B] High injection effect:

- The ambipolar transport equation that we have used to determine the minority charge concentration assumed Low injection.
- As V_{BE} ↑ses, the injected minority carrier concentration may approach, or even become larger than, the majority carrier concentration.
- If we assume quasi-charge neutrality (Remember, that $\boxed{\rho \approx 0}$ (space-charge) $\Rightarrow \boxed{\delta_p = \delta_n}$), then the majority carrier hole concentration in ptype base at $x=0$ will ↑se in fig(a), becoz of excess holes.

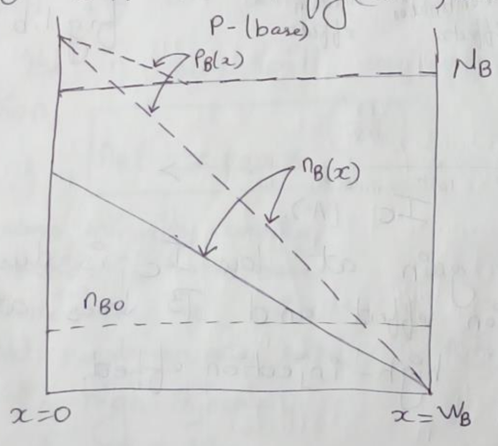

fig 1.a: Minority and majority carrier concentrations in the base under low and high injection.

⇒ Two effects occurs in the BJT at high injection:

a) The 1st effect is a reduction in emitter injection efficiency.

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- Since, the majority carrier hole concentration at $x=0$ ↑ses with high injection (more holes are injected back into emitter bcoz of F.B V_{BE}).
- An ↑se in hole injection causes an ↑se in I_{Ep} current, & an ↑se in I_{Ep} reduces the emitter injection efficiency $\gamma = \frac{I_{En}}{I_{En}+I_{Ep}}$; $\gamma = \frac{1}{\left(1+\frac{I_{Ep}}{I_{En}}\right)}$

b) The common emitter current gain ↓ses, with high injection. (β)

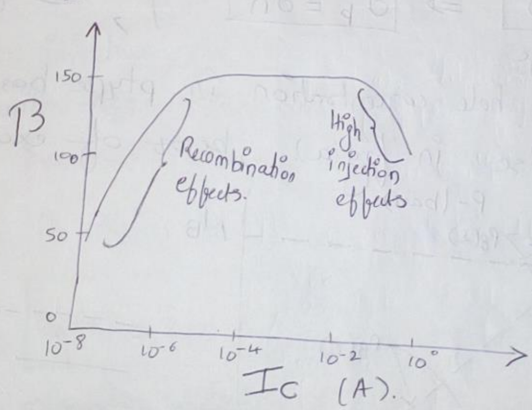

fig 1.b β Vs I_C

- The low current gain at low I_C is due to small recombination effect and β ↓ses at high I_C is due to high-injection effect.

ICT

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- At low injection, the majority carrier hole concentration is at $x=0$ for npn BJT is,

$$p_B(0) = p_{B0} = N_B$$

and the minority carrier electron concentration is,

$$n_B(0) = n_{B0}\, e^{\left(\frac{V_{BE}}{V_T}\right)}$$

The pn product is,

$$p_B(0)\, n_B(0) = p_{B0}\, n_{B0}\, e^{\left(\frac{V_{BE}}{V_T}\right)} \quad — (1)$$

- At high injection, eqn (1) still applies. However, $p_B(0)$ will also ↑se, and for very high injection it will ↑se at nearly the same rate as $n_B(0)$.
- The ↑se in $n_B(0)$ will asymptotically approach the function,

$$\boxed{n_B(0) \simeq n_{B0}\, e^{\left(\frac{V_{BE}}{2V_T}\right)}} \quad — (2)$$

- The excess minority carrier concentration in the base and hence the I_C, will ↑se at a slower rate with V_{BE} in high injection than low injection. This effect is shown in fig 1.c.

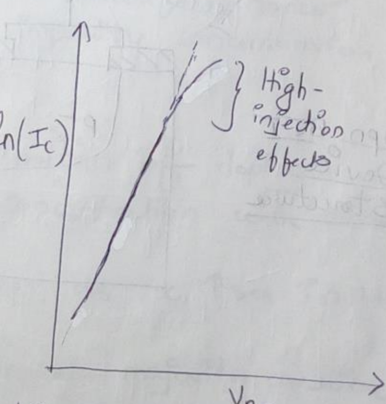
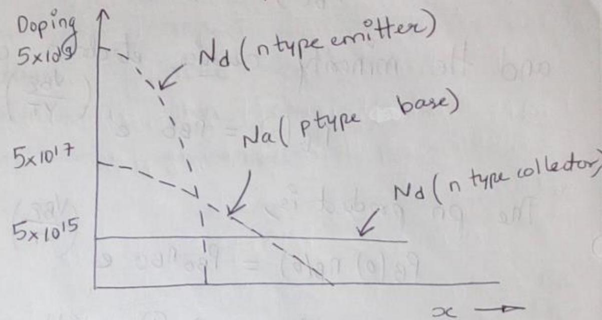


fig 1.c: $\ln(I_C)$ vs V_{BE}

C] Non-uniform Base doping:

· In analysis of BJT, we assumed uniformly doped regions. However, uniform doping rarely occurs.

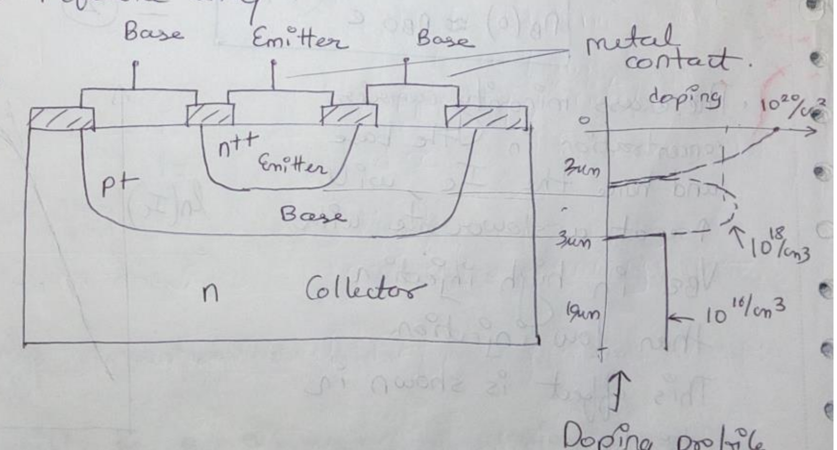
For understanding (Extra):
(We can start with a uniformly doped ntype substrate, diffuse acceptor atoms from the surface to a compensated ptype base, & then diffuse donor atoms from the surface to form a doubly compensated ntype emitter. The diffusion process results in a non-uniform doping profile).



fig(1.a): Impurity concentration profiles of a double-diffused npn BJT

For Reference only

npn BJT Device structure



Doping profile (highly non-uniform)

...Expt. (Practice Layouts in Lab):-
Tools: Microwind/Electric.

Extra!

Q. Non-uniform impurity concentration leads to an induced electric field?

⇒ Consider a non-uniformly doped semiconductor with donor impurity atoms. If the semiconductor is in thermal equilibrium, then fermi-level is constant throughout the semiconductor as shown in fig(b).

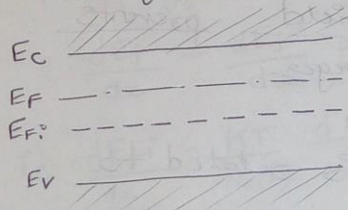


fig a: EBD of a uniformly doped semiconductor.

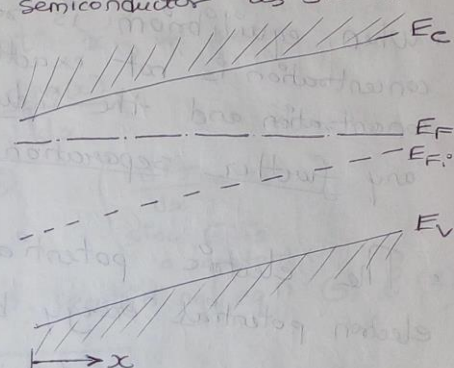


fig b: EBD for a semiconductor in equilibrium with a nonuniform donor impurity concentration.

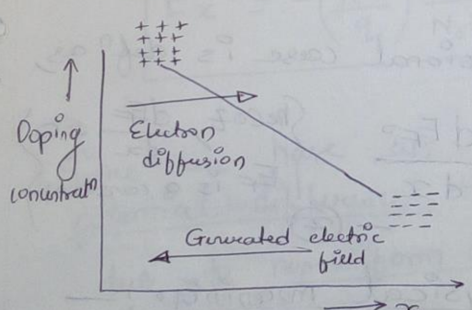


fig c: Variation of doping concentration with distance.

- The doping concentration ↓ses as x ↑ses in this case.

ie → There will be a diffusion of majority carrier e⁻s from the region of high concentration to

Extra 22R

region of low concentration, which is in +x direction

- The flow of e^-s leaves behind +vely charged donor ions.
- The separation of +ve and -ve charge induces an E-field i.e. directed to oppose the diffusion process
- When equilibrium is reached, the mobile carrier concentration is not exactly equal to fixed impurity concentration and the induced E-field prevents any further separation of charges.

- The electric potential (ϕ) is related to electron potential energy by charge (-q),

$$\phi = \frac{1}{q}(E_F - E_{Fi}) \quad \text{--- (1)}$$

The E-field for one-dimensional case is def^n as,

$$E_x = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_{Fi}}{dx} \quad \text{--- (2)}$$

{because, $\frac{dE_F}{dx} = 0$, E_F is a constant}

Rule: ⟸ Equation (2)'s physical meaning :—

* [If intrinsic fermi level (E_{Fi}) changes as a function of distance through a semiconductor in thermal equilibrium, an Electric field exists in the semiconductor]

Expr. (Practice Layouts in Lab):-
Tools: Microwind / ...

- If we assume a quasi-neutrality condition (in which the electron concentration is almost equal to donor impurity concencentration), then 23R

$$n_0 \approx n_i \exp\left(\frac{E_f - E_{fi}}{KT}\right) \approx N_d(x) \quad -③$$

Solving for $E_f - E_{fi}$ $\Rightarrow$

$$E_f - E_{fi} = KT \ln\left[\frac{N_d(x)}{n_i}\right] \quad -④$$

Now differentiate eqn ④ w.r.t 'x', we get

$$\frac{dE_f}{dx} - \frac{dE_{fi}}{dx} = \frac{KT}{N_d(x)} \frac{dN_d(x)}{dx}$$

ie $$-\frac{dE_{fi}}{dx} = \frac{KT}{N_d(x)} \frac{dN_d(x)}{dx} \quad -⑤$$

$\left(\frac{dE_f}{dx} \approx 0\right.$ since E_f is a constant$\left.\right)$

Thus, E-field can be written, combining eqn (5) & (2),

$$\boxed{E_x = -\left(\frac{KT}{q}\right)\frac{1}{N_d(x)}\frac{dN_d(x)}{dx}} \quad -⑥$$

$\Rightarrow$ Since we have an E-field, there will be a potential difference through the semiconductor due to non-uniform doping.

$\Downarrow$

This Result we are gonna use in **Non-uniform base doping concept!**

Tools: Microwind/Electric.

Tool: a TCAD Lab on nanohub.org (toTool)

> nanohub.org   FETToy, CNT Mobility, NanoMOS

* **Non-uniform base doping** ------ (continue)   24

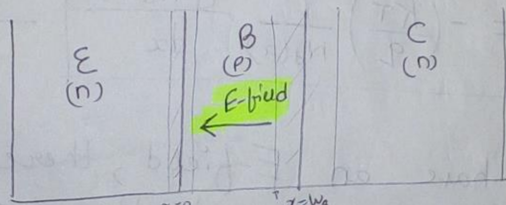
For a ptype base region (npn BJT) in thermal equilibrium, we can write

$$J_p = q\mu_p N_a E - qD_p \frac{dN_a}{dx} = 0 \quad -(i)$$

(J_p → Hole current density)

then,
$$E = \left(\frac{KT}{q}\right)\frac{1}{N_a}\frac{dN_a}{dx} \quad -(ii)$$
(Refer earlier eqn (6))

According to the example of fig (1.a), $\frac{dN_a}{dx}$ is -ve, and hence due to non-uniform doping in base, an induced E-field is in -ve x-direction.



Electron's are injected from n type emitter into the base and the minority carrier base electrons begin diffusing towards the collector region.

The induced E-field in the base, produces a force on the electrons in the direction towards the collector.

- The induced E-field, then AIDS the flow of minority carriers across the base region. This E-field is called "accelerating E-field". 25
- This E-field will produce a drift component of current ie in addition to existing diffusion current.
- Since minority carrier electron concentration varies across the base, drift current density will not be a constant.
- The induced electric field in the base due to non-uniform base doping will alter the minority carrier distribution through the base, such that the sum of drift and diffusion current will be a constant.

—— x ——