BIPOLAR TRANSISTOR

Bibliography:

- ***H. Mathieu***, « Physique des semi-conducteurs et des composants électroniques », 4° édition, Masson 1998.
- ***D.A. Neamen***, « semiconductor physics and devices », McGraw-Hill, Inc 2003.
- ***P. Leturcq et G.Rey***, « Physique des composants actifs à semi-conducteurs », Dunod Université, 1985.
- ***J. Singh***, « semiconductors devices :an introduction », McGraw-Hill, Inc 1994.
- ***Y. Taur et T.H. Ning***, « Fundamentals of Modern VLSI devices », Cambridge University Press, 1998.
- ***K.K. Ng***, « complete guide to semiconductor devices », McGraw-Hill, Inc 1995.
- ***D.J. Roulston***, « Bipolar semiconductor devices », McGraw-Hill, Inc 1990.

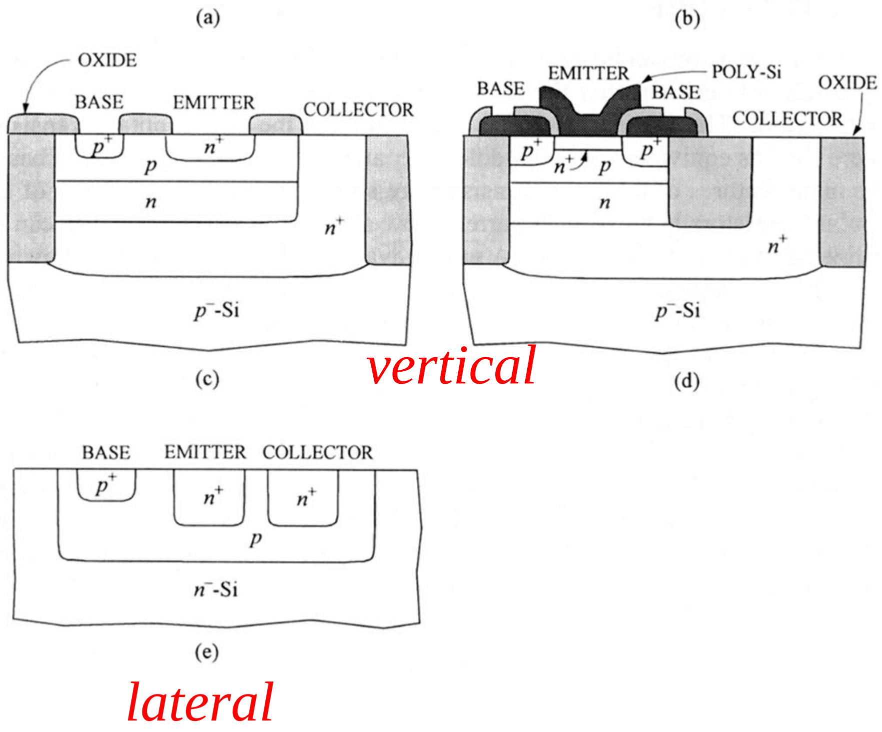
Plan

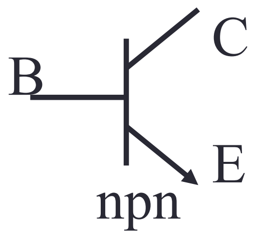
- Geometry
- Principle of operating
- Static characteristics
- Ebers-Moll Equations
- Static parameters (gain…)
- Second order effects
- Switching performances
- Transistor in HF domain
- Hetero-junction Bipolar Transistor (HBT or TBH)

Geometry

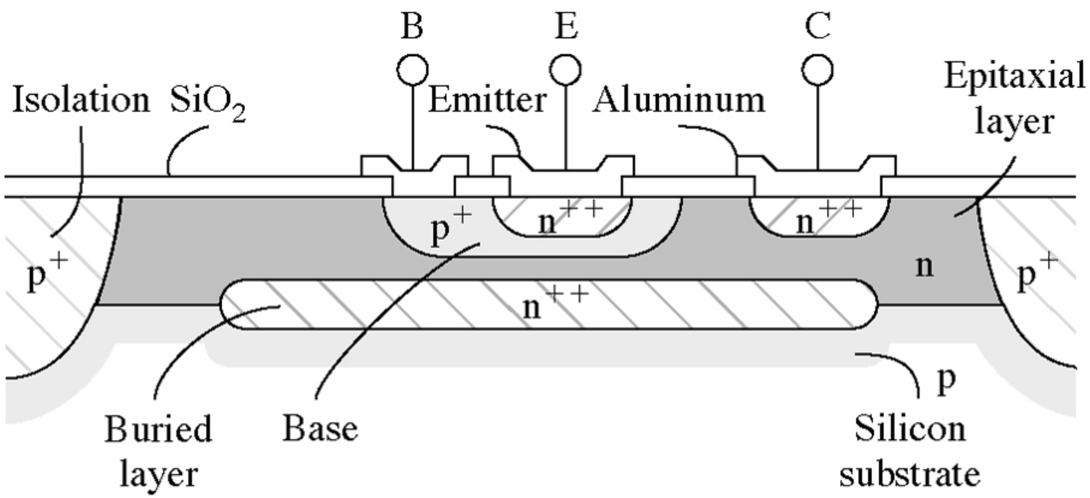
- Geometry:
  - Lateral
  - Vertical

- For digital circuits, *vertical design*





Geometry for IC

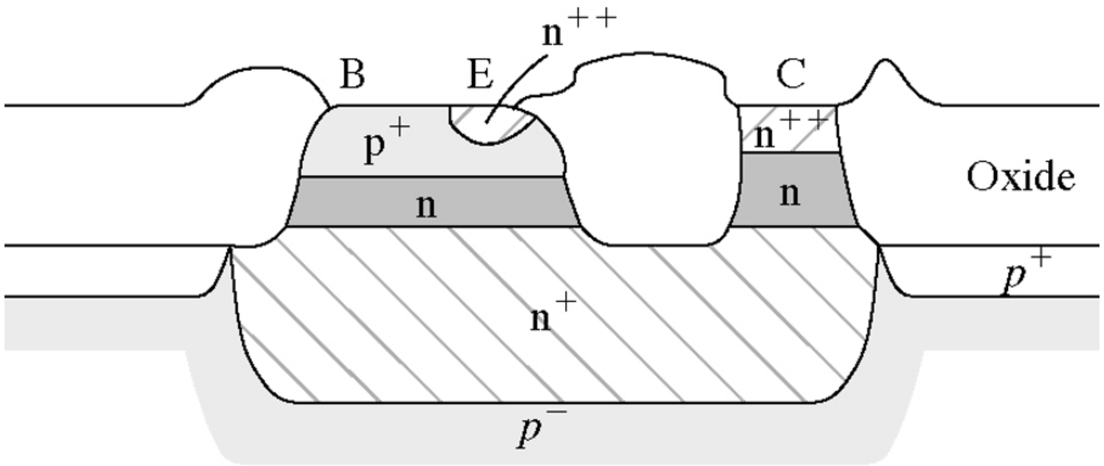


Conventional npn transistor

(a)

Muller et Kamins, « device electronics for IC »,2nd Ed., Wiley, 1986

Geometry with insulating oxide



(b)

Muller et Kamins, « device electronics for IC »,2nd Ed., Wiley, 1986

BJT always present: why?

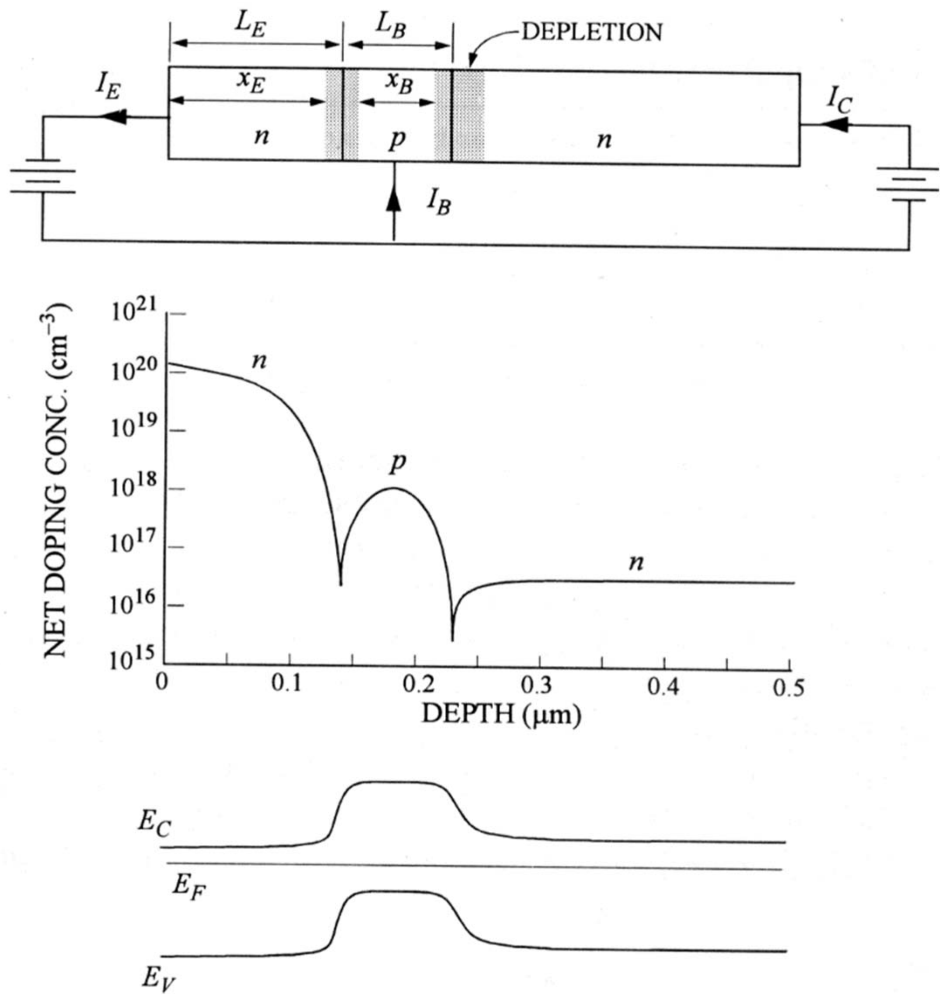
- speed
- Low noise
- High gain
- Low output resistance

→ Analogue amplifier

- Still present in mobile phone (analog part)
- Low density, mainly in power stage
- BiCMOS

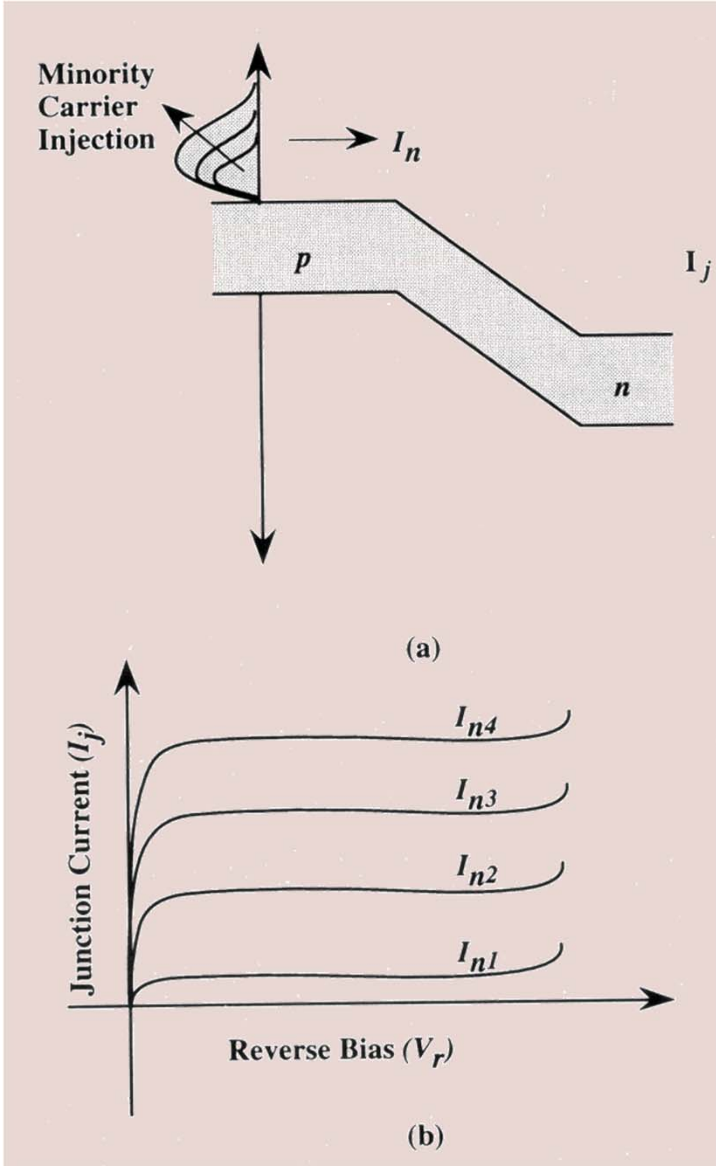
Working principle

- 2 PN Junctions with one common region (base)
  - The first Junction (EB) will inject carriers
  - The second one (CB) will collect carriers
- The base must be thin (lower than diffusion length)



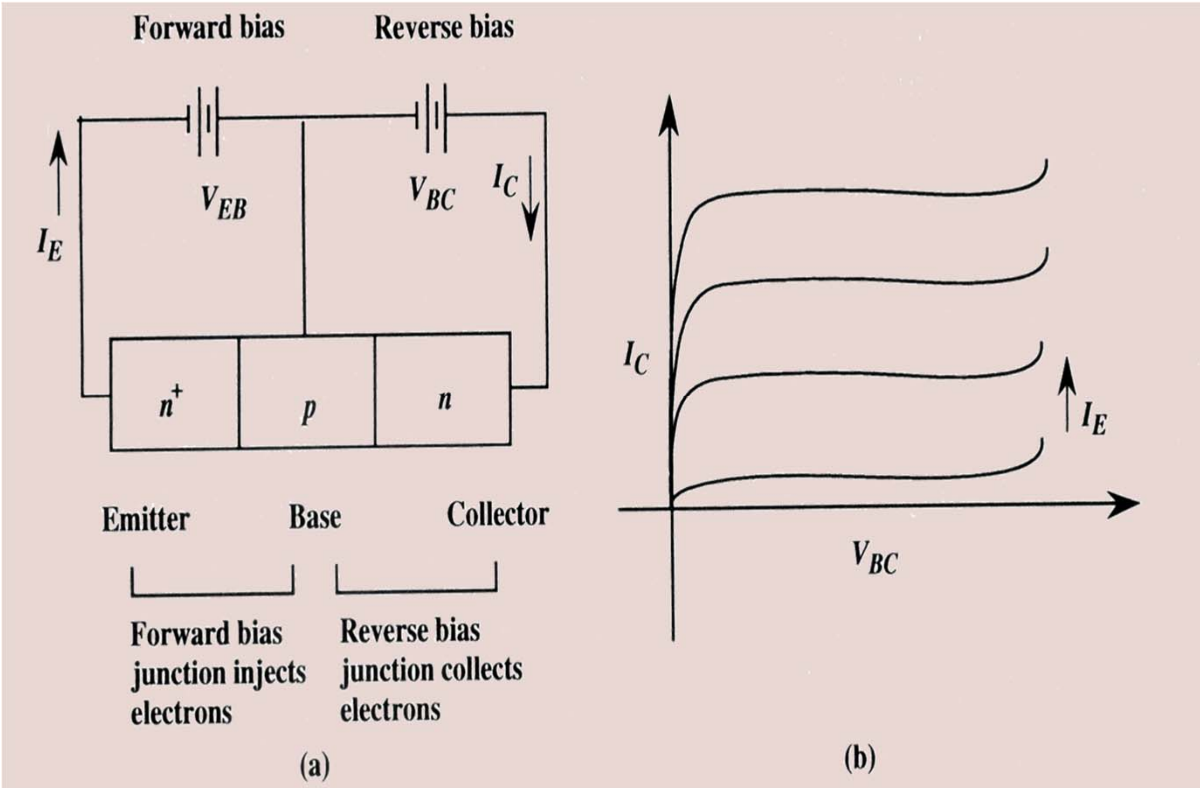
Working principle

- Reverse biased Junction:
  - Low current due to empty tank , reservoir.
  - By modifying the filling of the tank, we can modulate the collected current (collector)
  - We fill the reservoir (the base) par a forward bias of the EB junction.

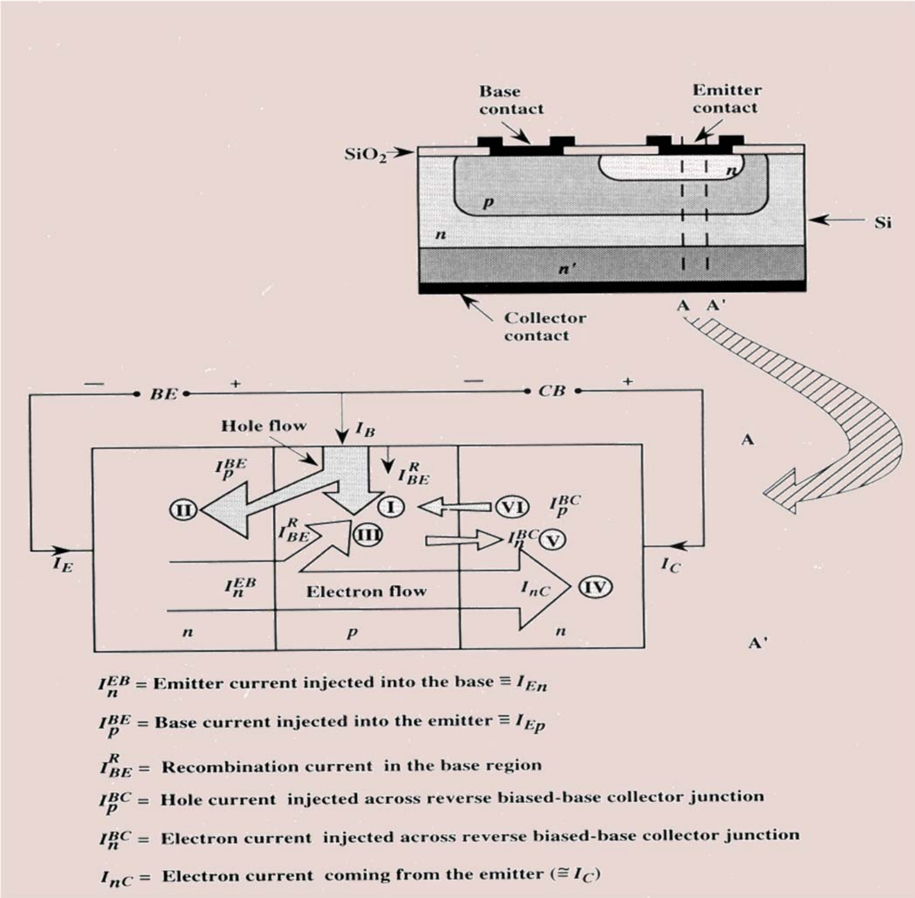


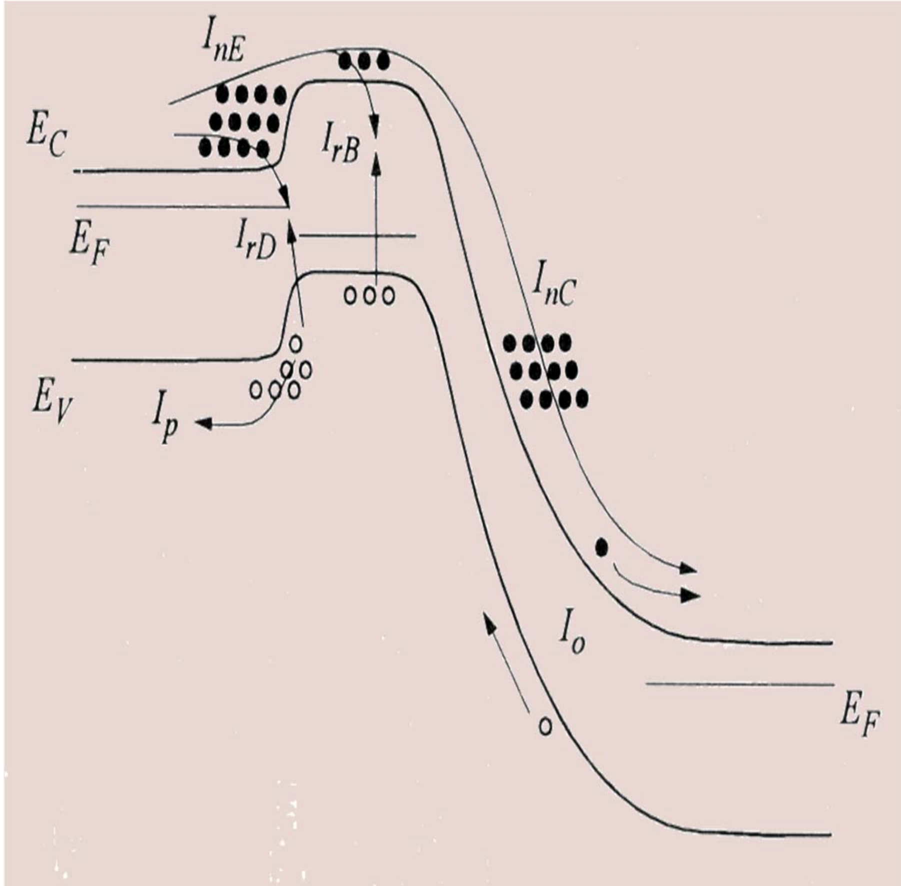
Working principle

- The reverve biasing CB junction creates a favorable electric field for the collect
- Conditions:
  - Thin base:
    - Avoid recombination effects
  - Ligthly doped base compared to emitter
    - favors one type of injected carriers (better injection efficiency)



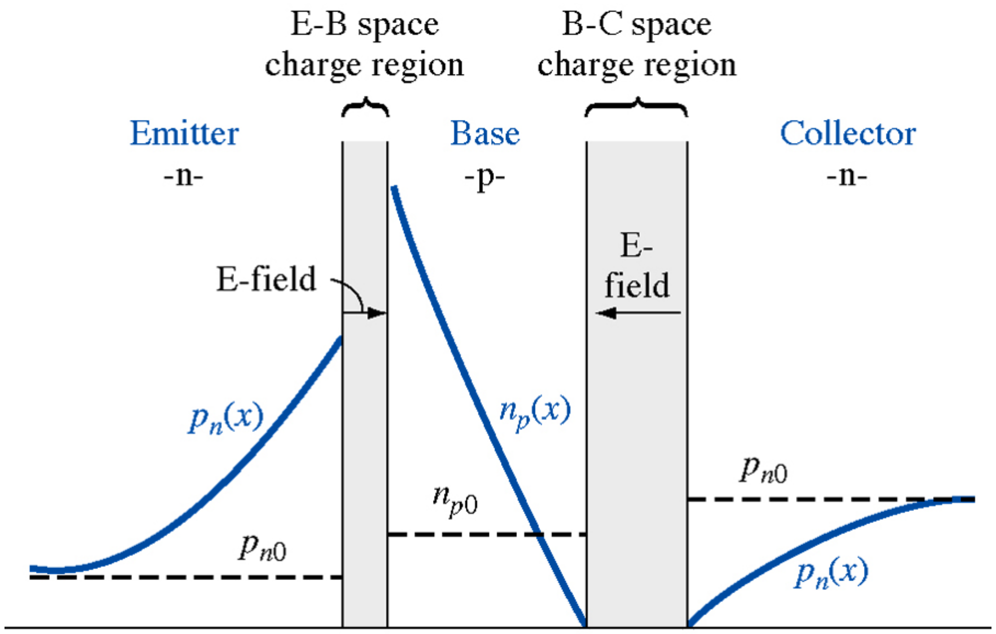
Statics characteristics





NPN Transistor

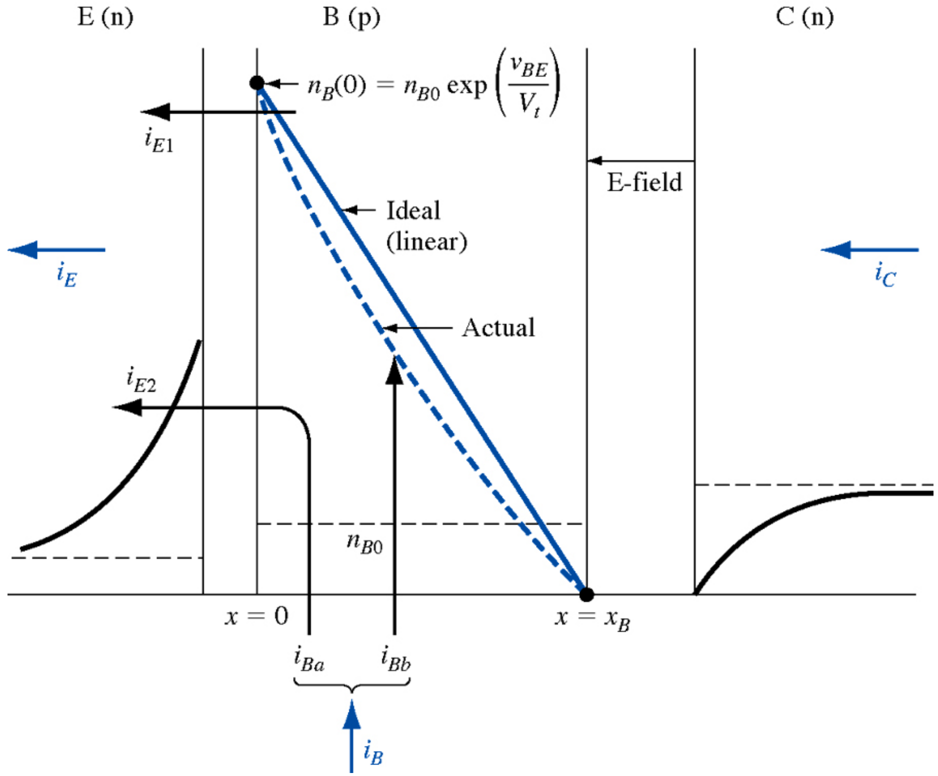
Minority carrier distribution in a forward biased npn transistor



(b)

With recombination

ideal



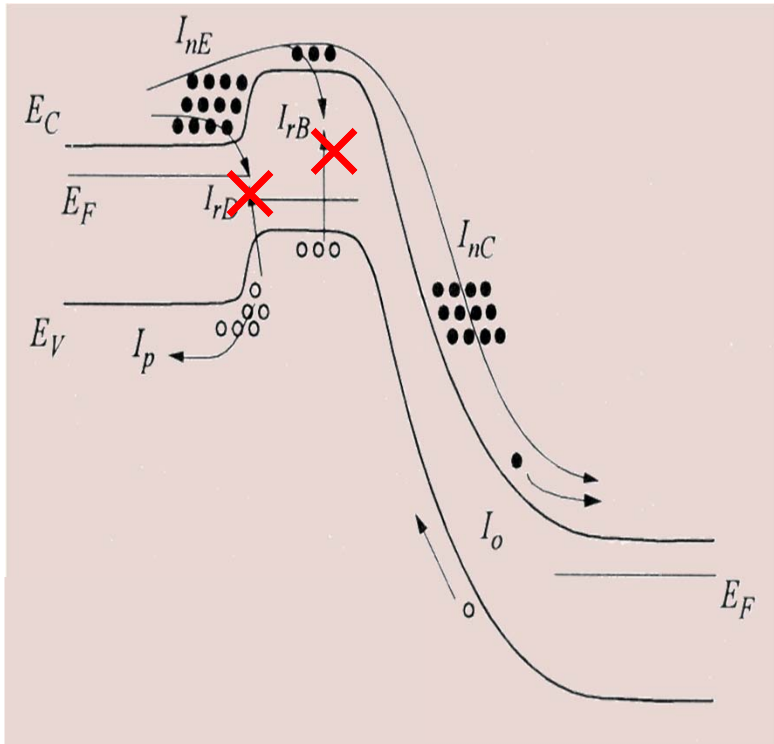
Statics characteristics + simplifying hypotheses

No recombination in the Base ! (✕)

1D Approximation

Homogeneous doping in the Base

Low Injection



NPN Transistor

Current components in the NPN Transistor

- In the neutral Base region:
  - Fundamental equation

$$J_P = eD_P\left[p(x)\times\frac{\mathrm{E}}{kT}-\frac{dp(x)}{dx}\right]$$
$$J_N = eD_N\left[n(x)\times\frac{\mathrm{E}}{kT}+\frac{dn(x)}{dx}\right]$$

$$\Rightarrow \quad p\frac{J_n}{eD_n}-n\frac{J_p}{eD_p}=\frac{d(p.n)}{dx}$$

- and $J_n >> J_p \quad , \quad n << p$

$$\Rightarrow \quad p\frac{J_n}{eD_n}=\frac{d(p.n)}{dx}$$

- Integrating from E-B to C-B:

avec $n_p * p_p = p_n * n_n = n_i^2 \exp(\frac{eV_A}{kT})$

$$\rightarrow \quad J_n = -eD_{nb}n_{iB}^2\frac{\left[\exp(\frac{eV_{BE}}{kT})-\exp(\frac{eV_{BC}}{kT})\right]}{\int_{E'}^{C'} p(x)dx}$$

- We obtain:

$$J_n = -eD_{nb}n_{iB}^2\frac{\left[(e^{\frac{eV_{BE}}{kT}}-1)-(e^{\frac{eV_{BC}}{kT}}-1)\right]}{\int_{E'}^{C'} p(x)dx}$$

- In forward active regime, J_n is negative (e⁻ toward *positive x*)

Current components in the NPN Transistor

$$J_n = -eD_{nb}n_{iB}^2 \frac{\left[(e^{\frac{eV_{BE}}{kT}}-1)-(e^{\frac{eV_{BC}}{kT}}-1)\right]}{\int_{E'}^{C'} p(x)dx} = -\left[\frac{eD_{nb}n_{iB}^2}{\int_{E'}^{C'} p(x)dx}(e^{\frac{eV_{BE}}{kT}}-1) - \frac{eD_{nb}n_{iB}^2}{\int_{E'}^{C'} p(x)dx}(e^{\frac{eV_{BC}}{kT}}-1)\right]$$

and: $\int_{E'}^{C'} p(x)dx = N_{A_B} \times W_{Beff}$ in the case of uniform base doping

So: $$I_n = -A_E\left[\frac{en_{iB}^2 D_{nb}}{N_{A_B}W_{Beff}}(e^{\frac{eV_{BE}}{kT}}-1) - \frac{en_{iB}^2 D_{nb}}{N_{A_B}W_{Beff}}(e^{\frac{eV_{BC}}{kT}}-1)\right] = -I_{Sn}\left[(e^{\frac{eV_{BE}}{kT}}-1)-(e^{\frac{eV_{BC}}{kT}}-1)\right]$$

with : $I_{Sn} = A_E \frac{en_{iB}^2 D_{nb}}{N_{A_B}W_{Beff}} = A_E \frac{en_i^2}{G_B}$ Saturation current of electrons in the PN narrow junction (or without recombination in the Base).

$G_B = \frac{n_i^2}{n_{iB}^2}\frac{N_{A_B}}{D_{nb}}W_{Beff} = \frac{n_i^2}{n_{iB}^2}\frac{p}{D_{nb}}W_{Beff}$ Gummel number in the Base (s/cm^4)

Current components in the NPN Transistor

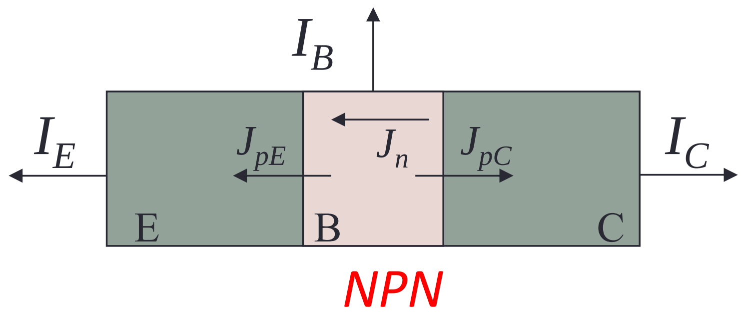
- Emitter current
- Collector current

$$J_{pE} = -J_{spE}\left(\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right)$$

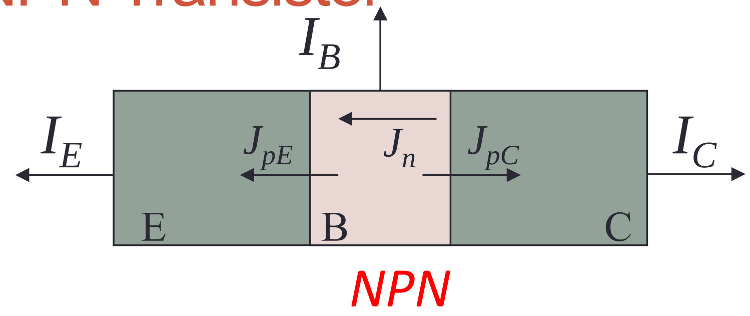
$$J_{pC} = J_{spC}\left(\exp\left(\frac{eV_{BC}}{kT}\right) - 1\right)$$

- We get:

$$I_E = I_{pE} + I_n$$
$$I_C = +I_{pC} - I_n$$
$$I_B = -I_C - I_E = -I_{pE} - I_{pC}$$



Current components in the NPN Transistor



- And :

$$I_E = I_n + I_{pE} = -[I_{sn} + I_{spE}](\exp\frac{eV_{BE}}{kT} - 1) + I_{sn}(\exp\frac{eV_{BC}}{kT} - 1)$$

$$I_C = -I_n + I_{pC} = +I_{sn}(\exp\frac{eV_{BE}}{kT} - 1) - [I_{sn} - I_{spC}](\exp\frac{eV_{BC}}{kT} - 1)$$

$$I_B = -I_E - I_C = -I_{pE} - I_{pC} = +I_{spE}\left(\exp(\frac{eV_{BE}}{kT}) - 1\right) - I_{spC}\left(\exp(\frac{eV_{BC}}{kT}) - 1\right)$$

Statics characteristics

- Forward active region:
  - E-B (forward) and C-B (reverse)

$$I_E = -\left(\frac{Ae^2 n_i^2 D_{nB}}{Q_B + Q_S} + I_{SpE}\right)\exp\frac{eV_{BE}}{kT} = -(I_{Sn} + I_{SpE})\exp\frac{eV_{BE}}{kT}$$

$$I_B^* = -I_E - I_C = -I_{SpE}\exp\frac{eV_{BE}}{kT}$$

$$I_C = +\left(\frac{Ae^2 n_{iB}^2 D_{nB}}{Q_B + Q_S}\right)\exp\frac{eV_{BE}}{kT} = I_{Sn}\exp\frac{eV_{BE}}{kT} = \frac{Aen_{iB}^2 D_{nB}}{N_{A_B} W_{Beff}}\exp\frac{eV_{BE}}{kT} = \frac{Aen_i^2}{G_B}\exp\frac{eV_{BE}}{kT}$$

Gummel number concept

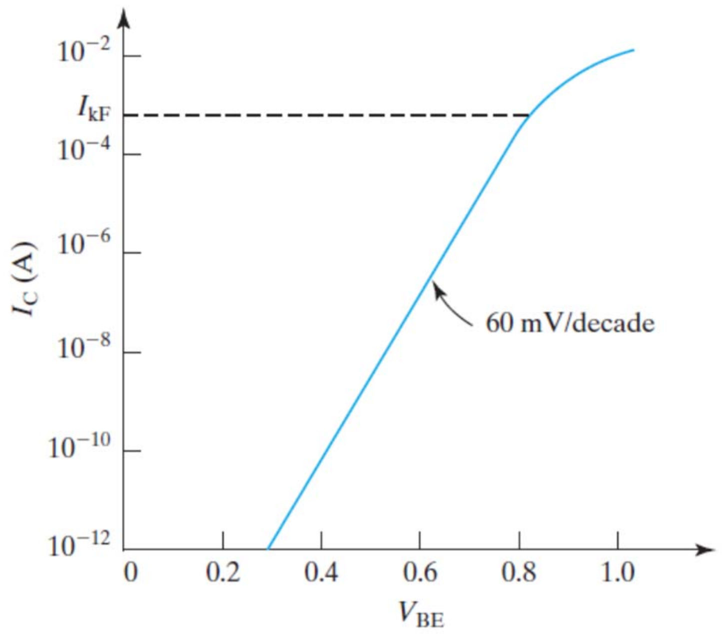
$$I_C = \frac{Aen_{iB}^2 D_{nB}}{N_{A_B} W_{Beff}} \exp\frac{eV_{BE}}{kT} = \frac{Aen_i^2}{G_B} \exp\frac{eV_{BE}}{kT}$$

$$\ln(I_c) = \ln(\frac{Aen_i^2}{G_B}) + \frac{e}{kT} V_{BE}$$

The concept of a Gummel number simplifies the I_C model because G_B contains all the subtleties of transistor design that affect I_C:

$$G_B = \frac{n_i^2}{n_{iB}^2} \frac{N_{A_B}}{D_{nb}} W_{Beff}$$

$$\tau_{tB} = \frac{W_{Beff}^2}{2D_{nB}}$$



Statics characteristics

- Emitter injection efficiency:

$$\gamma_E = \frac{I_n}{I_{pE}} = \frac{I_{Sn}\exp(eV_{BE}/kT)}{I_{SpE}\exp(eV_{BE}/kT)} = \frac{I_{Sn}}{I_{Sp}}$$

- DC common base current gain:

$$\alpha = \frac{I_C}{I_E} = \frac{1}{1+\frac{J_{Sp}.(Q_B+Q_S)}{e^2 n_i^2 D_{nB}}} = \frac{I_{Sn}}{I_{Sn}+I_{Sp}} < 1 \quad \text{but close to 1}$$

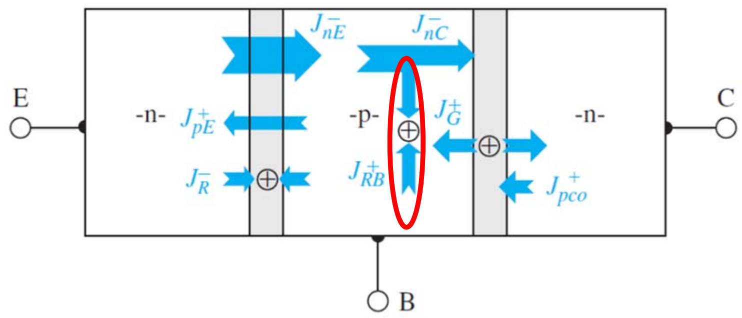
- DC common emitter current gain :

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} = \frac{I_{Sn}}{I_{Sp}} = \gamma_E$$

NB:if we neglect recombination process β and γ_E are equivalent

Statics characteristics

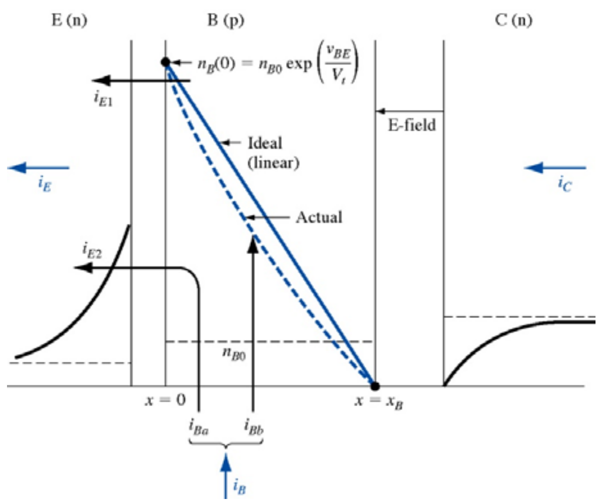
- Base transport factor:
  - Take into account recombination in neutral base region (Qs is the excess charge in the base)

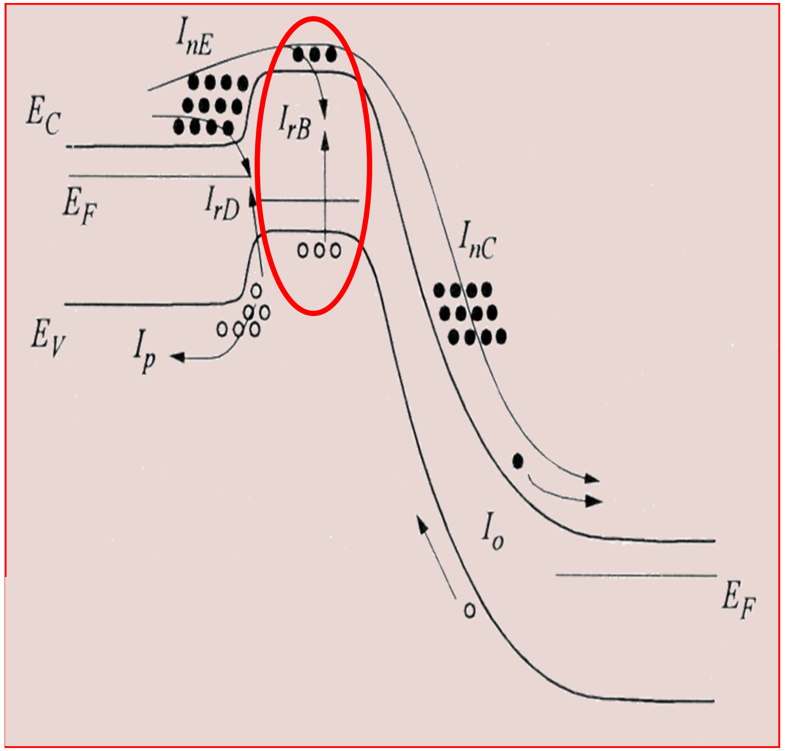


$$I_{rB} = \frac{Q_s}{\tau_n} \approx \frac{AeW_{B_{eff}}(n_p(0) - n_p)/2}{\tau_n} \Rightarrow I_{rB} \approx \frac{AeW_{B_{eff}}}{2\tau_n} x \frac{n_i^2}{N_{A_B}} x \exp\left(\frac{eV_{BE}}{kT}\right)$$

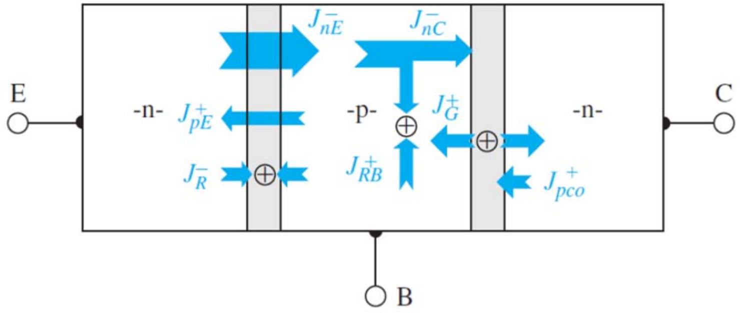
$$I_C = \frac{Q_s}{\tau_{tB}} = \frac{Aen_{iB}^2 D_{nB}}{N_{A_B} W_{Beff}} \exp\frac{eV_{BE}}{kT}$$

$$\delta = \frac{I_C}{I_{rB}} = \frac{2L_n^2}{W_{B_{eff}}^2} = \frac{\tau_n}{\tau_{tB}} > 1$$



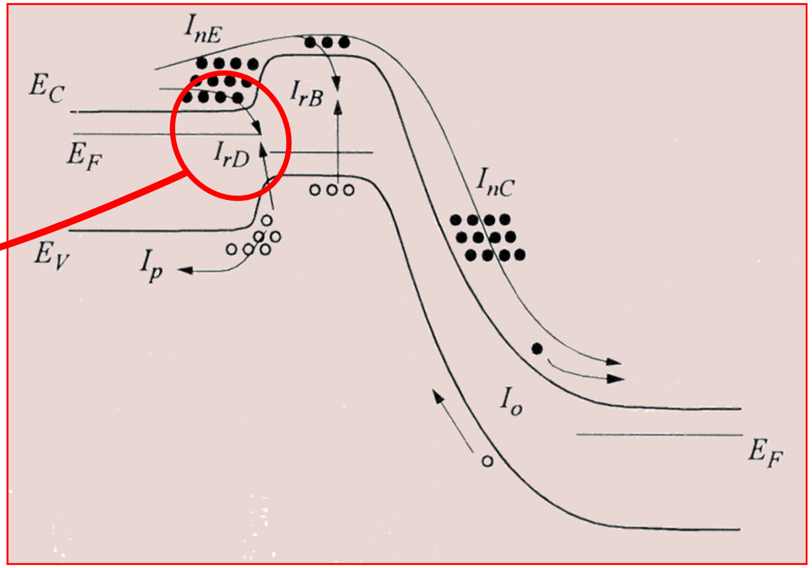


Statics characteristics



- Recombination factor:
  - Take into account recombination in depleted base region

$$I_{rD} = \frac{Aen_i}{2\tau} W_T \exp\left(\frac{eV_{BE}}{2kT}\right)$$



with W_T, width of E-B space charges.

When we add up all the contribution to the base current we get:

$$I_B = I_B^* + I_{rB} + I_{rD}$$

Statics characteristics

- The common emitter gain can be expressed as:

$$\frac{1}{\beta}=\frac{I_B}{I_C}=\frac{I_B^*+I_{rB}+I_{rD}}{I_C}=\frac{1}{\gamma_E}+\frac{1}{\delta}+\frac{I_{rD}}{I_C}$$

- I_B intrisic base current (no recombination)
- I_{rB} recombination current in the neutral base region
- I_{rD} recombination current in the depletion zone of EB junction

Modern Transistors:

$$\gamma_E=\frac{I_{Sn}}{I_{SpE}}=\frac{n_{iB}^2 D_{nB}}{n_{iE}^2 D_{pE}}\times\frac{N_{D_E}}{N_{A_B}}\times\frac{W_{Eeff}}{W_{Beff}}\approx\frac{N_{D_E}}{N_{A_B}}\approx 1000$$

$$\delta=\frac{2L_n^2}{W_{B_{eff}}^2}\approx\frac{2x10^{-5}}{10^{-8}}\approx 2000$$

$$\frac{I_C}{I_{rD}}=\frac{I_{Sn}\exp\frac{eV_{BE}}{kT}}{I_{GR}^0\exp\left(\frac{eV_{BE}}{2kT}\right)}=\frac{\frac{Aen_i^2 D_{nB}}{N_{A_B}W_{Beff}}\exp\frac{eV_{BE}}{kT}}{\frac{Aen_i}{2\tau}W_T\exp\left(\frac{eV_{BE}}{2kT}\right)}=\frac{n_i D_{nB}2\tau}{N_{A_B}W_{Beff}W_T}\exp\left(\frac{eV_{BE}}{2kT}\right)\approx\frac{10^5}{10^8}\exp\left(\frac{eV_{BE}}{2kT}\right)$$

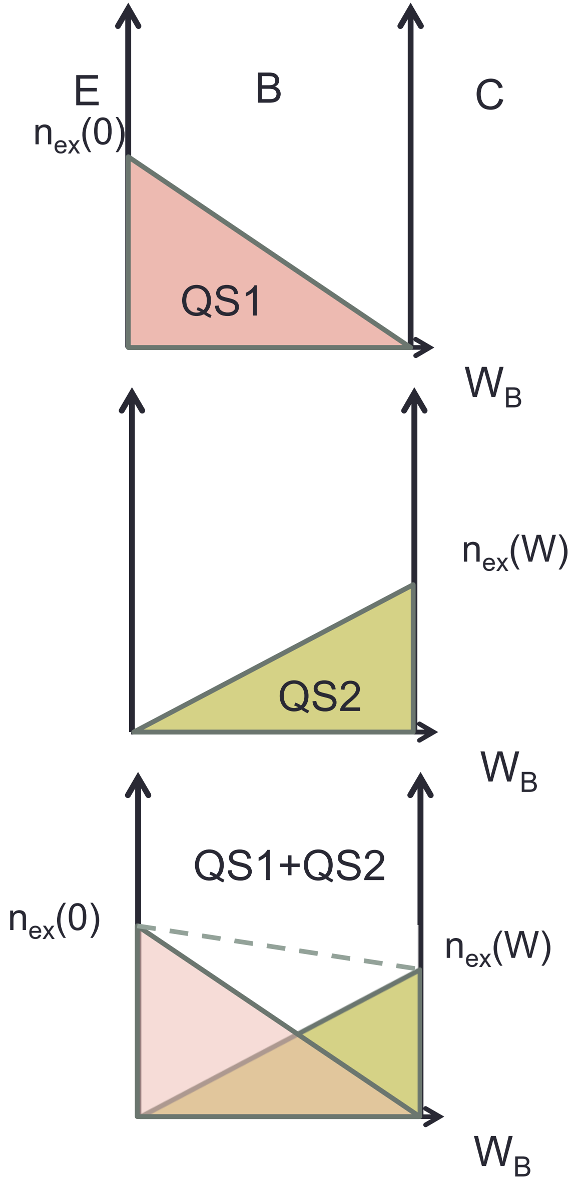
If V_{BE}>0,72V then exp() larger than 10^6

Other modes of operation

- Saturation mode (regime):
  - The two junctions are forward biased.

$$I_E \cong -\left(\frac{Ae^2 n_i^2 D_{nB}}{Q_S + Q_B} + I_{spE}\right) e^{\frac{eV_{BE}}{kT}} + \frac{Ae^2 n_i^2 D_{nB}}{Q_S + Q_B} e^{\frac{eV_{BC}}{kT}}$$

$$I_C \cong \frac{Ae^2 n_i^2 D_{nB}}{Q_S + Q_B} e^{\frac{eV_{BE}}{kT}} - \left(\frac{Ae^2 n_i^2 D_{nB}}{Q_S + Q_B} + I_{spC}\right) e^{\frac{eV_{BC}}{kT}}$$



Saturation mode

- Low injection : (Q_S<<Q_B):
  - Current is due to saturation charge injected into the base, *ie* $Q_{ST} = Q_{S1} + Q_{S2}$
  - If we deal with « narrow » junction, this charge is simply given by the surface of ½ trapeze (linear decay)

$$Q_{S1} = -\frac{1}{2}W_B e n(x=0) = -\frac{1}{2}W_B e \frac{n_i^2}{N_A} e^{\frac{eV_{BE}}{kT}} = -\tau_t J_{sn} e^{\frac{eV_{BE}}{kT}}$$

$$Q_{S2} = -\frac{1}{2}W_B e n(x=W_B) = -\frac{1}{2}W_B e \frac{n_i^2}{N_A} e^{\frac{eV_{BC}}{kT}} = -\tau_t J_{sn} e^{\frac{eV_{BC}}{kT}}$$

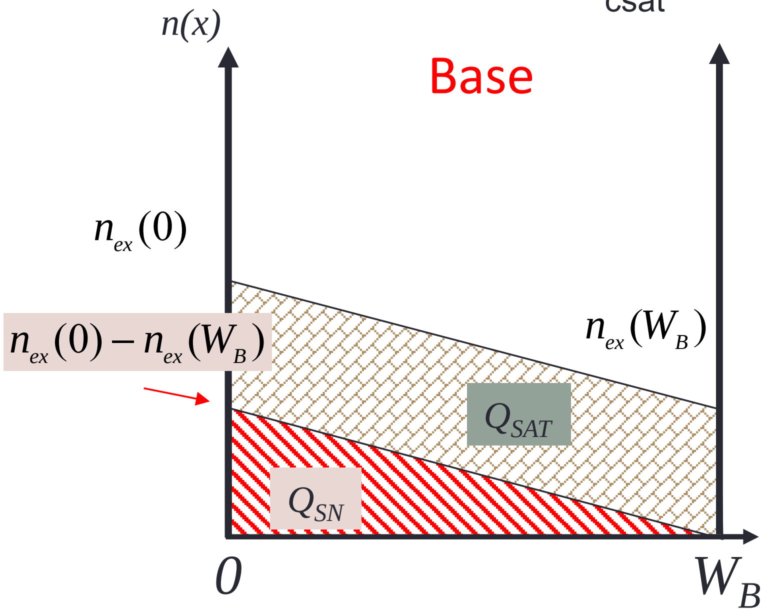
$$Q_{ST} = -\tau_t J_{sn} \left(e^{\frac{eV_{BE}}{kT}} + e^{\frac{eV_{BC}}{kT}}\right)$$

$$J_{Sn} = \frac{e n_{iB}^2 D_{nb}}{N_{A_B} W_{Beff}}$$

$$\tau_{tB} = \frac{W_{Beff}^2}{2D_{nB}}$$

Saturation mode

- Low injection: ($Q_S \ll Q_B$):
  - An other « view » of saturation charge (from *Ablard*):
    - We consider transistor in active mode with a charge Q_{SN} and a charge Q_{SAT} (we have to determine) which supply the same saturation current I_{csat}.



Responsible for the degradation of dynamic performance

$$Q_{ST} = Q_{S1} + Q_{S2} = Q_{SN} + Q_{SAT}$$

$$Q_{SN} = -\frac{1}{2} e(n(0) - n(W_B))W_B$$

$$Q_{SN} = -\tau_t J_{sn} e^{\frac{eV_{BE}}{kT}} + \tau_t J_{sn} e^{\frac{eV_{BC}}{kT}}$$

We get :

$$Q_{SAT} = Q_{ST} - Q_{SN} =$$

$$Q_{SAT} = -\tau_t J_{sn} (e^{\frac{eV_{BE}}{kT}} + e^{\frac{eV_{BC}}{kT}}) + \tau_t J_{sn} e^{\frac{eV_{BE}}{kT}} - \tau_t J_{sn} e^{\frac{eV_{BC}}{kT}}$$

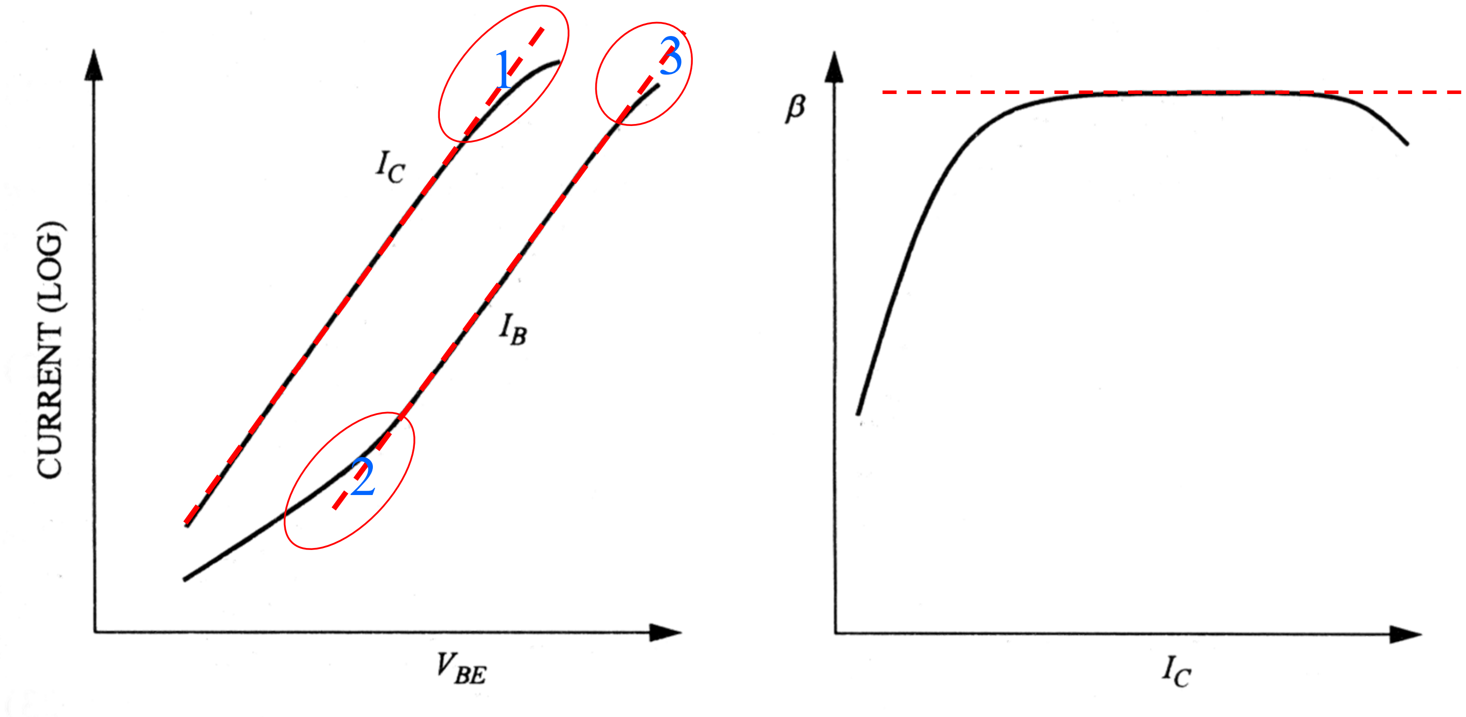
$$Q_{SAT} = -2\tau_t J_{sn} e^{\frac{eV_{BC}}{kT}}$$

Nonideal Effects

$$I_C = I_{Sn} \exp \frac{eV_{BE}}{kT}$$

$$I_B^* = I_{SpE} \exp \frac{eV_{BE}}{kT}$$

- *« Gummel plot »:*
  - Graph of I_C and I_B versus V_{BE}



Nonideal Effects

- Early effect / collector punchthrough
- Base – collector junction breakdown
- Emitter and Base serie resistance (3)
- I_c « collapse » fort high current (1)
- « crowding effect »

Early effect / collector punchthrough

- At "first glance" Ic is independent of V_{CB}

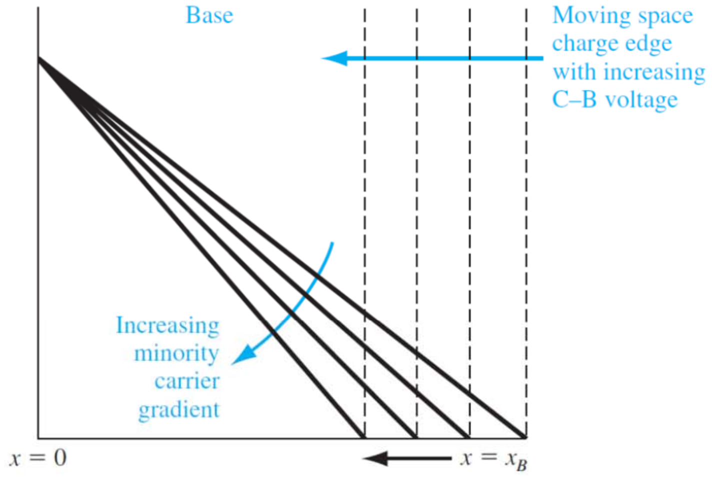
$$I_C = -\left(\frac{Ae^2 n_i^2 D_{nB}}{Q_B + Q_S}\right)\exp\frac{eV_{BE}}{kT} = -\frac{Ae^2 n_i^2 D_{nB}}{\int_{E'}^{C'} p(x)dx}\exp\frac{eV_{BE}}{kT} = -\frac{Ae^2 n_i^2 D_{nB}}{N_{A_B} \times W_{Beff}}\exp\frac{eV_{BE}}{kT}$$

- In fact we have the modulation of the width of the neutral region in the base, so in the same way Q_B+Q_S, and so I_c !

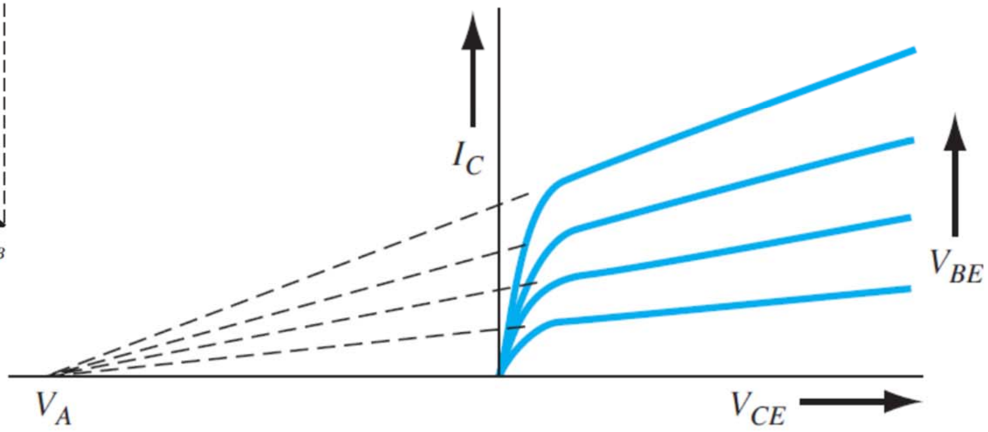
⇒ if V_{BC} ↑ ZCE B-C ↑ W_{Bef} ↓

⇒ I_c ↑

Early effect / base punchthrough



$$\left|V_A\right| \approx \frac{Q_{pB}}{C_{dBC}} = \frac{eN_B W_B}{\varepsilon_{SC} / W_{ZCE_{BC}}}$$



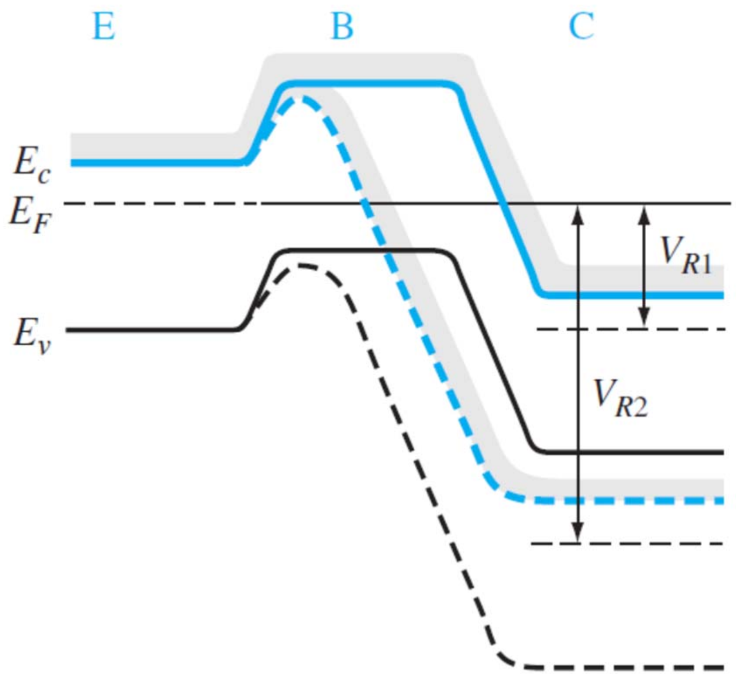
Collector current is due to diffusion of electrons in the base

$$\frac{dI_C}{dV_{CE}} \equiv g_o = \frac{I_C}{V_{CE} + V_A} = \frac{1}{r_o} \quad (h_{22})$$

Early effect / base punchthrough

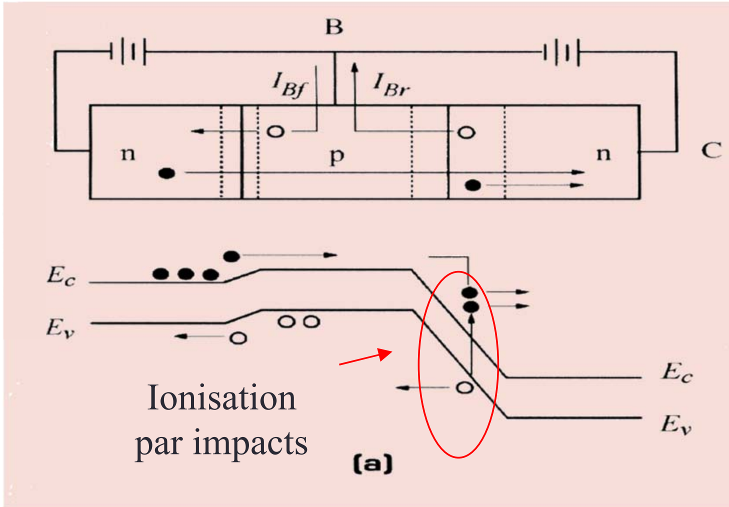
- At the limit:
  - The BC space charge « depletes » totaly the neutral base
  - collector injects directly current into the emitter because energy barrier is lowering
  - Current only limited by serie resistance R_{serie} from E and C
  - For a thin Base region, need to increase base doping to limit SCE enter into the base

$$V_{pt} = \frac{eW_B^2 N_{A_B}(N_{A_B} + N_{D_C})}{2\varepsilon_{SC} N_{D_C}}$$



Base - Collector junction breakdown

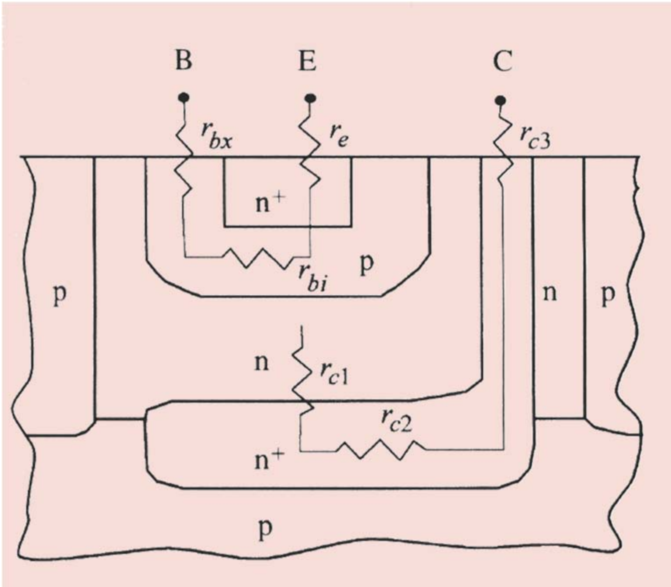
- Avalanche of BC:
  - Often occurs before punchthrough
  - How to prevent it?
    - Lowering the electric field:
      - Reduce the doping gradient in the collector
      - Lightly doped layer between base and collector



$$I_B = I_{Bf} - I_{Br}$$

Emitter and Base resistance (effet 3)

- At low current negligeable effects
- In high speed circuits, B-C allways reverse biased (r_{c2} *and* r_{c3} as low as possible)
  - Resistances r_c have no effects on current flow
- Only r_e and r_b play a major role .
  - IR drop Voltage



$$\Delta V_{BE} = -r_e I_E + I_B r_b = r_e I_C + I_B (r_e + r_b)$$

$$V'_{BE} = V_{BE} - \Delta V_{BE}$$

$$I_C + I_E + I_B = 0$$

$$I'_B = I_B \exp(-\frac{e\Delta V_{BE}}{kT})$$

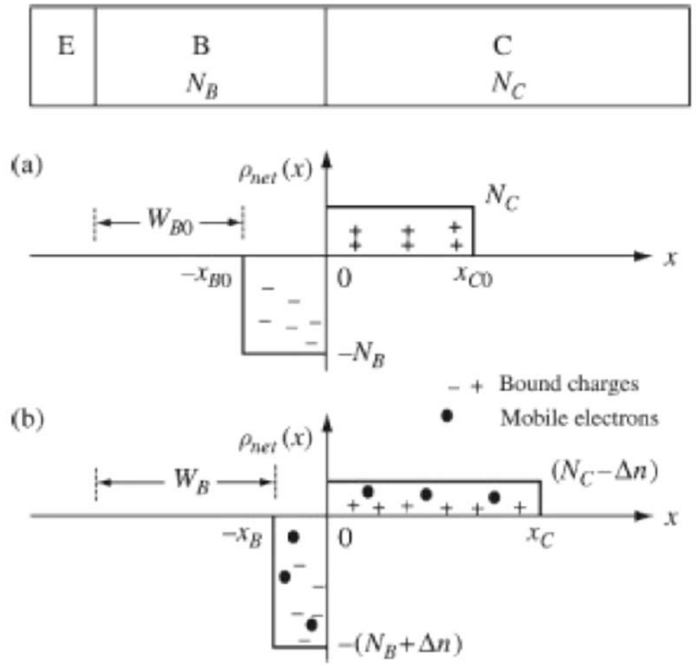
Measured current: $I_{B'}$

Collector « collapse » for high injection level (effect 1)

- Number of physical mechanisms can cause this falloff of I_{C0}:
  - Increase of the charge (holes) into the base (maintain neutrality)
  - Increase the width of the quasineutral base layer (push off the space charge into the collector): *Kirk effect*

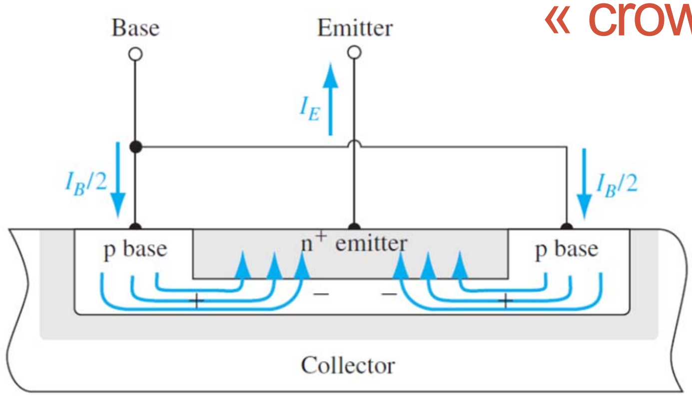
$$|I_C| = A_E J_{C0} \exp\frac{eV_{BE}}{kT}$$

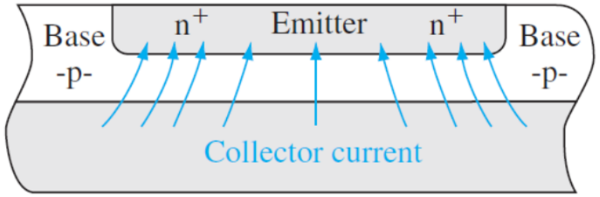
$$|I_C| = A_E \frac{eD_{nB} n_{ieB}^2}{\int_E^C p_p(x)\,dx} \exp\frac{eV_{BE}}{kT}$$



And the effect #2 ????????????????

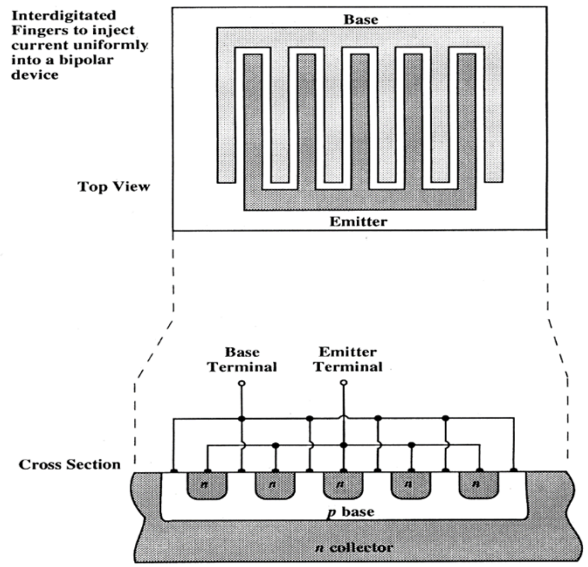
« crowding effect »





- The view of a 1D devices is an approximation
- Drop voltage IR in the base.
- The edge of the emitter contact is more biased than the core/center
- Favour a high density of current essentially along the edges
- Not a good thing for high power devices

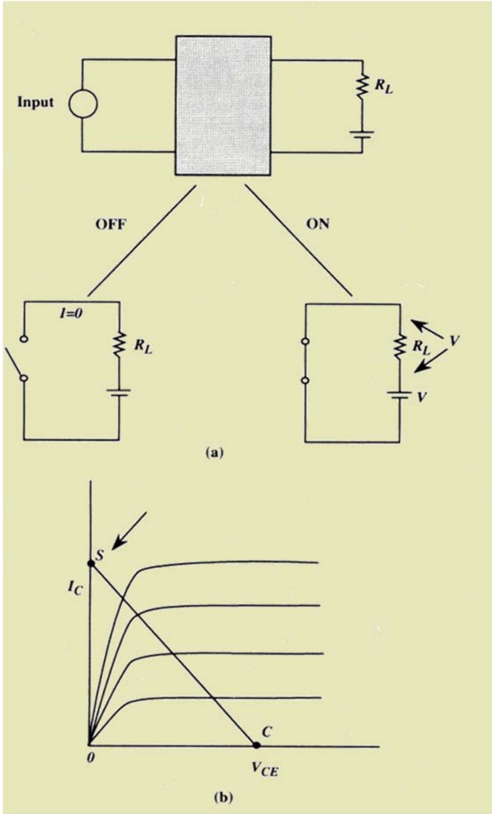
- *Solutions: interdigitated approach*



Bipolar Transistor: a switch ?

ON state: the switch is closed (saturation mode)

OFF state: the switch is open (cutoff mode)

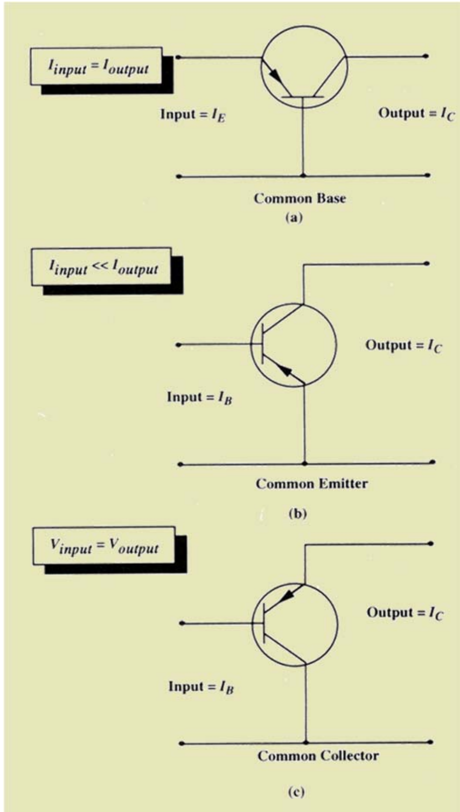


Bipolar Transistor: a switch ?

Input signal as low as possible

input power as low as possible

common emitter



Bipolar Transistor: a switch ?

Switching velocity?

Limiting factors?

- Turn on transient:
  - Continuity equation for the charge:

$$I_B = \frac{Q_B}{\tau_n} + \frac{dQ_B}{dt}$$

- Excess Base charge can be written:

$$Q_B(t) = I_B \tau_n [1 - \exp(-\frac{t}{\tau_n})]$$

- Collector current is given by:

$$I_C(t) = \frac{Q_B(t)}{\tau_t}$$

transit time

in the base (narrow)

$$\frac{Q_B(t)}{\tau_t} = I_c = I_B \frac{\tau_n}{\tau_t} [1 - \exp(-\frac{t}{\tau_n})]$$

Bipolar Transistor: a switch ?

$$V_{CE} = V_{CB} + V_{BE}$$

- Turn on:
  - I_C increases until the saturation regime is reached:

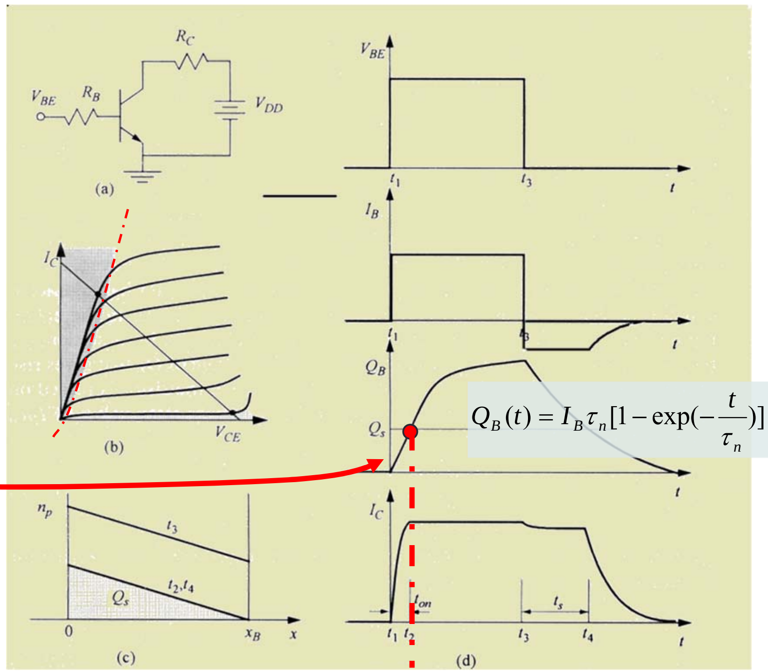
$$I_{C_{sat}} \approx \frac{V_{DD}}{R_C}$$ (we neglect V_{CEsat})

  - The limit charge $Q_B(t_{on})$ *to saturate the transistor is given by* :

$$Q_S = \frac{I_{C_{sat}} d_{pB}^2}{2D_{nB}}$$

  - The on state time is given by:

$$t_{ON} = \tau_n \ln\left[\frac{1}{1-(Q_S/I_B\tau_n)}\right] = \tau_n \ln\left[\frac{1}{1-(I_c/I_B\delta)}\right]$$



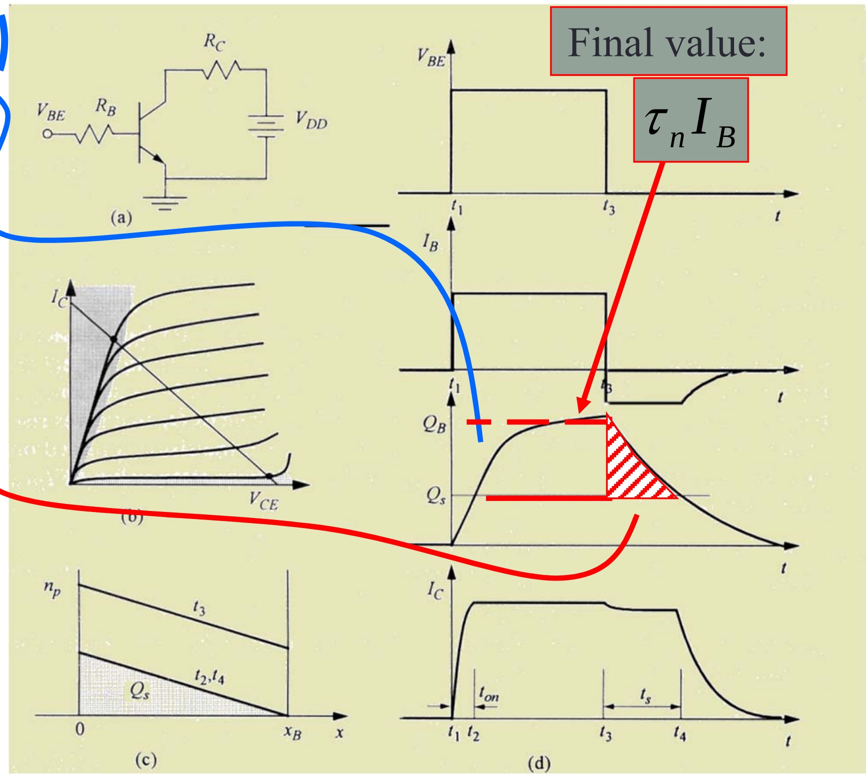
Bipolar Transistor: a switch ?

- *Remark: the charge can increase over QB(ON) to over saturate the transistor.this charge is injected from the collector*

- Turn off time : input with a « 0 »:
  - **Evacuation of the stored charge**
    - **This is the storage time** t_S

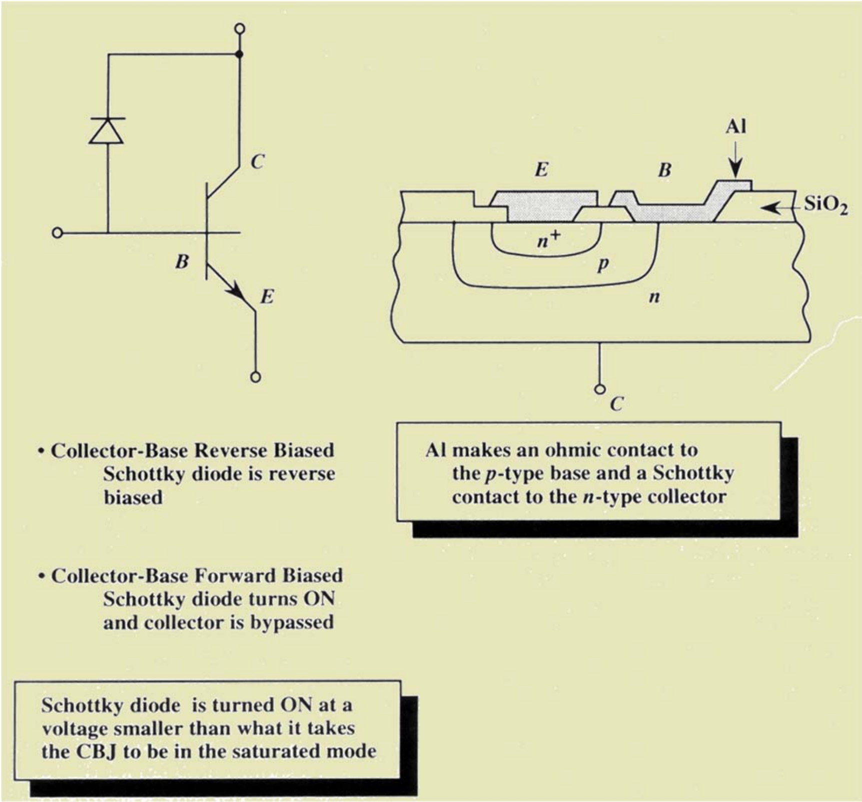
$$t_S = \tau_n \ln\left(\frac{I_B \tau_n}{Q_S}\right)$$

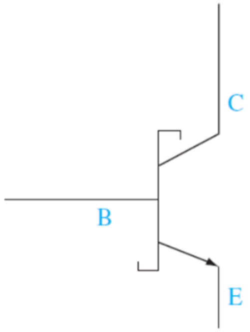
    - **after, this is the same mechanism than for PN Junction**



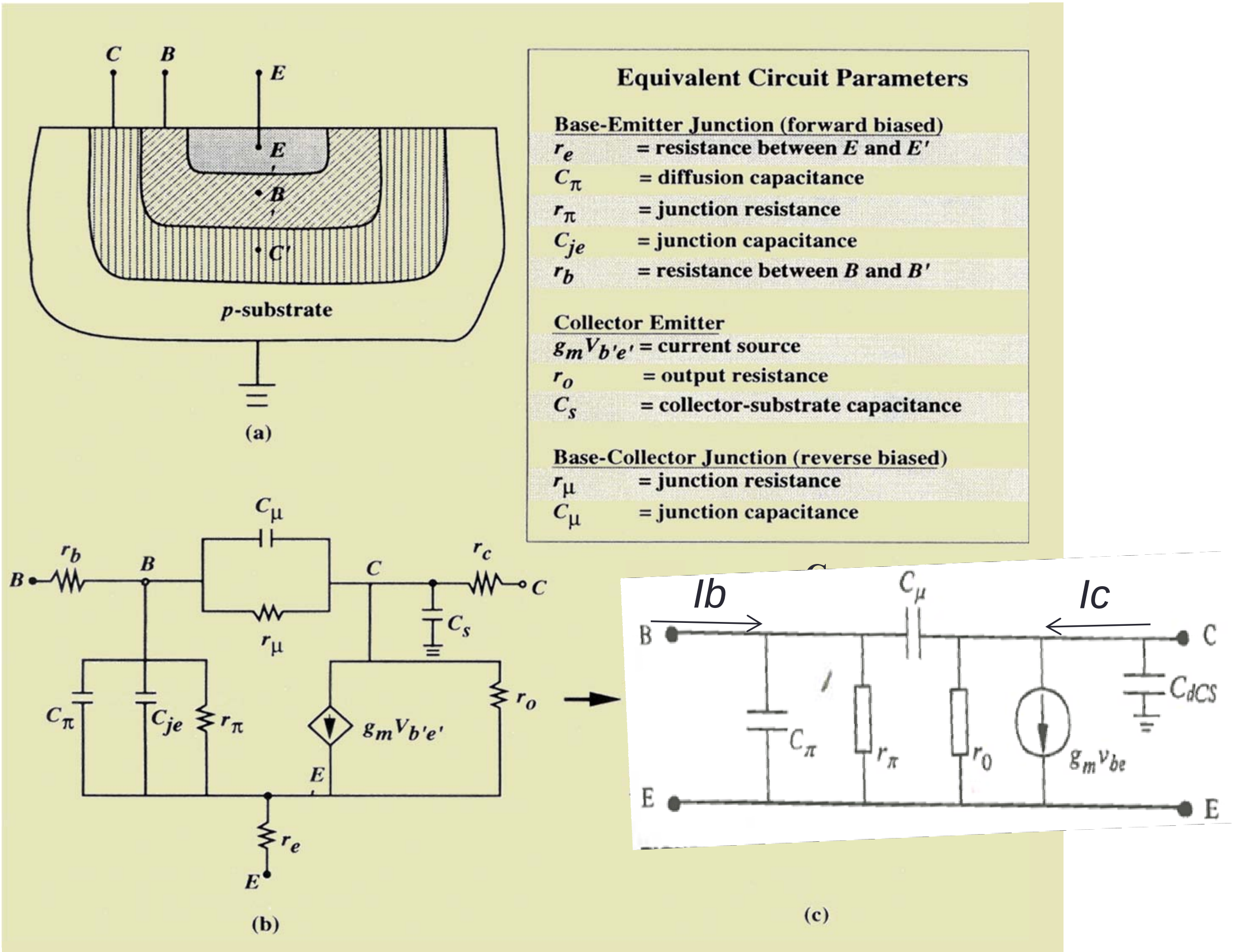
Bipolar Transistor: a switch ?

- Storage time (desaturation) limits the switching time
- 2 ways to reduce it:
  - Add impurities which decrease strongly the lifetime into the base (pb with transport factor)
  - Schottky Diode in // with CB junction: avoid saturation of the transistor





AC signal : equivalent circuit



Transistor and *ac signal*: equivalent circuit

- ***Transconductance*** :links the variation of the collector current to the base – emiter voltage:

$$g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{eI_C}{kT} \quad \Leftrightarrow i_c = g_m . v_{BE}$$

- ***Input resistance*** : links the variation of Base current to the base – emiter voltage:

$$r_\pi = \left(\frac{\partial I_B}{\partial V_{BE}} \right)^{-1} = \frac{kT}{eI_B} = \frac{\beta}{g_m} = h_{11} \approx \frac{25mV}{I_B} \Rightarrow \beta = g_m \, . r_\pi = h_{21}$$

- ***Output resistance:***

$$r_o = \left(\frac{\partial I_C}{\partial V_{CE}} \right)^{-1} \approx \frac{V_A}{I_C} = \frac{1}{h_{22}}$$

Transistor and *ac signal*: equivalent circuit

- ***Capacitance*** C_π :

$$C_\pi = C_{SE} + C_{T_{EB}}$$

  - Storage capacitance

$$C_{SE} = \tau_F g_m$$

  - transit time

$$\tau_F = t_E + t_{t_B} + t_{t_{BE}} + t_{t_{BC}}$$

- ***Capacitance*** C_μ : CB junction capacitance reverse biased

$$C_\mu = C_{T_{CB}}$$

- ***Collector –substrate (depletion layer) capacitance:***

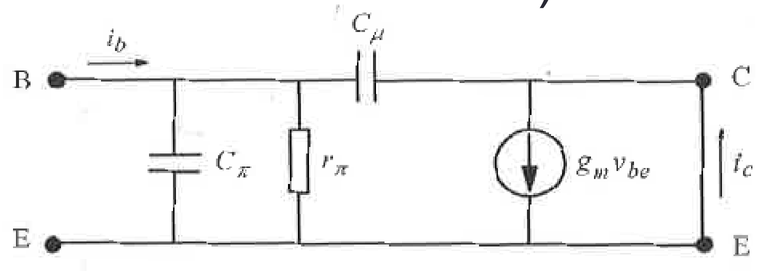
$$C_{dCS}$$

Transistor and *ac signal*: equivalent circuit

- Cut off frequency (current gain =1 when load as a short circuit)
  - We neglect (no Early Effect) r_0

$$i_c = g_m v_{be} - j\omega C_\mu v_{be}$$

$$i_b = \left(\frac{1}{r_\pi} + j\omega C_\pi + j\omega C_\mu \right) v_{be}$$



- Current gain is given by:

$$\beta(\omega) = \frac{i_c}{i_b} = \frac{g_m - j\omega C_\mu}{(1/r_\pi) + j\omega(C_\pi + C_\mu)} = h_{21} = \frac{1 - j\omega C_\mu / g_m}{(1/g_m r_\pi) + j\omega(C_\pi + C_\mu)/g_m}$$

$$if\,\omega = 0 \text{ then } \beta(0) = \frac{i_c}{i_b} = \frac{g_m}{(1/r_\pi)} = g_m r_\pi = h_{21} = \beta_0 \text{ static gain}$$

Transistor and *ac signal*: equivalent circuit

- In modern devices , in general $\omega C_{\mu} << g_{m}$
- At low frequency:

$$\beta(\omega) = \frac{i_c}{i_b} \approx \frac{g_m r_\pi}{1 + j\omega r_\pi (C_\pi + C_\mu)}$$

- At high frequency, the imaginary term dominates and :

$$\beta(\omega) \approx \frac{g_m}{j\omega(C_\pi + C_\mu)}$$

Transistor en *ac*: schéma équivalent

- We get the « cutoff frequency » by considering $i_C/i_B=1$

$$1 = \frac{g_m}{2\pi f_T (C_\pi + C_\mu)}$$

$$2\pi f_T = \frac{g_m}{C_\pi + C_\mu}$$

- By replacing all the terms by their expressions

$$\frac{1}{2\pi f_T} = \tau_F + \frac{kT}{eI_C}(C_{SE} + C_{T_{BC}}) + C_{T_{BC}}(r_e + r_c)$$

Forward Transit time

Resistance neglected

Transistor en *ac*: schéma équivalent

- Maximun oscillation frequency ⇔Power gain=1
  - Laborious and tedious calculation/ we have to take into account the base resistance

$$f_{\max} = \sqrt{\frac{f_T}{8\pi r_b C_{dBC}}}$$

Heterojunction Bipolar Transistor

- Current gain:

$$\alpha = \left[1 - \frac{n_{i_E}^2}{N_{D_E}} \frac{D_{p_E}}{D_{n_B}} \frac{N_{A_B}}{n_{i_B}^2} \frac{W_{Beff}}{L_{p_E}}\right]\left[1 - \frac{W_{Beff}^2}{2L_{n_B}^2}\right]$$

- In the case of narrow base:

$$\alpha = \left[1 - \frac{n_{i_E}^2}{N_{D_E}} \frac{D_{p_E}}{D_{n_B}} \frac{N_{A_B}}{n_{i_B}^2} \frac{W_{Beff}}{L_{p_E}}\right]$$

Heterojunction Bipolar Transistor

$$\alpha = \left[1 - \frac{n_{i_E}^2}{N_{D_E}} \frac{D_{p_E}}{D_{n_B}} \frac{N_{A_B}}{n_{i_B}^2} \frac{W_{Beff}}{L_{p_E}} \right]$$

- If we want a gain β with a high value, we need α close to 1. It means:
  - Lowering base doping
  - Lowering base width (careful with punchthrough!)

⇨ Increase of the base resistance ⇔ f_{max} *decreases*

Heterojunction Bipolar Transistor

$$\alpha = \left[1 - \frac{n_{i_E}^2}{N_{D_E}} \frac{D_{p_E}}{D_{n_B}} \frac{N_{A_B}}{n_{i_B}^2} \frac{W_{Beff}}{L_{p_E}} \right]$$

- Other solution:
  - Increase emitter doping
    - Improve emitter efficiency
  - Problem: « gap shrinking » ⇔ $\Delta E_g = E_{g(base)} - E_{g(émetteur)} > 0.$

$$n_i^2(émetteur) = n_i^2(Base)\exp(\frac{\Delta E_g}{kT})$$

  - This « problem » can be transform in opportunity !! (next two slides)

Heterojunction Bipolar Transistor

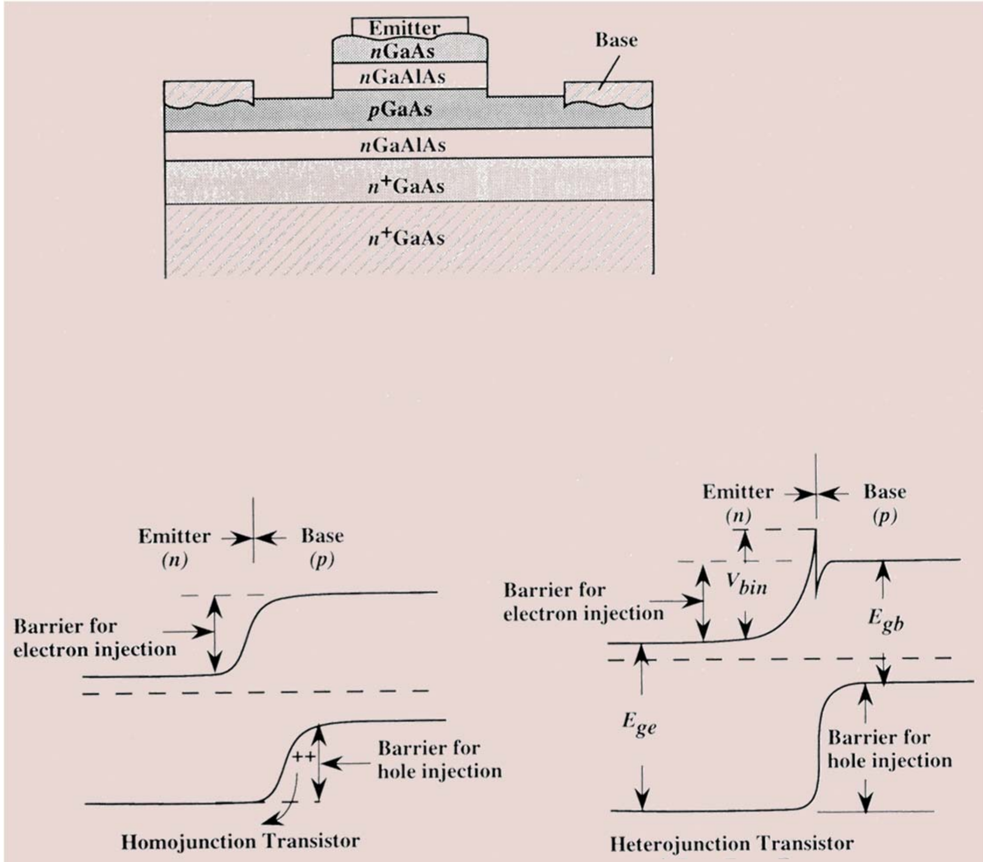
$$\alpha = \left[1 - \frac{n_{i_e}^2}{N_{D_E}} \frac{D_{p_E}}{D_{n_B}} \frac{N_{A_B}}{n_{i_B}^2} \frac{W_{Beff}}{L_{p_E}} \exp\frac{\Delta E_g}{kT}\right]$$

$$\beta = \frac{\alpha}{1-\alpha} = \left[\frac{N_{D_E}}{N_{A_B}} \frac{D_{n_B}}{D_{p_E}} \frac{L_{p_E}}{W_{Beff}} \exp(-\frac{\Delta E_g}{kT}) - 1\right]$$

We see that it is difficult to have at the same time a large emitter doping, a lightly doped and thin base and a large gain

Heterojunction Bipolar Transistor

- We design a structure with a negative energy gap difference: this is an HBT



$$\Delta Eg = Eg_b - Eg_e$$

(From Singh)

Requirements for a bipolar device

- High gain
- High emitter efficiency
- High speed

Demands and Problems for a BJT

Demands

Problems

Heavy emitter doping

Bandgap shrinkage causing base injection

Low base doping
Narrow base width

High base resistance

Solution: Heterojunction Bipolar Transistors

- Emitter can be heavely doped using a SC with Eg larger than the base semiconductor
- Base can be heavely doped and be made narrow without increasing base resistance
- Collector can be chosen from a material to increase breakdown voltage

LINEAR SYSTEMS

Linear Integrated Systems

LS301 LS302 LS303

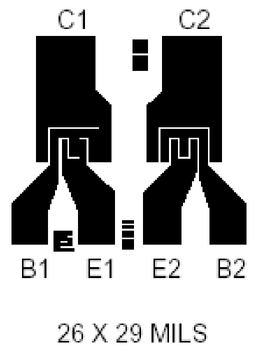
HIGH VOLTAGE SUPER-BETA MONOLITHIC DUAL NPN TRANSISTORS

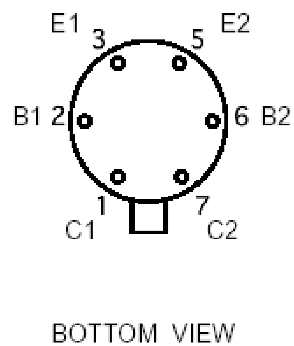
FEATURES	
VERY HIGH GAIN	$h_{FE} \geq 2000$ @ 1.0µA TYP.
LOW OUTPUT CAPACITANCE	$C_{OBO} \leq 2.0$pF
TIGHT V_{BE} MATCHING	$\lvert V_{BE1}-V_{BE2}\rvert$ = 0.2mV TYP.
HIGH f_T	100MHz

ABSOLUTE MAXIMUM RATINGS NOTE 1 @ 25°C (unless otherwise noted)		
I_C	Collector Current	5mA

Maximum Temperatures	
Storage Temperature	-65° to +200°C
Operating Junction Temperature	+150°C

Maximum Power Dissipation	ONE SIDE	BOTH SIDES
Device Dissipation @ Free Air	250mW	500mW
Linear Derating Factor	2.3mW/°C	4.3mW/°C

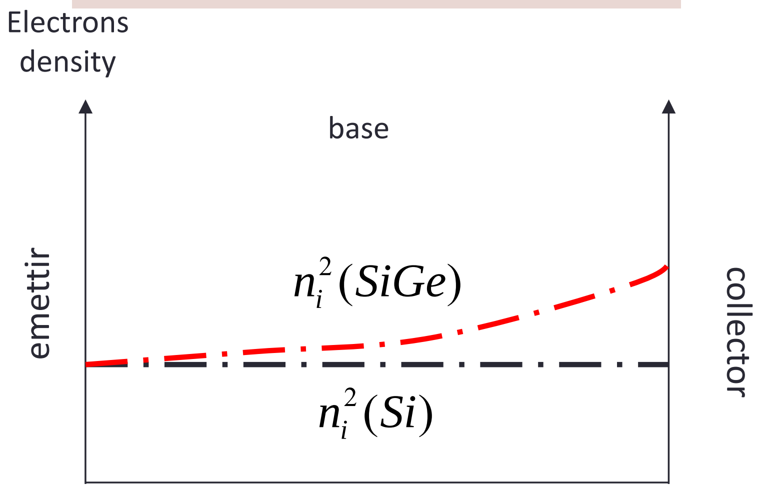


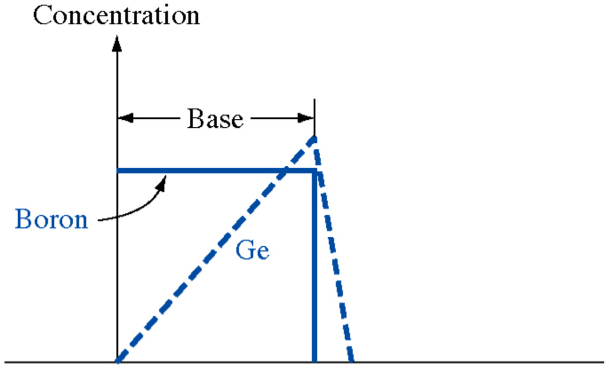


Transistor with a Silicon – Germanium base

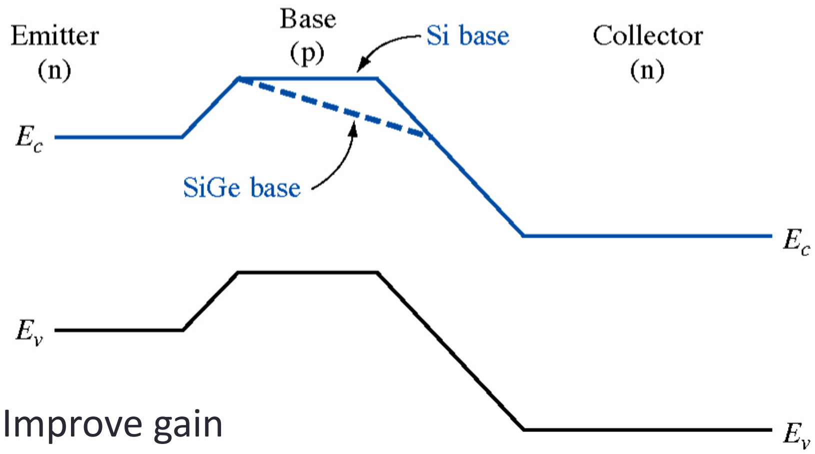
$$I_E = -\left(\frac{Ae^2 n_i^2 D_{nB}}{Q_B + Q_S} + I_{SpE}\right)\exp\frac{eV_{BE}}{kT}$$

$$I_C = +\left(\frac{Ae^2 n_i^2 D_{nB}}{Q_B + Q_S}\right)\exp\frac{eV_{BE}}{kT}$$





(a)



(b)

- Improve gain
- Improve transist time
- Increase Early voltage