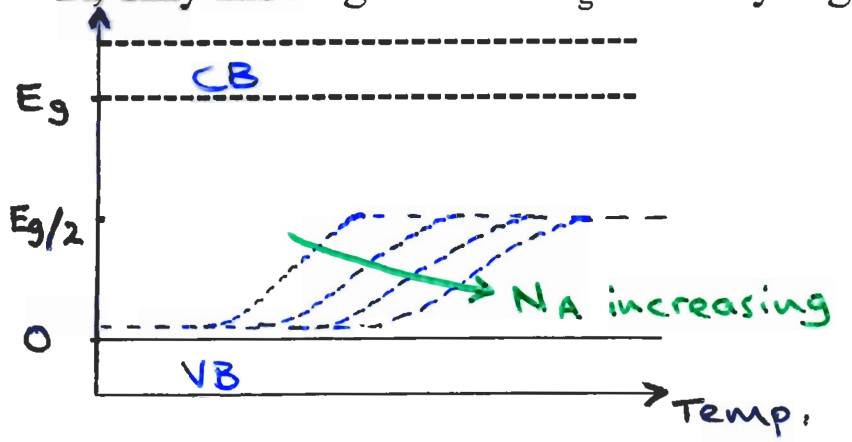
As Nd ↑ , 'intrinsic' behaviour sets in at higher temperatures.



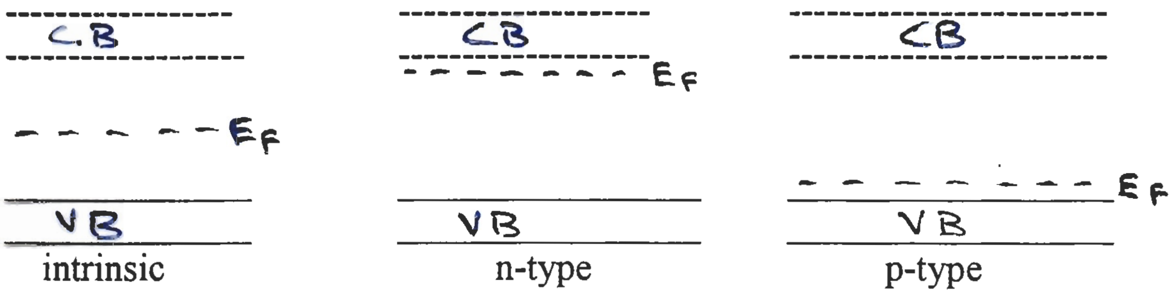
Precise position of E_F is by calculation. σ_i can be higher than σ_n at very high temperatures, so not true extrinsic behaviour.

P-type

By similar arguments, E_F well below mid-gap and near V.B., only moving towards $E_g/2$ at very high T's.



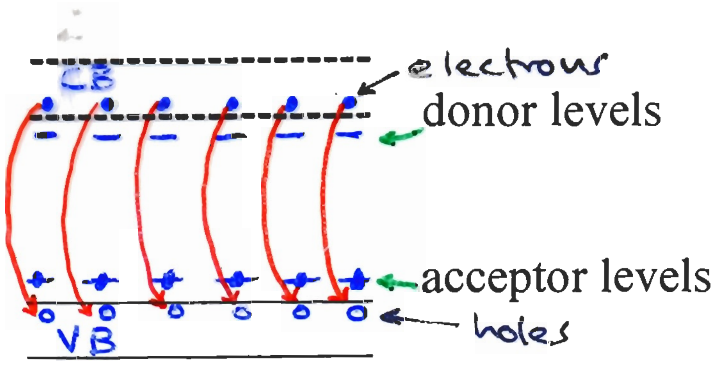
Summary: (at RT)



Compensation Doping

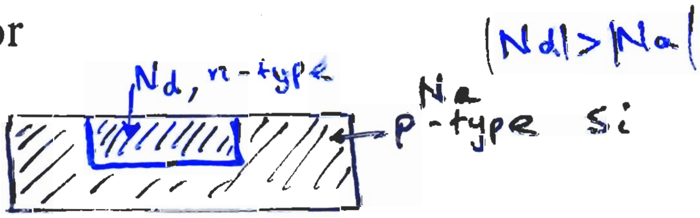
Occurs when semiconductor is doped with *both* acceptors and donors

Compensation occurs when the extra e^- of donors fall into incomplete bands of acceptors, so that no e^- or holes produced (-recombination)

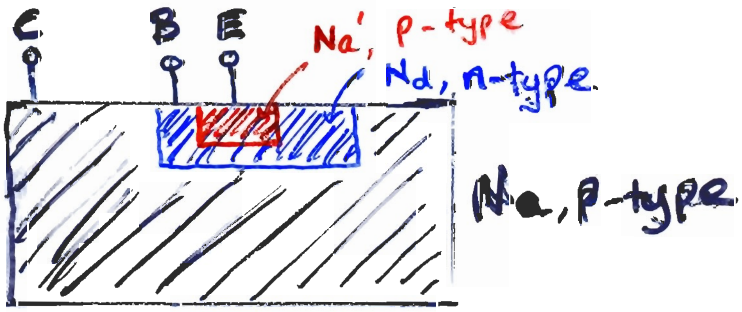


e.g. planar diode, transistor

planar diode



p-n-p transistor
usually
|Na'|>|Nd|>|Na|



so there are semiconductors containing N_d and N_a – need to know σ for device design.

e.g. Si doped with $10^{21} m^{-3}$ acceptors (N_a), i.e. p-type initially
Then doped with 10^{22} m^{-3} donors (N_d).
All the 10^{21} holes from acceptors **recombine** with 10^{21} electrons from donors, leaving the material
n-type $10^{22} - 10^{21} = 9.\ 10^{21}$ m^{-3} – still a high concentration.

Net density $n(9.\ 10^{21}) < N_d\ (10^{22})$ because of the presence of acceptors – called **compensation**.

Therefore magnitude of $|N_d - N_a|$ determines net carrier density and the sign (+ or -) gives the majority carrier type.

$N_d > N_a$ – n-type

$N_a > N_d$ – p-type

General Case

$$
\begin{array}{rcccl}
\text{acceptors} & \rightarrow & N_a \quad N_d & \leftarrow & \text{donors} \\
\text{electrons} & \rightarrow & n \quad p & \leftarrow & \text{holes}
\end{array}
$$

temp.

For electrical neutrality, assuming that T is such that dopants are completely ionised:

negative charge = positive charge

$$n + N_a = p + N_d \qquad (3)$$

always, $np = n_i^2$ (4)

Using (3) in (4) $n + (N_a - N_d) = n_i^2/n$

$$n^2 + (N_a - N_d)n - n_i^2 = 0$$

$$n = \frac{(N_d - N_a) \pm \sqrt{(N_d - N_a)^2 + 4n_i^2}}{2}$$

$$n = \frac{(N_d - N_a)}{2} + \frac{(N_d - N_a)\sqrt{1 + \left(\frac{2n_i}{(N_d - N_a)}\right)^2}}{2}$$

carriers from dopants   intrinsically generated carriers

For p-type level, use eqn. (4)

$p = n_i^2/n$

can always use this relationship – especially when $n_i \sim (N_d - N_a)$

Case 1: Extrinsic (doped) material

$(N_d - N_a) >> n_i$

e.g. $10^{22} - 10^{21} >> 10^{16}$

2^{nd} term under $\sqrt{}$ $\rightarrow 1$, and

$$n \approx \frac{(N_d - N_a)}{2} + \frac{(N_d - N_a)\sqrt{1}}{2} = N_d - N_a$$

$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_d - N_a}$$

$\frac{10^{32}}{10^{22}}$

e.g. $n = 9.\ 10^{21}\ m^{-3}$, $p \approx 10^{\cancel{22}\ 10}\ m^{-3}$

If $N_a > N_d$, $p = N_a - N_d$ and

$$n = \frac{n_i^2}{N_a - N_d}$$

Case 2: Near Intrinsic Semiconductor

- made by doping extrinsic material with just sufficient opposite type dopant to attempt to fully compensate and hence produce a net carrier concentration due to dopants of near zero – carriers then nearly all come from e-h pairs from intrinsic process.

i.e. $n_i >> |N_d - N_a|$

'1' is negligible in 2^{nd} term under √ , therefore

$$n \approx \frac{(N_d - N_a)}{2} + \frac{(N_d - N_a)\sqrt{\left(\frac{2n_i}{(N_d - N_a)}\right)^2}}{2}$$

$$n \approx \frac{(N_d - N_a)}{2} + n_i \approx n_i = p$$

Practically it is difficult to get the dopants to cancel exactly to get this condition

e.g. if $10^{22}m^{-3}$ donors and want to make it intrinsic ($\sim 10^{16}m^{-3}$), we need acceptors of $1.000001 \times 10^{22}m^{-3}$ – impossible to control to this accuracy!