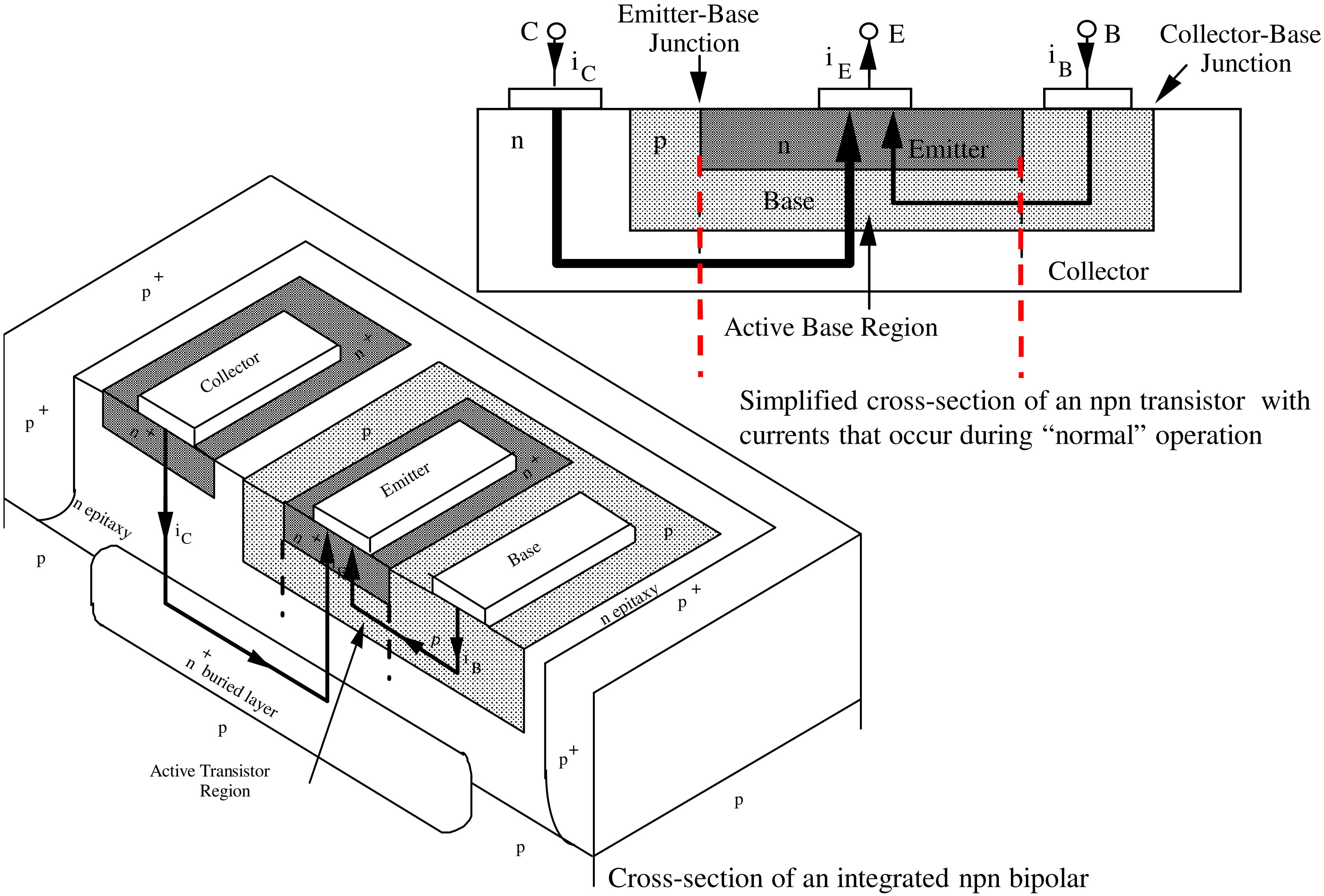
The Bipolar Junction Transistor

- Physical Structure of the Bipolar Transistor
- Operation of the NPN Transistor in the Active Mode
- Transit Time and Diffusion Capacitance
- Injection Efficiency and Base Transport Factor
- The Ebers-Moll Model of the BJT
- The PNP Transistor
- Graphical Representation of the BJT Characteristics
- The Early Effect

Appendices:

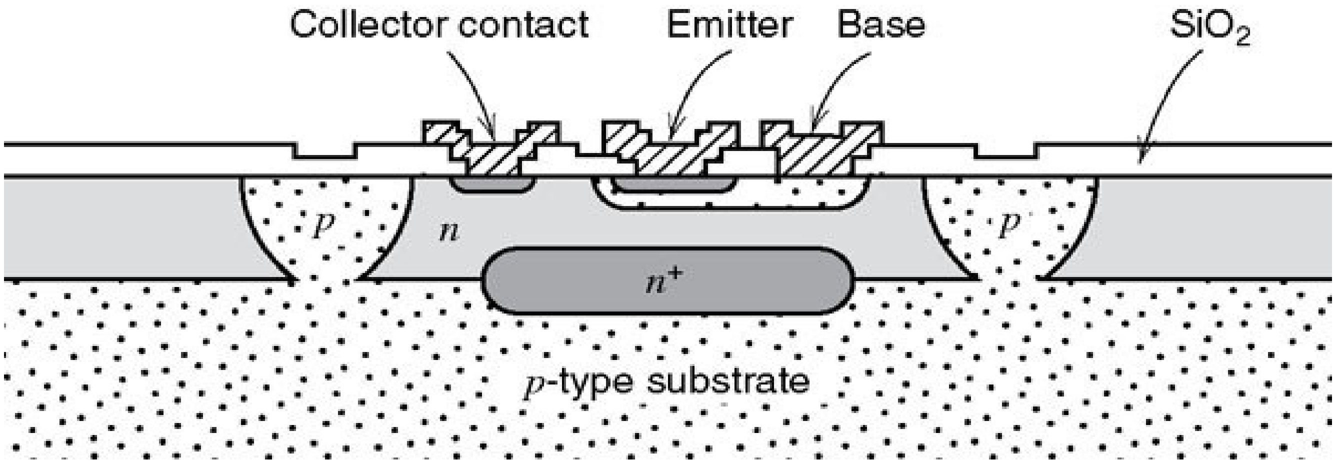
- BJT parameters for simulation

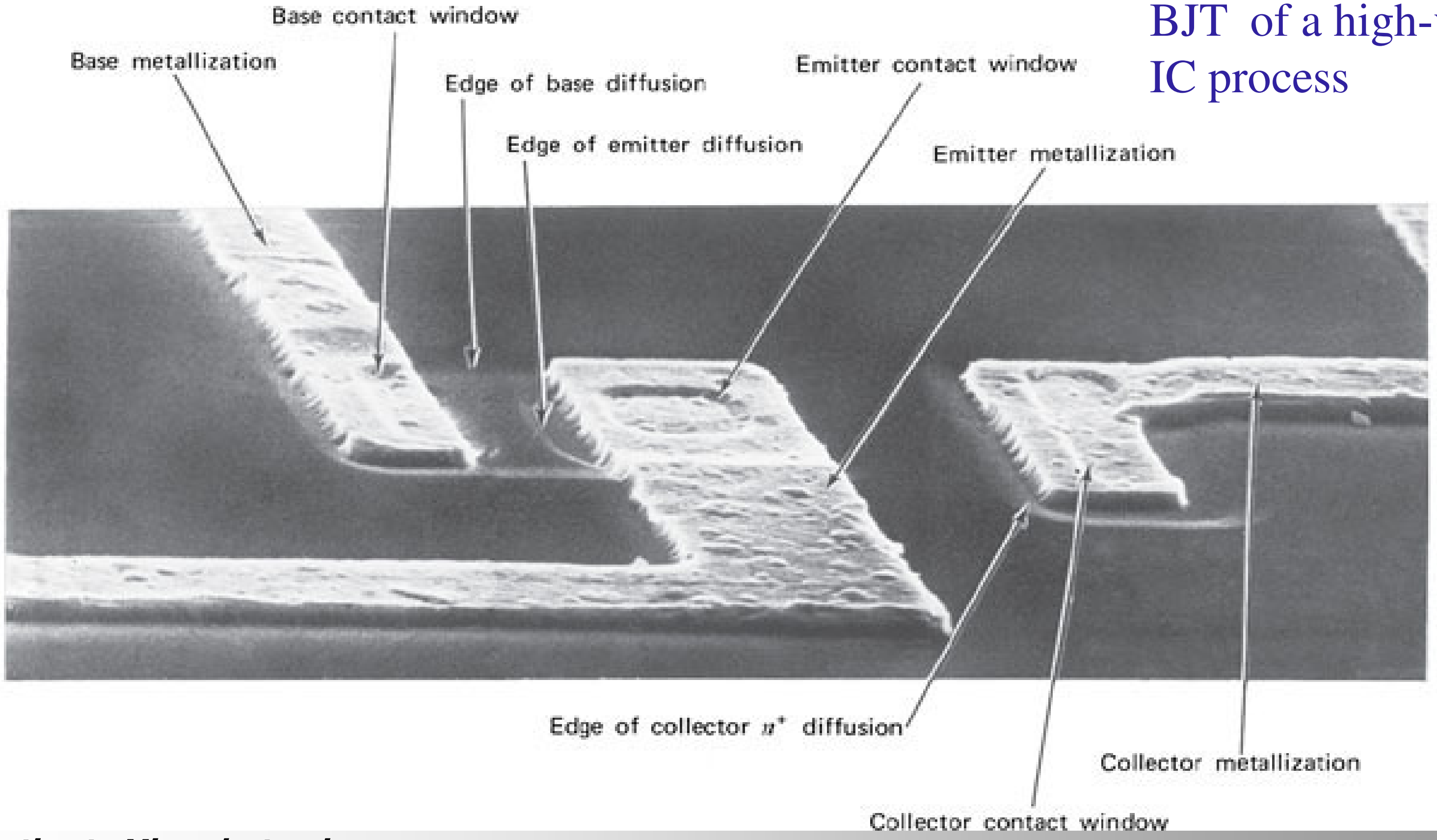
Physical Structure of the BJT



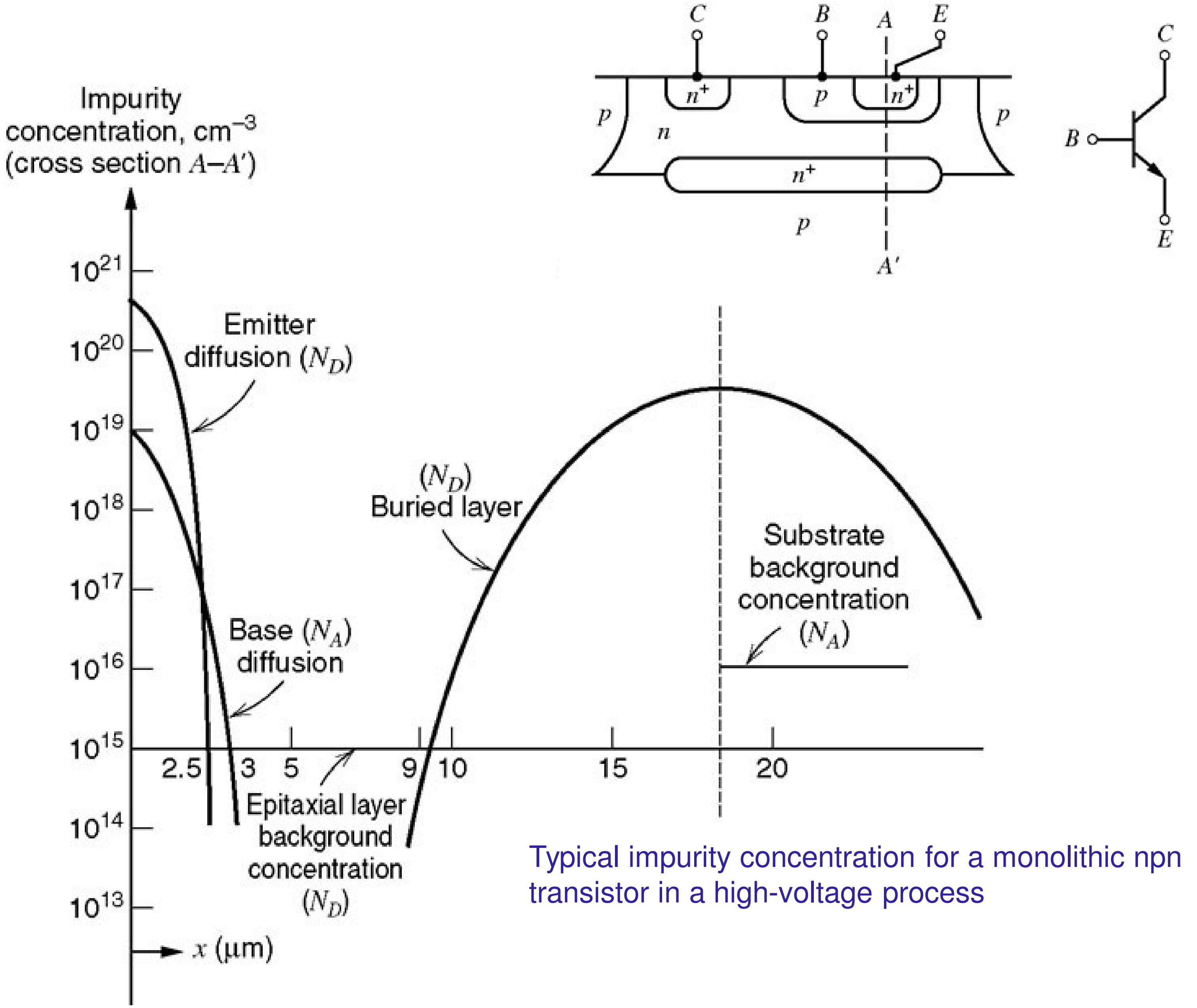
Simplified cross-section of an npn transistor with currents that occur during “normal” operation

Cross-section of an integrated npn bipolar junction transistor

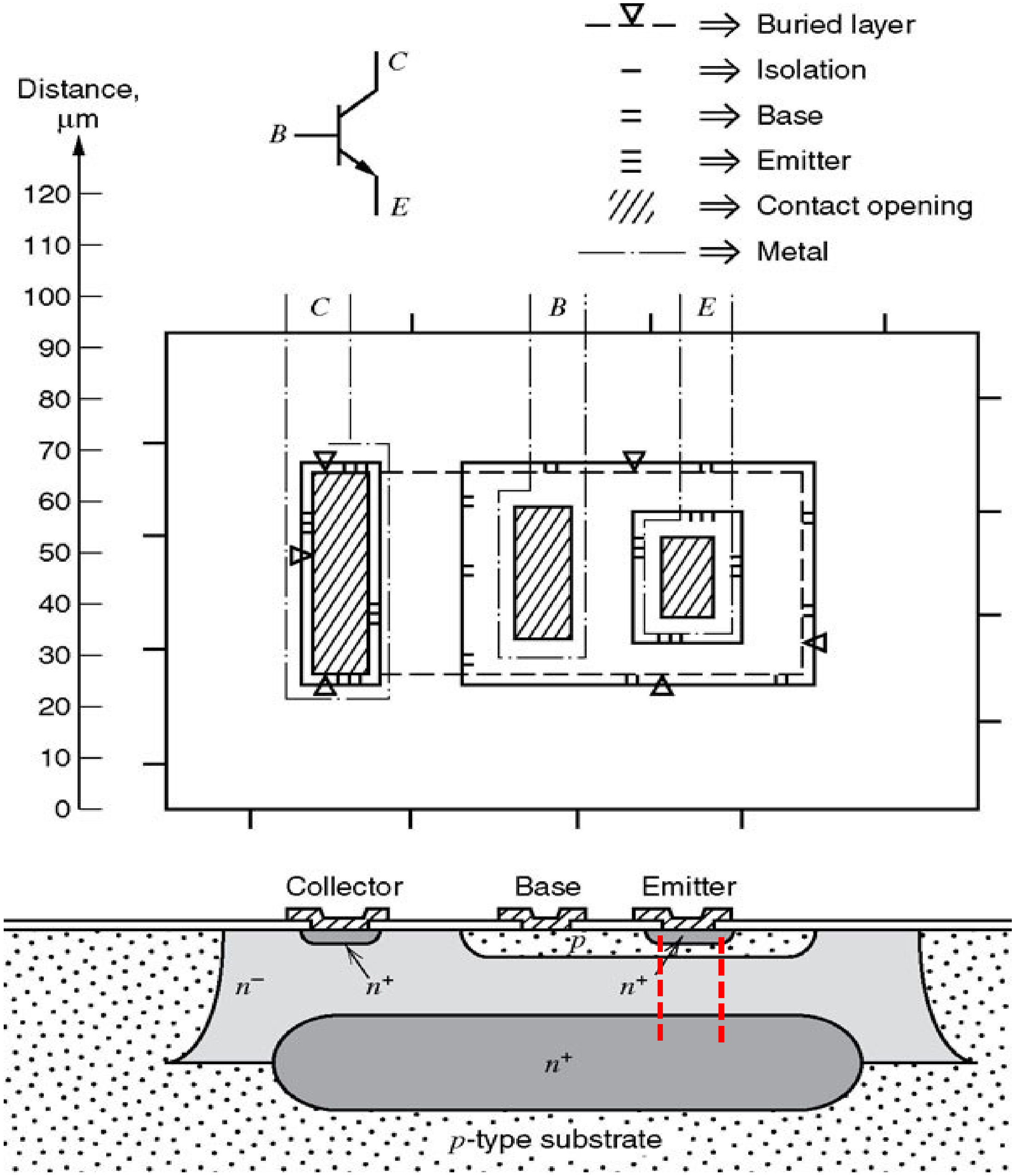




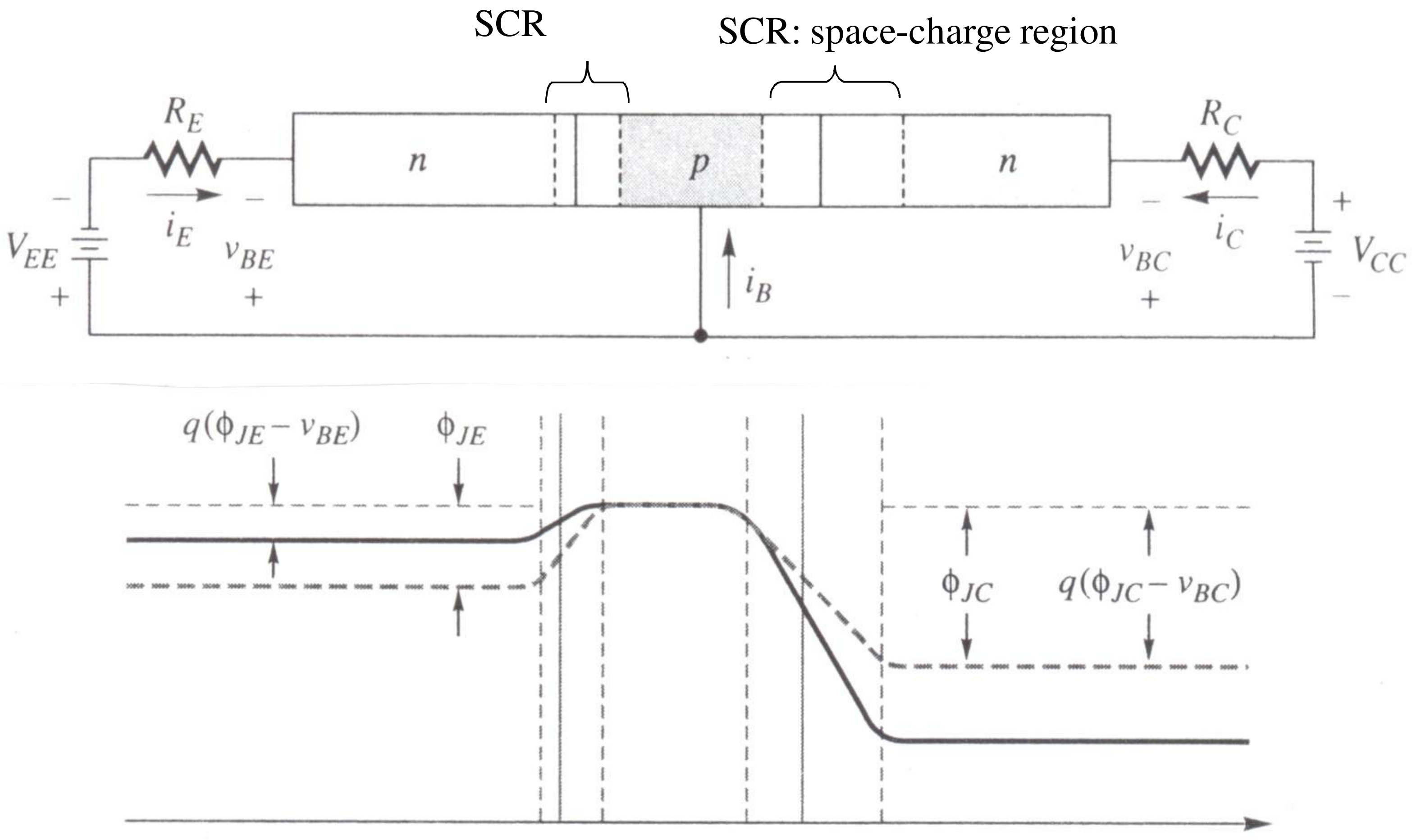
BJT of a high-voltage IC process



Typical impurity concentration for a monolithic npn transistor in a high-voltage process


Distance, µm
120
110
100
90
80
70
60
50
40
30
20
10
0
C
B
E
Buried layer
Isolation
Base
Emitter
Contact opening
Metal
C
B
E
Collector
Base
Emitter
p
n⁻
n⁺
n⁺
n⁺
p-type substrate

Operation of the BJT in the Active Mode



(a) npn transistor with base-emitter junction forward biased, base-collector junction reverse biased. (b) Potential-energy barriers for electrons.

Operation of the BJT in the Active Mode (∗)

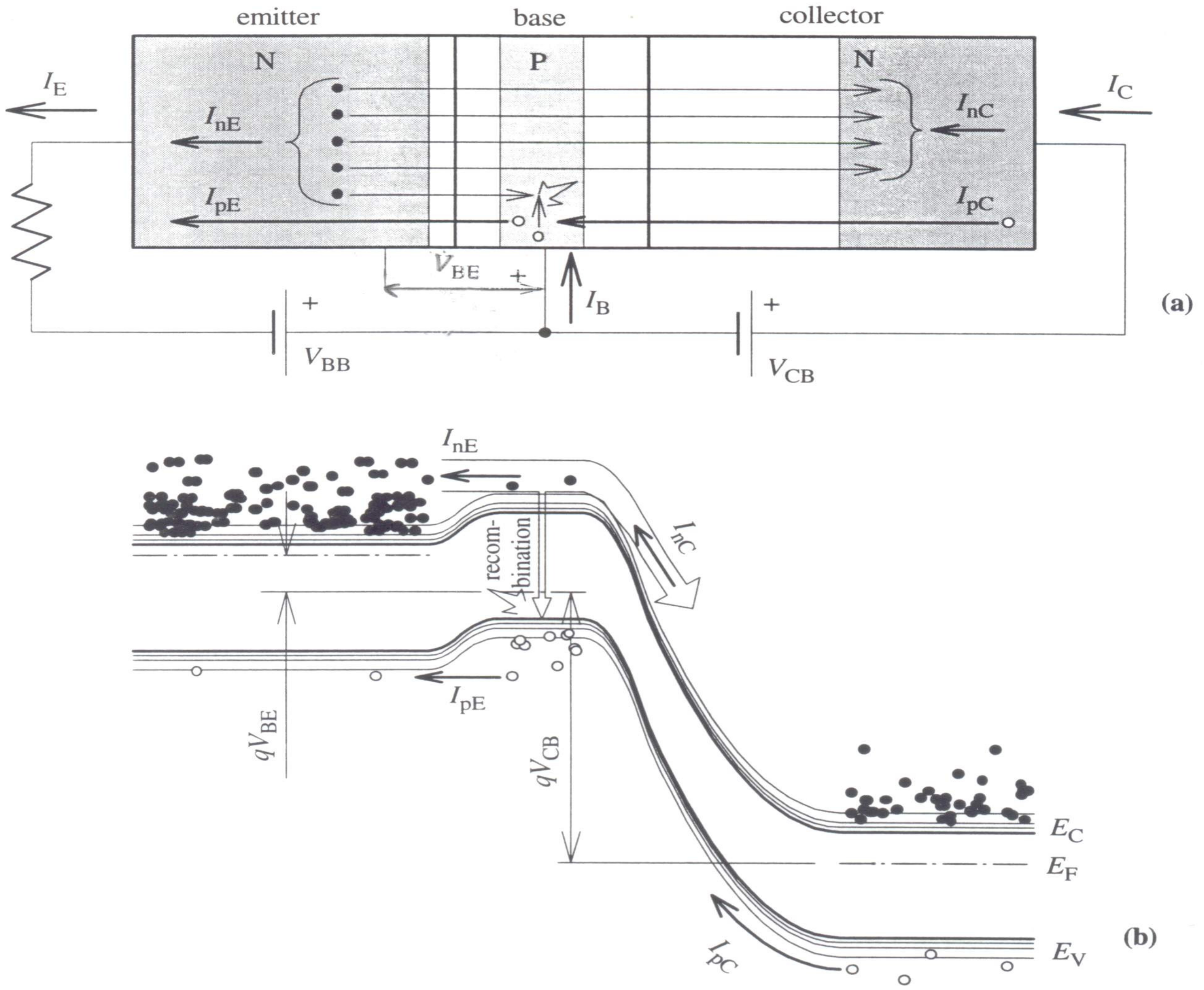
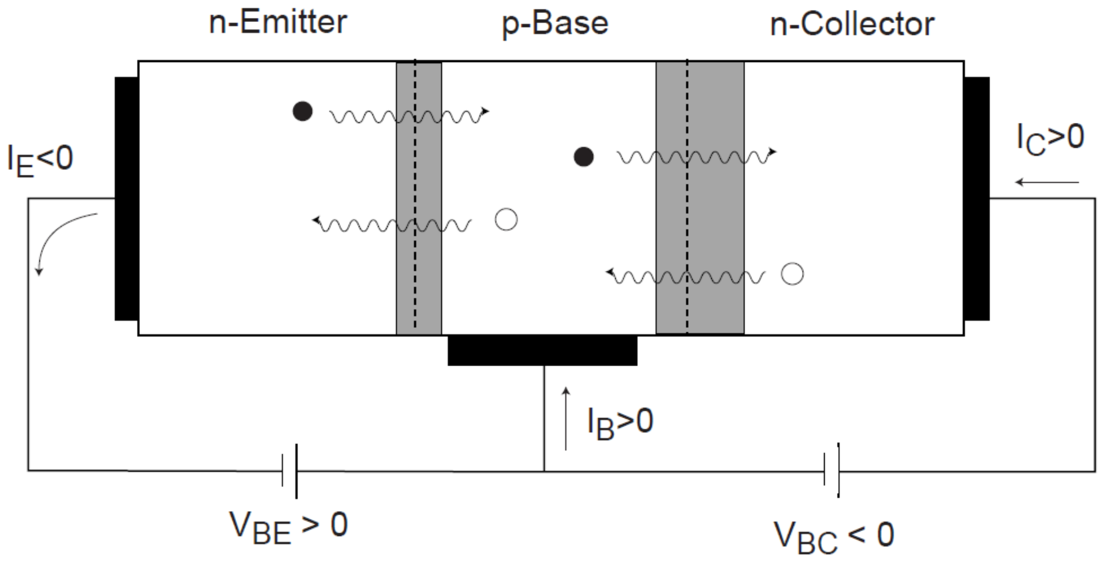


Illustration of BJT currents, using the BJT cross section (a) and energy-band diagram (b).

(∗) S. Dimitrijev, Understanding Semiconductor Devices, Oxford, New York, 2000.

Basic Operation: **forward-active regime**



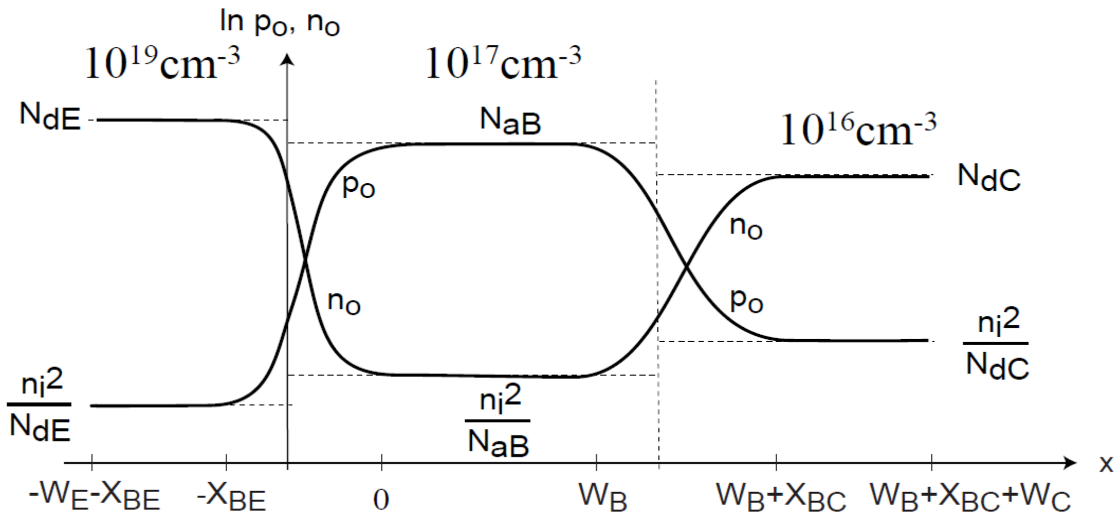
$V_{BE}>0$ ⇒ injection of electrons from the ***Emitter*** to the ***Base***
injection of holes from the ***Base*** to the ***Emitter***

$V_{BC}<0$ ⇒ extraction of electrons from the ***Base*** to the ***Collector***
extraction of holes from the ***Collector*** to the ***Base***

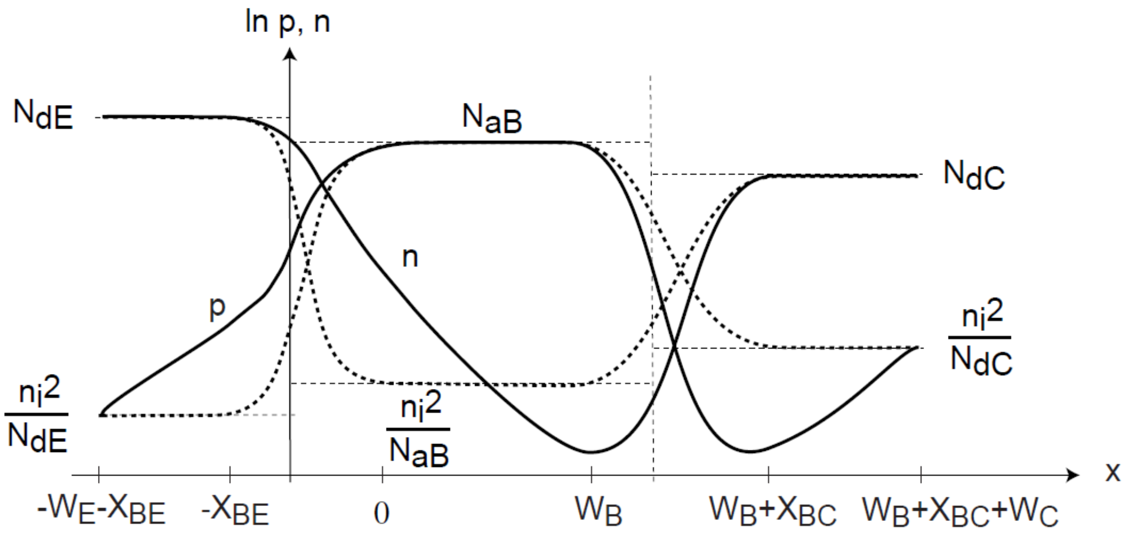
> ***Transistor Effect*** : electrons injected from the ***Emitter*** to the ***Base***, extracted by the ***Collector***

Basic Operation: forward-active regime

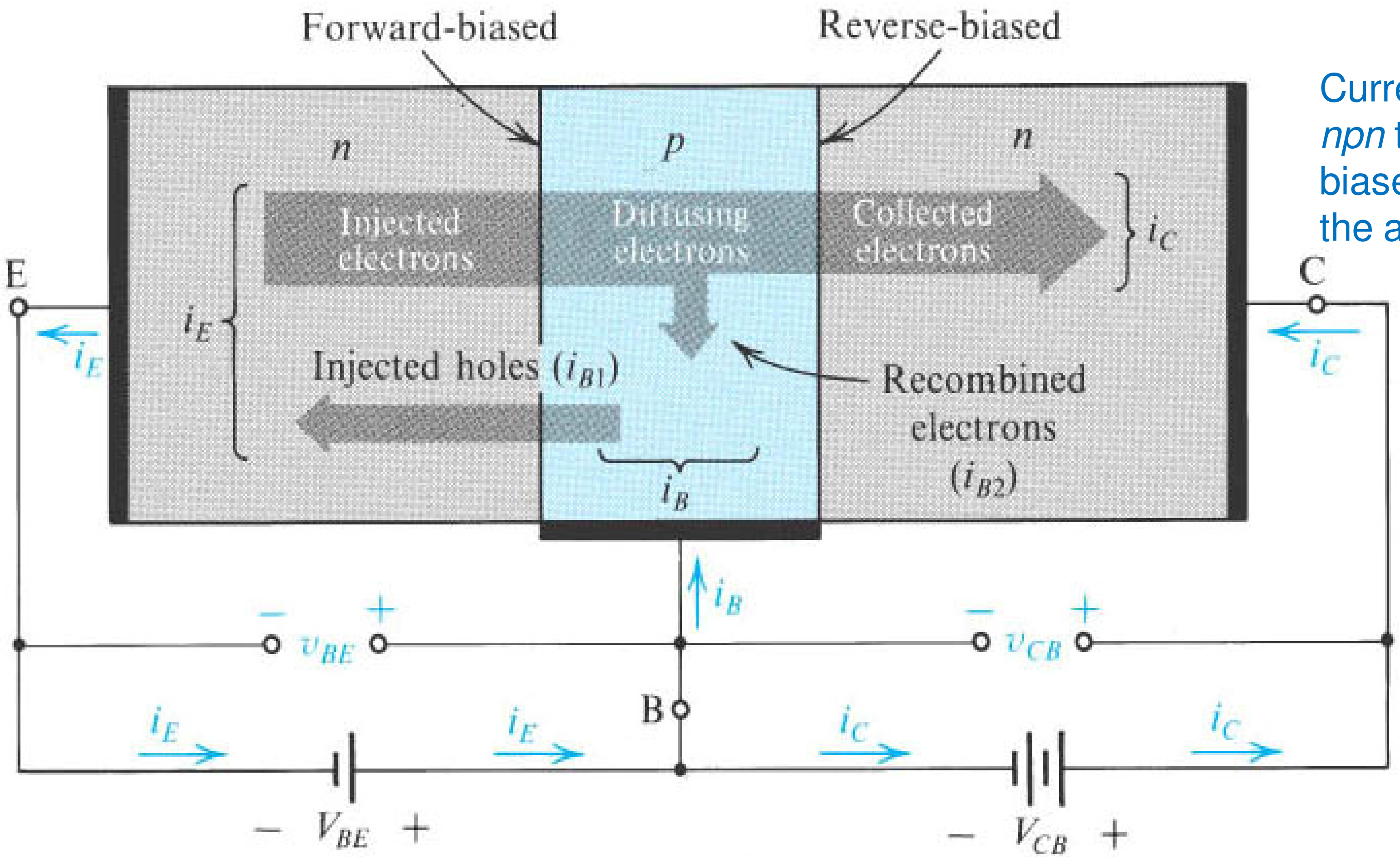
- **Carrier profiles in thermal equilibrium:**



- **Carrier profiles in forward-active regime:**



BJT in the Active Mode

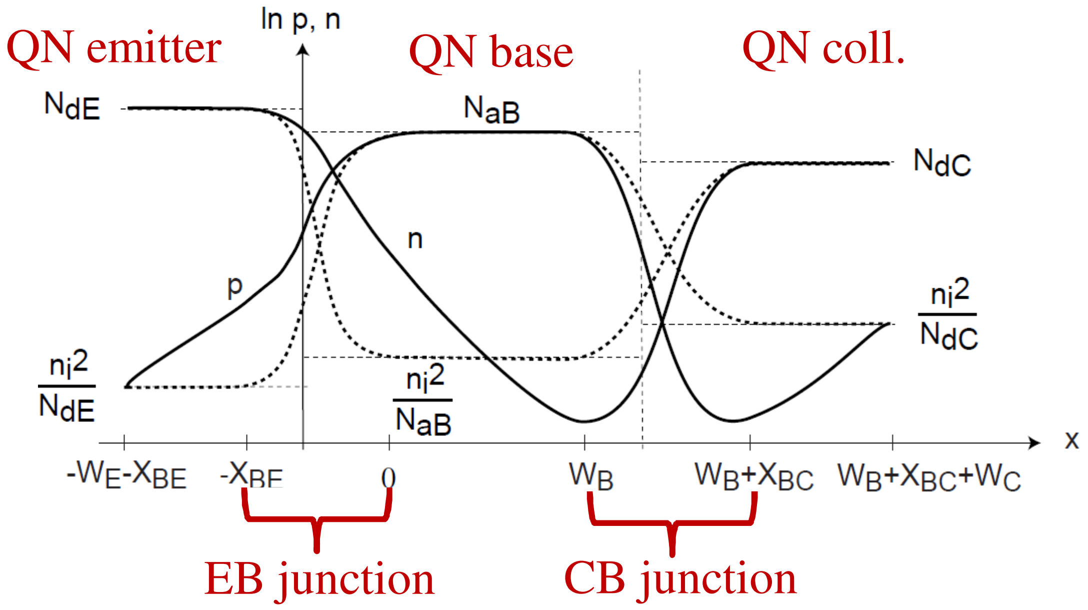


Current flow in an *npn* transistor biased to operate in the active mode.

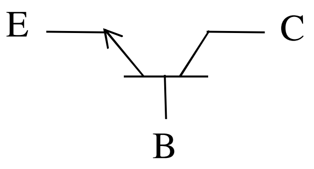
- •The electron flux “stream” is greater than the hole flux stream.
- Electrons are supplied by the emitter contact, injected across the base-emitter SCR and diffuse across the base
- Electric field in the base-collector SCR extracts electrons into the collector.
- Holes are supplied by the base contact and diffuse across the emitter.
- The reverse injected holes recombine at the emitter ohmic contact.

BJT in the Active Mode

Carrier profiles in forward-active regime:



QN = quasi-neutral



Hypotheses:

- One-dimensional device
- Ohmic contacts at E, B, and C
- 3 QN regions and 2 depletion regions
- Low injection level
- High emitter efficiency
- Einstein relationship
- Boltzmann statistics valid in the depletion region
- $W_B << L_n$ – negligible recombination in the base

The electron (collector) current - npn transistor

One-dimensional device + Einstein relationship

$$\left.\begin{aligned} J_n &= qn\mu_n E + qD_n \frac{dn}{dx} \rightarrow \frac{J_n}{qn\mu_n} - \frac{\phi_t}{n}\frac{dn}{dx} = E \\ J_p &= qp\mu_p E - qD_p \frac{dp}{dx} \rightarrow \frac{J_p}{qp\mu_p} + \frac{\phi_t}{p}\frac{dp}{dx} = E \end{aligned}\right\} \frac{pJ_n}{D_n} - \frac{nJ_p}{D_p} = q\frac{d(pn)}{dx} \quad \text{(1)}$$

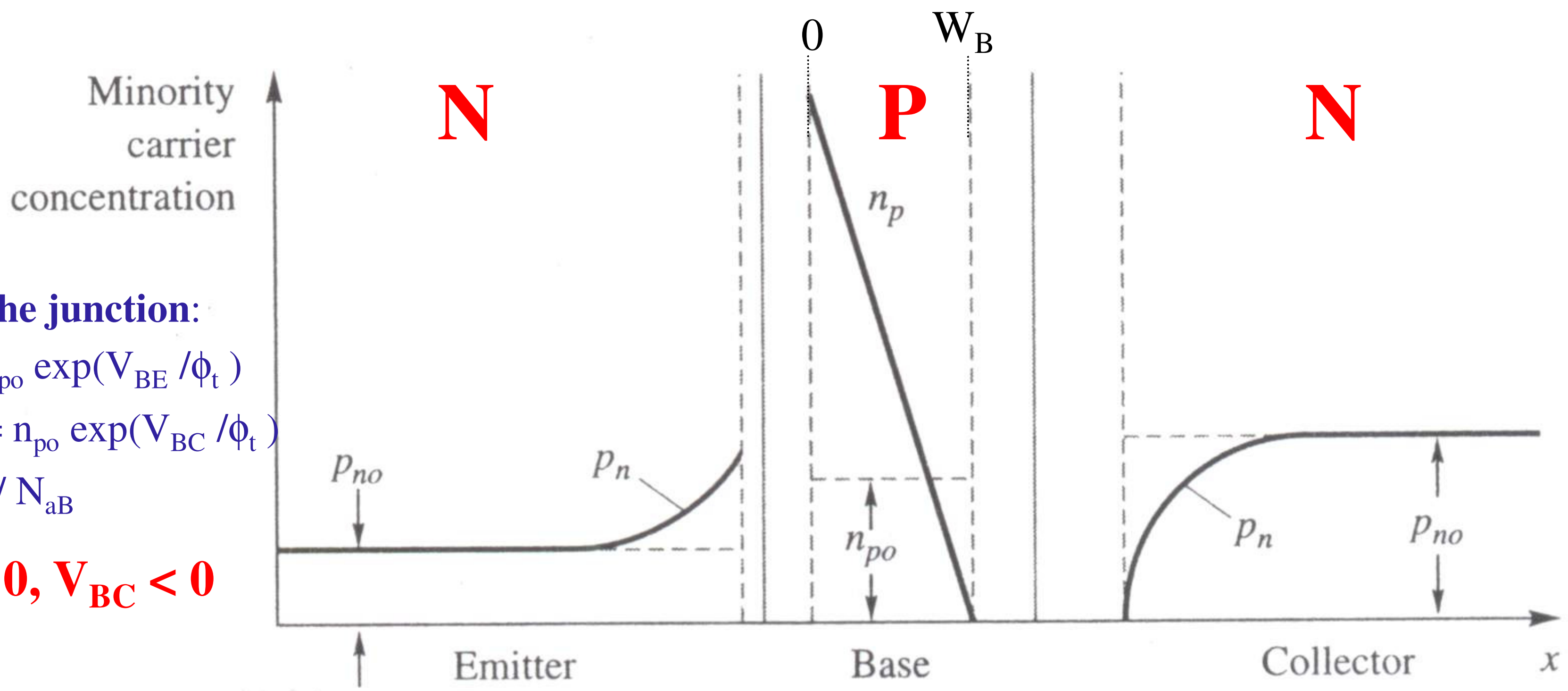
In the QN base (1) becomes

$$\left.\begin{aligned} &\text{Low injection level} \qquad p \cong N_{aB} >> n \\ &\text{High emitter efficiency} \qquad J_n >> J_p \end{aligned}\right\} \frac{pJ_n}{D_n} \cong q\frac{d(pn)}{dx} \quad \text{(2)}$$

For negligible recombination $J_n \cong \text{constant}$. Integrating (2) from 0 to W_B results in

$$J_n \int_0^{W_B} p\,dx \cong qD_n \int_0^{W_B} d(pn) = qD_n \cdot pn\Big|_0^{W_B} \underset{\substack{\uparrow \\ \text{Boltzmann statistics}}}{\cong} -qD_n n_i^2\left[e^{\frac{V_{BE}}{\phi_t}} - e^{\frac{V_{BC}}{\phi_t}}\right]$$

$$\int_0^{W_B} p\,dx \cong \int_0^{W_B} N_{aB}\,dx \rightarrow I_n = AJ_n = -\frac{qAD_n n_i^2}{\int_0^{W_B} N_{aB}\,dx}\left[e^{\frac{V_{BE}}{\phi_t}} - e^{\frac{V_{BC}}{\phi_t}}\right] = -I_S\left[e^{\frac{V_{BE}}{\phi_t}} - e^{\frac{V_{BC}}{\phi_t}}\right]$$



(c) Minority carrier concentrations in the various regions of the transistor.

Law of the junction:

$n_p(0) = n_{po} \exp(V_{BE} / \phi_t)$

$n_p(W_B) = n_{po} \exp(V_{BC} / \phi_t)$

$n_{po} = n_i^2 / N_{aB}$

$V_{BE} > 0, V_{BC} < 0$

For constant impurity concentration in the base and low injection level

$$p \cong N_{aB} \rightarrow \frac{\cancel{p} J_n}{D_n} \cong q \frac{d\left(\cancel{p} n\right)}{dx} \rightarrow \frac{dn}{dx} = \frac{J_n}{qD_n} = \frac{I_n}{qAD_n} \rightarrow \textbf{Diffusion current}$$

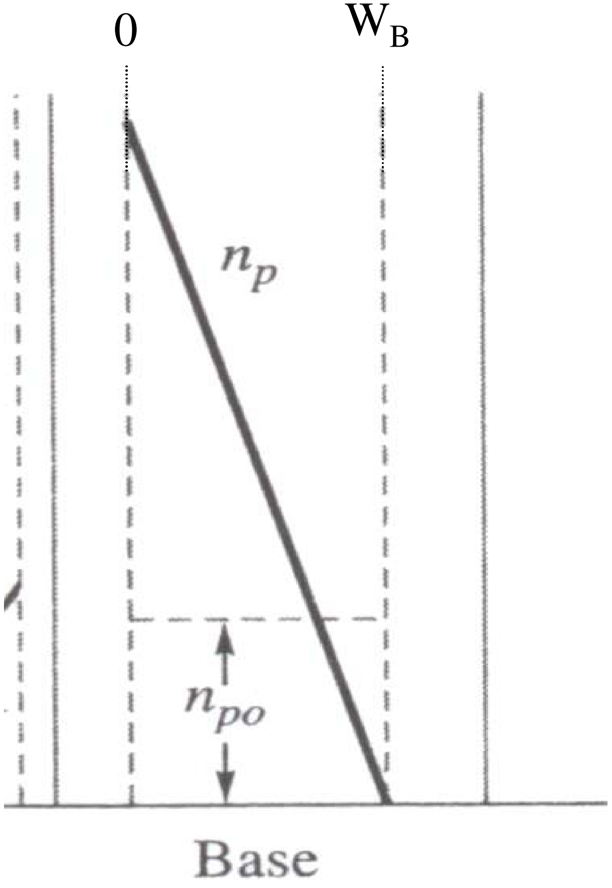
$$I_n = -\frac{qAD_n n_i^2}{\int_0^{W_B} N_{aB} dx}\left[e^{\frac{V_{BE}}{\phi_t}} - e^{\frac{V_{BC}}{\phi_t}}\right] = -\frac{qAD_n n_i^2}{N_{aB} W_B}\left[e^{\frac{V_{BE}}{\phi_t}} - e^{\frac{V_{BC}}{\phi_t}}\right]$$

BJT in the Active Mode

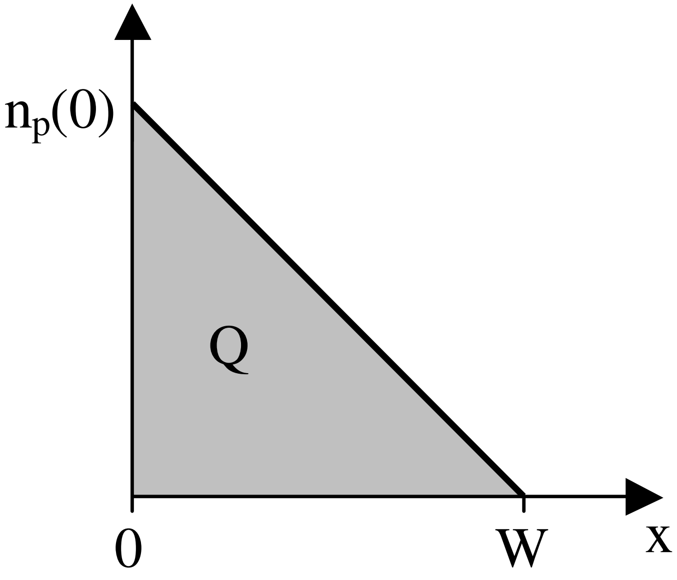
$V_{BE} > 0, V_{BC} < 0$

$$n_{p0} = \frac{n_i^2}{N_{aB}}; \quad n_p(0) = n_{p0} e^{\frac{V_{BE}}{\phi_t}}; \quad n_p(W_B) = n_{p0} e^{\frac{V_{BC}}{\phi_t}}$$

$$n_p(x) \cong n_p(0)\left[1 - \frac{x}{W_B}\right]$$



Forward Transit Time



$$Q = \frac{q\, n_p(0) A_E W}{2}$$

$$\tau_F = \frac{Q}{I_C} = \frac{W^2}{2D_n}$$

If $W = 10^{-4}$ cm (= 1μm),

$D_n = 12.5\ \text{cm}^2/\text{s}$ $(=\mu_n\, \phi_t)$

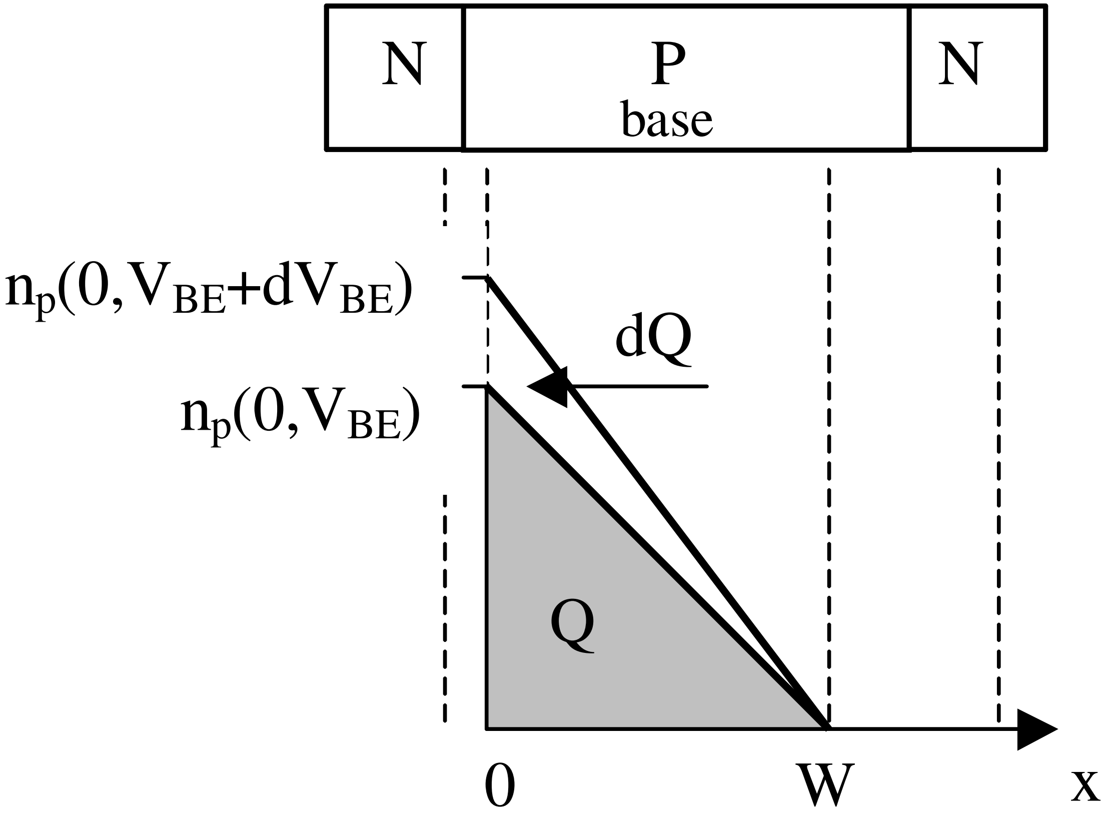
$$\tau_F = \frac{10^{-8}\,\text{cm}^2}{2\text{x}12.5\,\text{cm}^2/\text{s}}$$

$$\boxed{\tau_F = 4\times10^{-10}\,\text{s}}$$

Excess minotity charge stored in the neutral base

Operating frequency $\boxed{f \le \frac{1}{2\,\pi\,\tau_F}}$

Diffusion Capacitance (C_D)



$$C_D = \frac{dQ}{dV_{BE}}$$

$$Q = \tau_F I_C$$

$$I_C = I_S e^{V_{BE}/\phi_t}$$

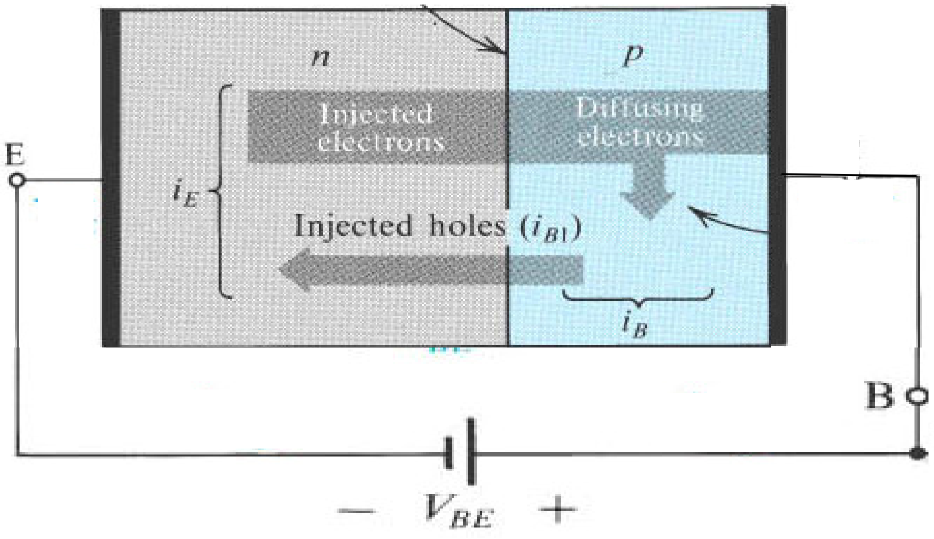
$$\frac{dQ}{dV_{BE}} = \tau_F \frac{dI_C}{dV_{BE}}$$

$$\boxed{C_D = \tau_F \left(\frac{I_C}{\phi_t}\right)}$$

Ex: $\tau_F = 4 \text{ x}10^{-10}\text{s}$, $I_C = 1$ mA → $C_D = 16$ pF

Emitter efficiency

EB junction of npn transistor is an N^+P junction. Electrons from the emitter are injected into the base, but holes from the base are also injected into the emitter. The ratio $\gamma = J_n/J_p$ is designated as emitter efficiency.



Let us, once again, use

$$\frac{pJ_n}{D_n} - \frac{nJ_p}{D_p} = q\frac{d(pn)}{dx} \qquad \textbf{(1)}$$

At the ohmic contacts E and B,

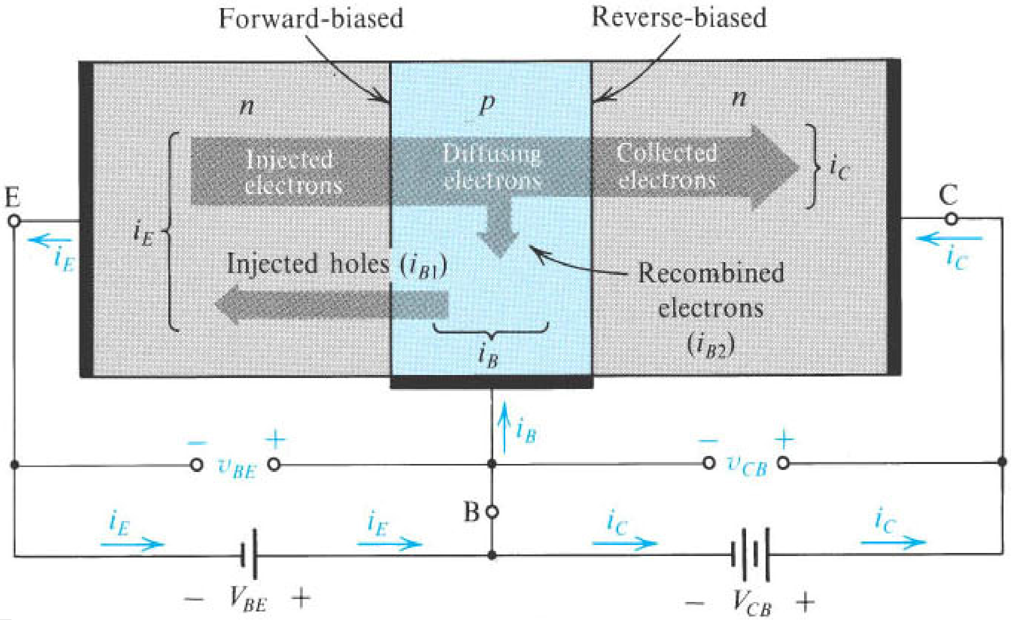
$$pn = n_i^2$$

Integrating (1) from E to B yields

$$\int_E^B \frac{pJ_n dx}{D_n} = \int_E^B \frac{nJ_p dx}{D_p} \xrightarrow[\text{recombination}]{\text{Negligible}} \gamma = \frac{J_n}{J_p} = \frac{D_n}{D_p}\frac{\int_E^B ndx}{\int_E^B pdx} \xrightarrow[\text{injection}]{\text{Low-level}}$$

$$\longrightarrow \int_E^B ndx \cong \int_{\substack{\text{Emitter}\\\text{region}}} N_{dE}dx; \quad \int_E^B pdx \cong \int_{\substack{\text{Base}\\\text{region}}} N_{aB}dx$$

$$\gamma = \frac{J_n}{J_p} = \frac{D_n}{D_p}\frac{\int_{\substack{\text{Emitter}\\\text{region}}} N_{dE}dx}{\int_{\substack{\text{Base}\\\text{region}}} N_{aB}dx}$$



Emitter efficiency

If the recombination current is negligible, we have

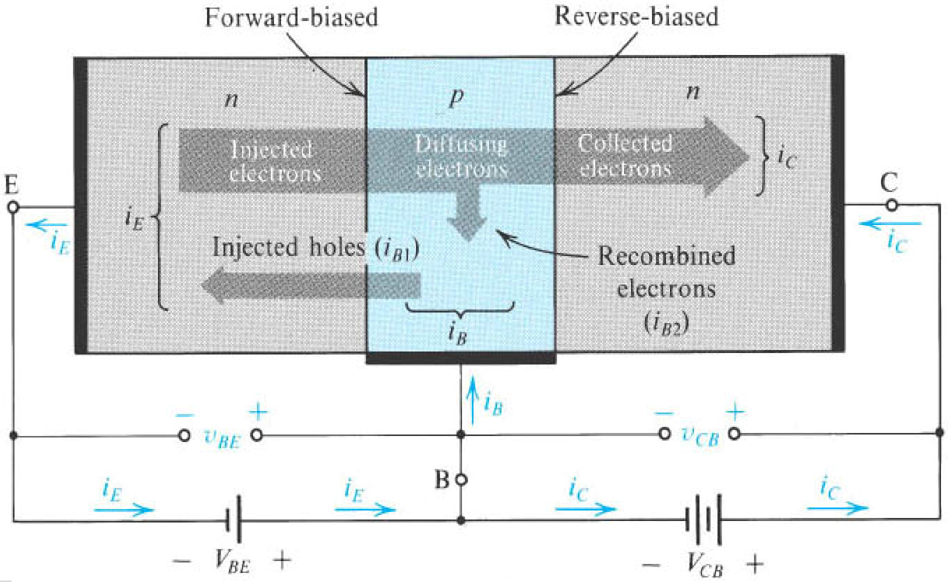
$$I_p = \frac{I_n}{\gamma} = \frac{D_p}{D_n} \frac{\int_{\substack{\text{Base}\\ \text{region}}} N_{aB}\,dx}{\int_{\substack{\text{Emitter}\\ \text{region}}} N_{dE}\,dx} I_n \ll I_n$$

Base transport factor - α_T

$$\alpha_T = \frac{I_{nC}}{I_{nE}} = \frac{1}{\cosh\left(W_B / L_n\right)} \cong 1 - \frac{W_B^2}{2L_n^2}$$

Example: $$\frac{W_B}{L_n} = \frac{0.2\mu\text{m}}{20\mu\text{m}} \rightarrow \alpha_T \cong 1 - \frac{W_B^2}{2L_n^2} = 1 - \frac{1}{20000}$$

The base current



$$I_B = I_{B1} + I_{B2} + I_{B3} \cong \frac{I_C}{\gamma} + (1-\alpha_T) I_C + I_{B3}$$

The Base Current

I_{B1}: holes injected from the base region into the emitter region

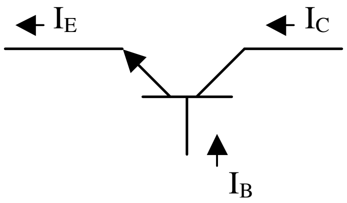
I_{B2}: some electrons that diffuse across the base do not reach the collector, but on the way they recombine with holes. The missing holes must be replaced from the external circuit.

I_{B3} : recombination current in the EB junction (important at low current levels)

Usually $I_{B2} << I_{B1}$ →$I_B \cong I_{B1} + I_{B3}$

$$\boxed{I_E = I_B + I_C}$$

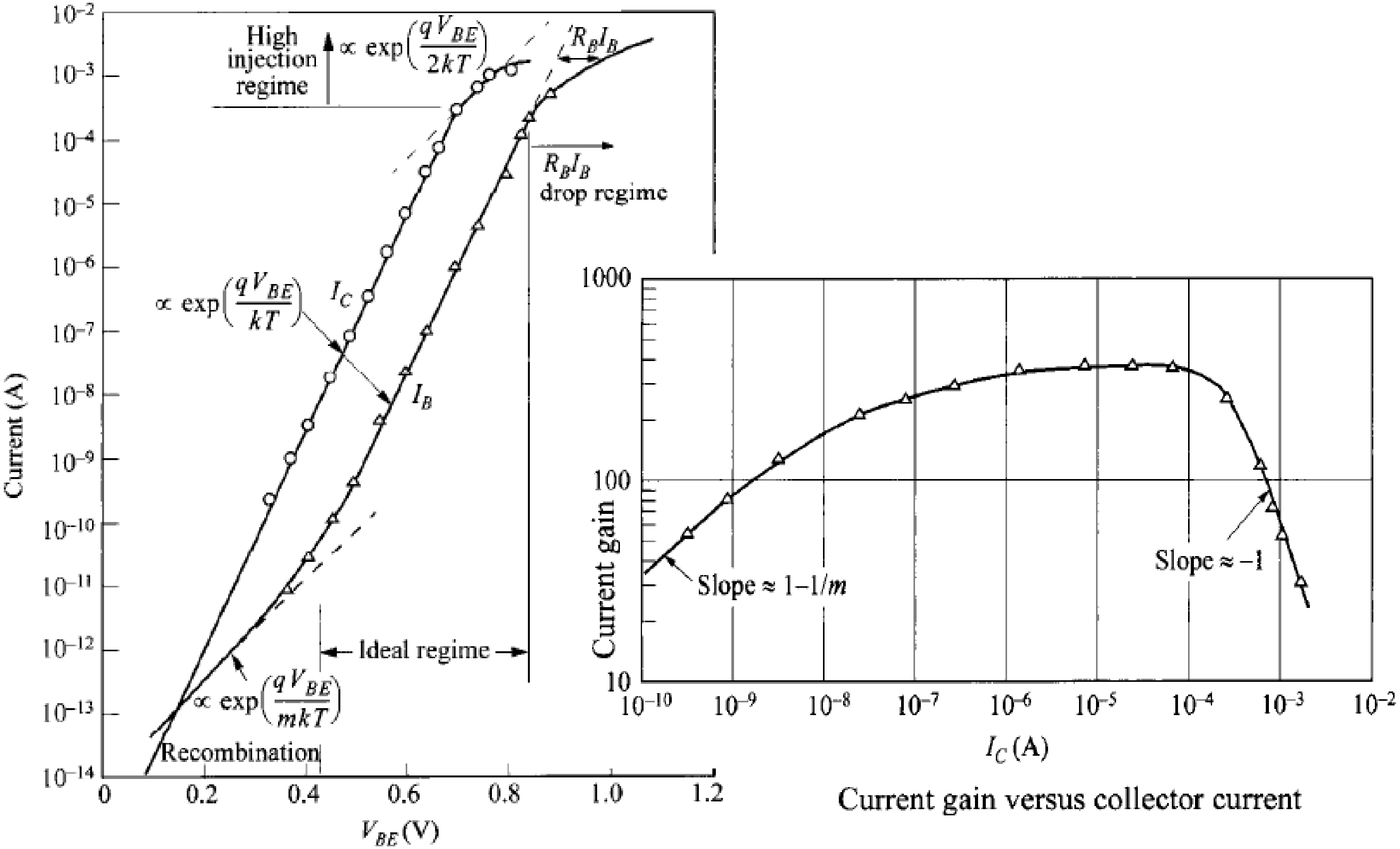
Forward-active mode



$$\boxed{I_C = \alpha_F I_E}$$

$$\boxed{\beta_F = \frac{\alpha_F}{1-\alpha_F}}$$

$$\boxed{I_C = \beta_F I_B}$$

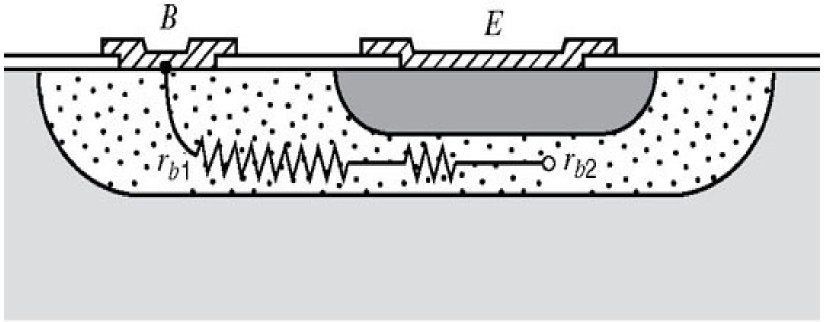


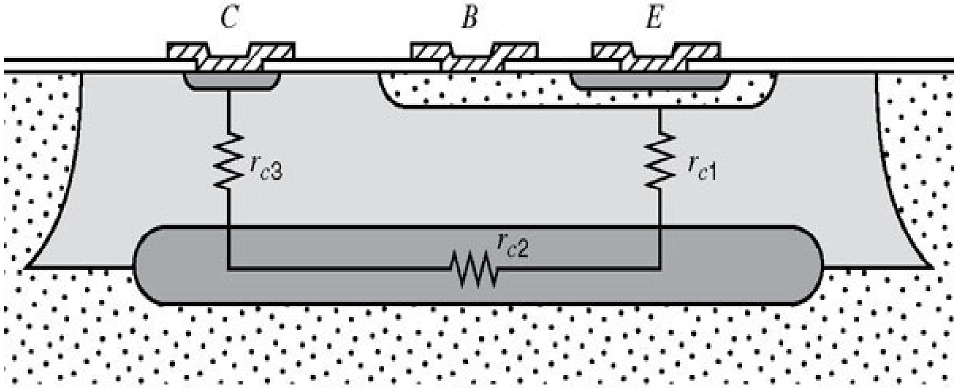
Collector and base currents as a function of base-emitter voltage

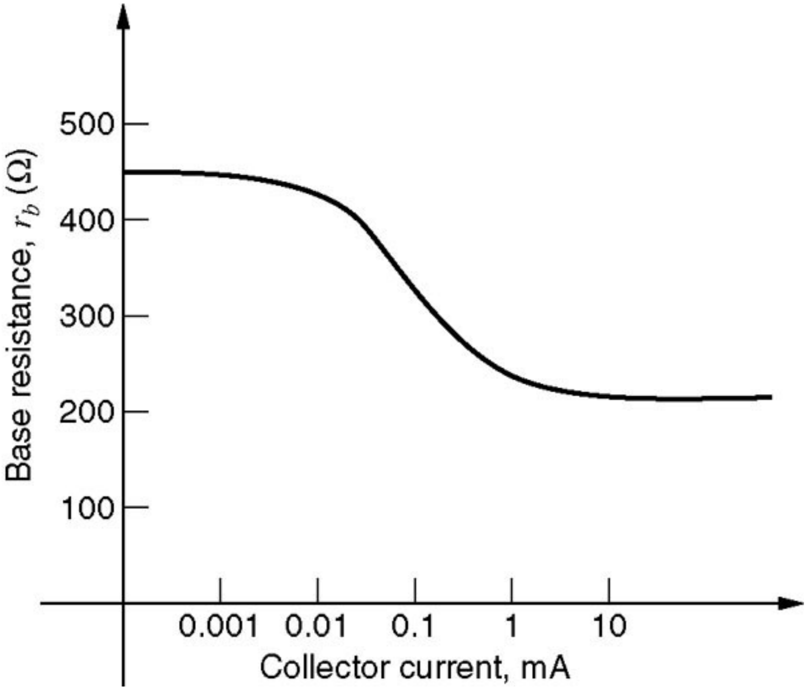
(After Ref. 14.)

Current gain versus collector current

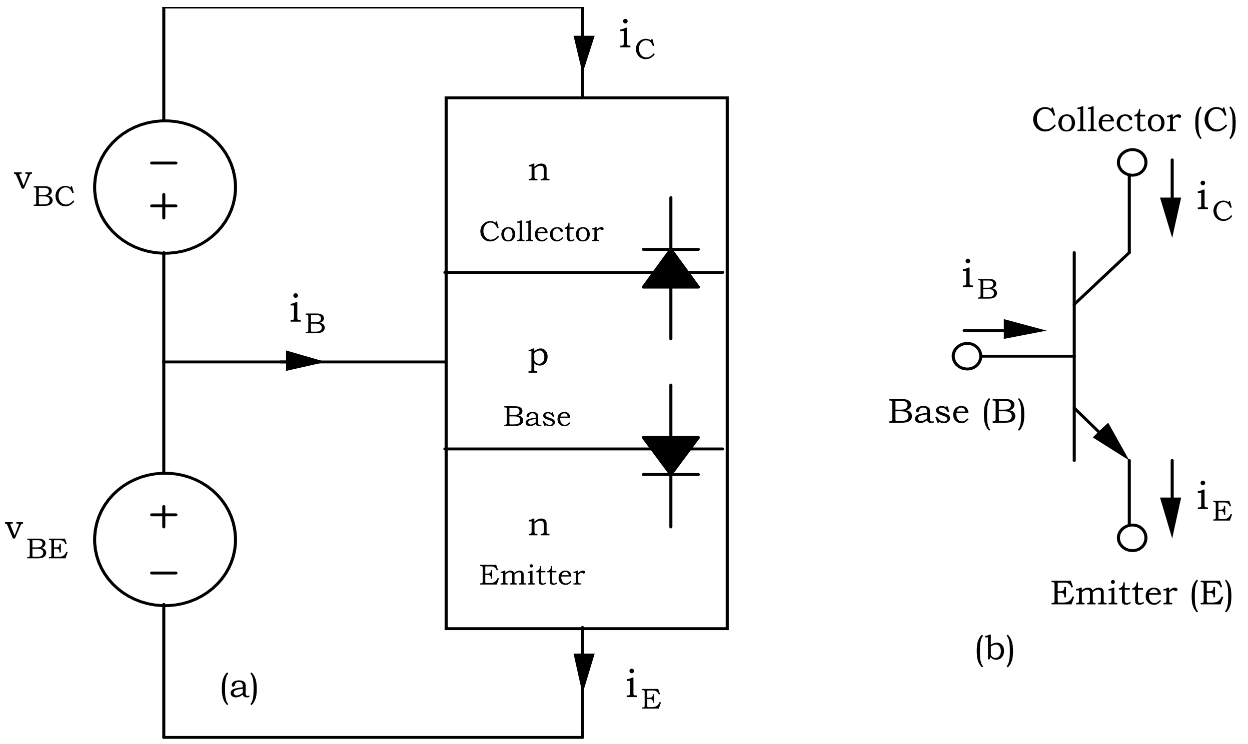
Base and collector resistances







The (Ebers-Moll) Transport Model of the NPN Transistor

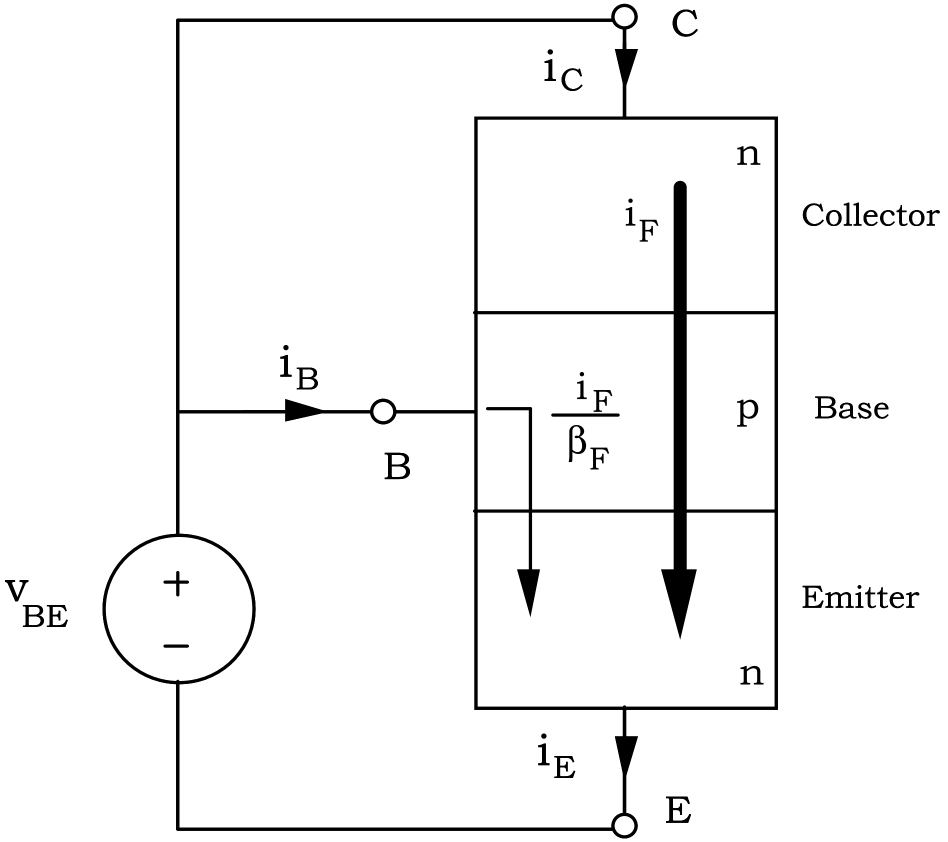


$$i_E = i_B + i_C$$

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

(a) Idealized npn transistor structure for a general bias condition
(b) Circuit symbol for the npn transistor

Forward Transport Current



NPN transistor with $V_{BE} > 0$ and $V_{BC} = 0$.

$$i_C = i_F = I_S\left[\exp\left(\frac{v_{BE}}{\phi_t}\right) - 1\right]$$

$$i_B = \frac{i_F}{\beta_F} = \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{\phi_t}\right) - 1\right]$$

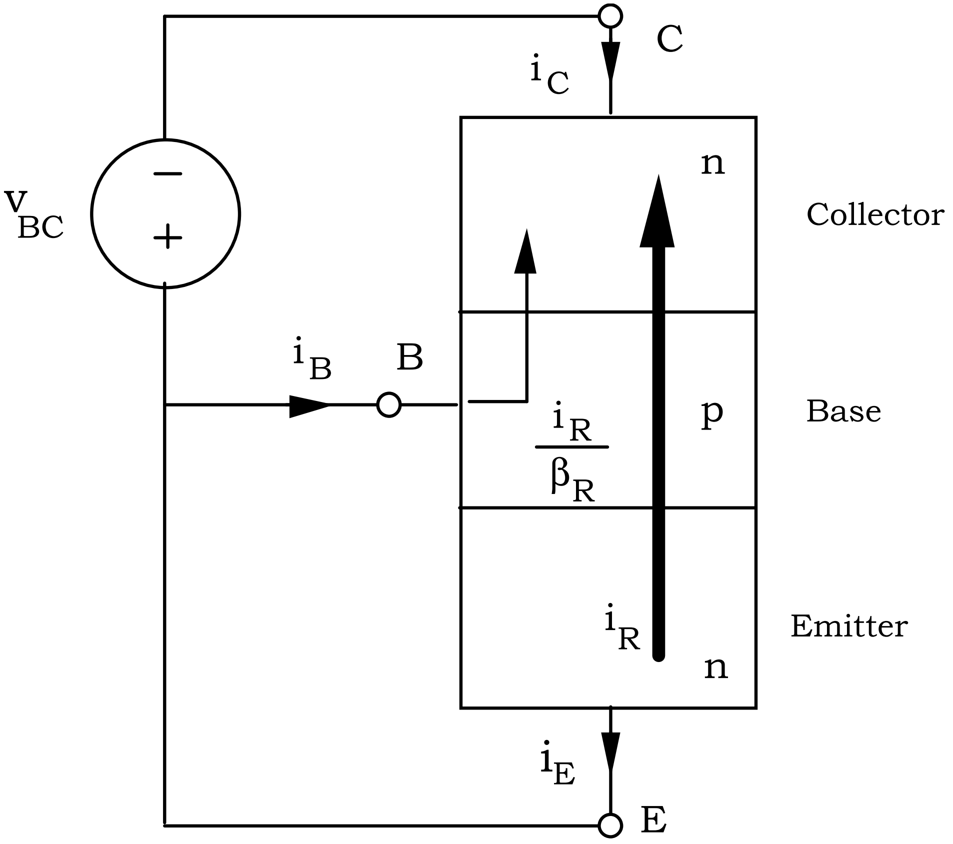
$20 \leq \beta_F \leq 500$ (typically)

β_F: forward common-emitter current gain

$$i_E = i_C + i_B = \frac{\beta_F + 1}{\beta_F} i_C = \frac{i_C}{\alpha_F}$$

α_F: forward common-base current gain

Reverse Transport Current



Transistor with V_{BC} >0 and $V_{BE} = 0$.

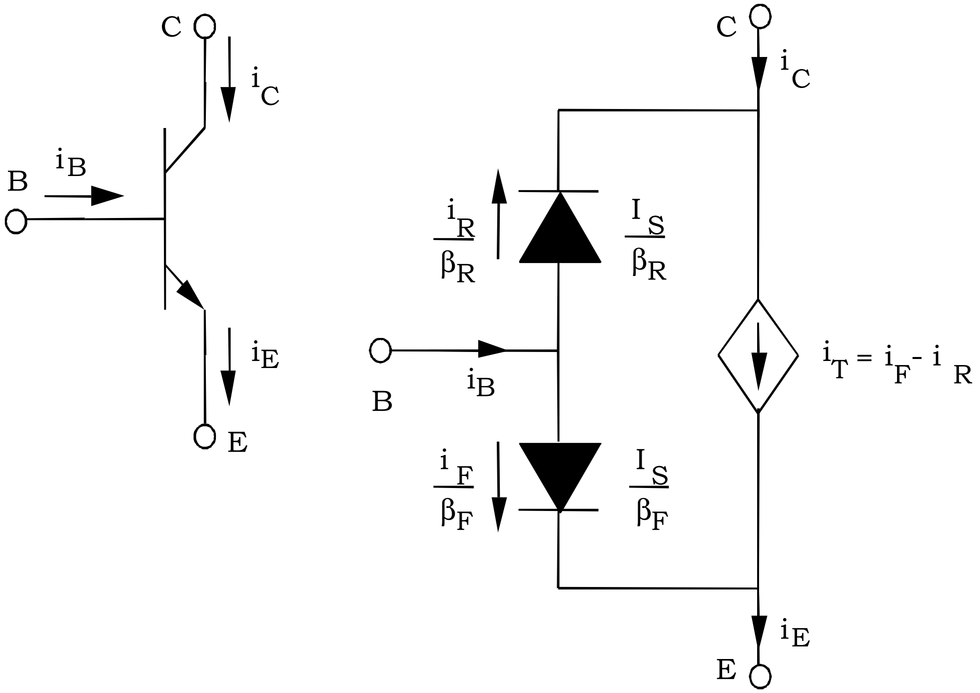
$$i_E = -i_R = -I_S\left[\exp\left(\frac{v_{BC}}{\phi_t}\right) - 1\right]$$

$$i_B = \frac{i_R}{\beta_R} = \frac{-I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{\phi_t}\right) - 1\right]$$

$$0.02 \le \beta_R \le 20$$

$$i_C = \frac{i_E}{\alpha_R} = \frac{\beta_R + 1}{\beta_R} i_E$$

The Transport Model of the NPN Transistor



$$i_F = I_S\left[\exp\left(v_{BE}/\phi_t\right)-1\right]$$

$$i_R = I_S\left[\exp\left(v_{BC}/\phi_t\right)-1\right]$$

$$i_B = \frac{i_F}{\beta_F} + \frac{i_R}{\beta_R}$$

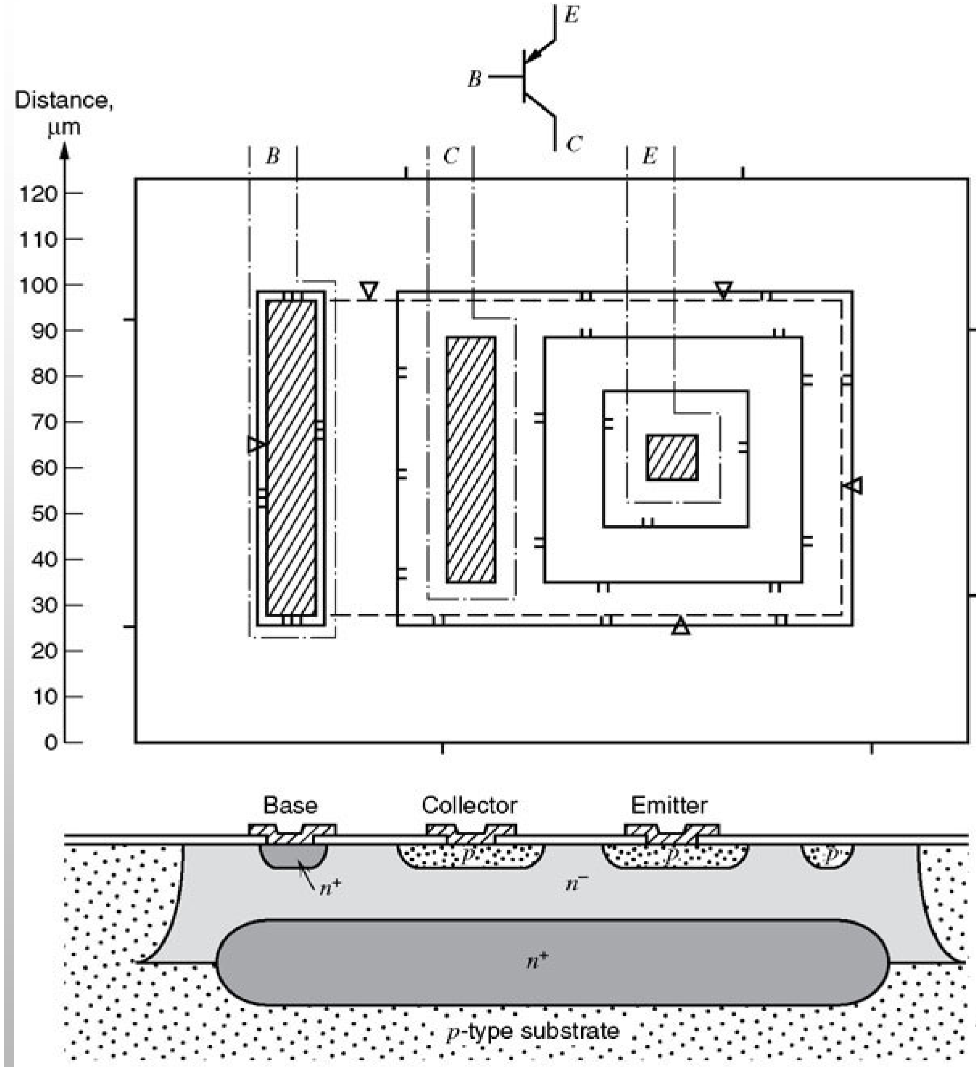
$$i_C = i_T - \frac{i_R}{\beta_R}$$

$$i_E = i_T + \frac{i_F}{\beta_F}$$

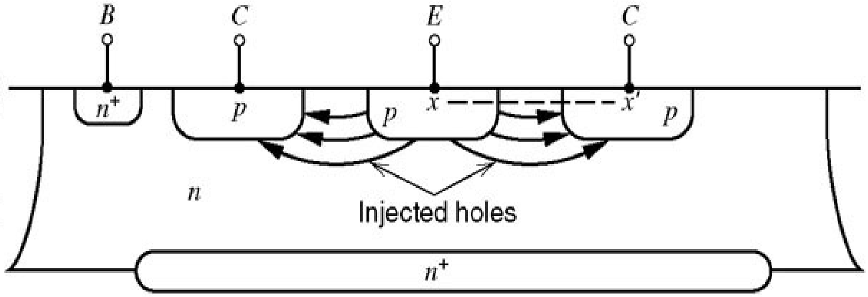
$$i_T = I_S\left[\exp\left(v_{BE}/\phi_t\right)-\exp\left(v_{BC}/\phi_t\right)\right]$$

Transport model equivalent circuit for the npn transistor

The lateral PNP transistor

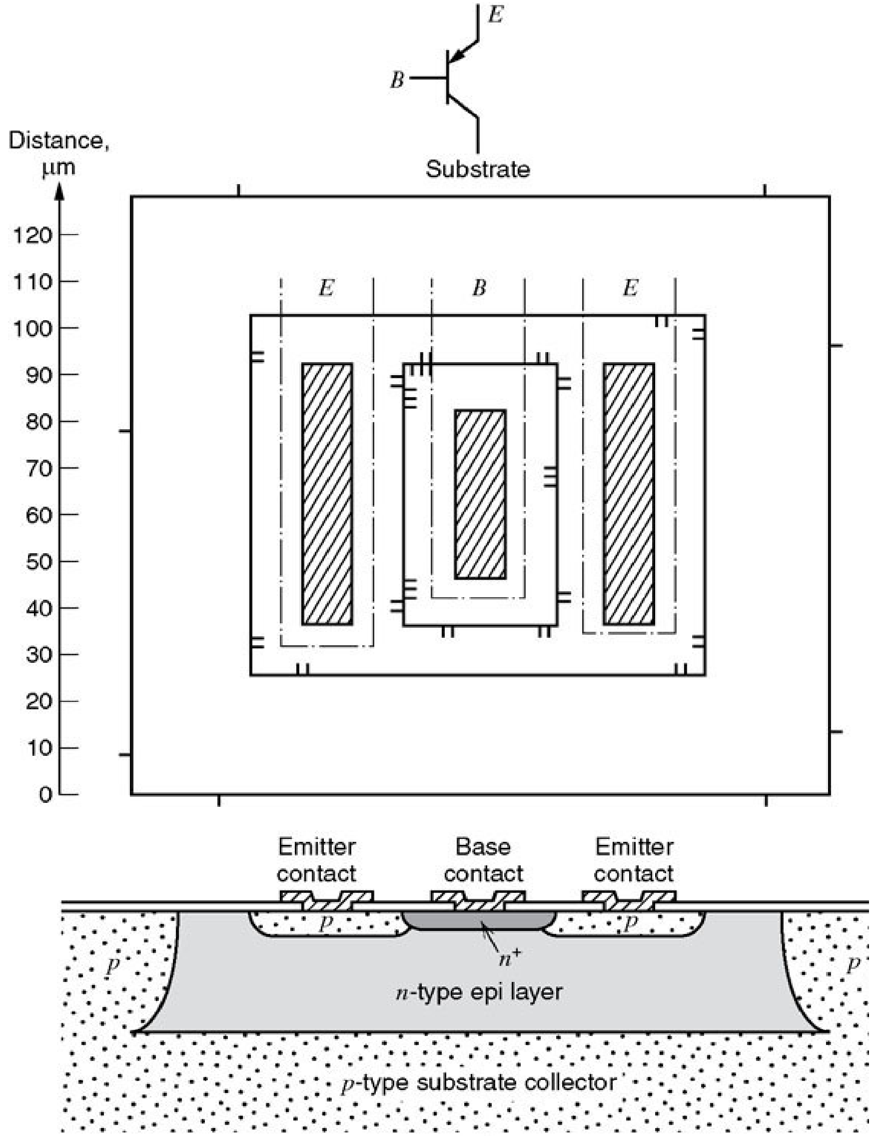


Lateral pnp structure

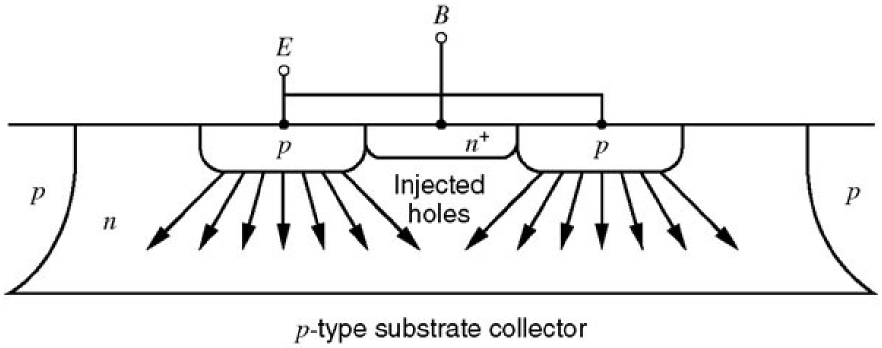


Minority carrier flow in the lateral *pnp* transistor

The substrate PNP transistor

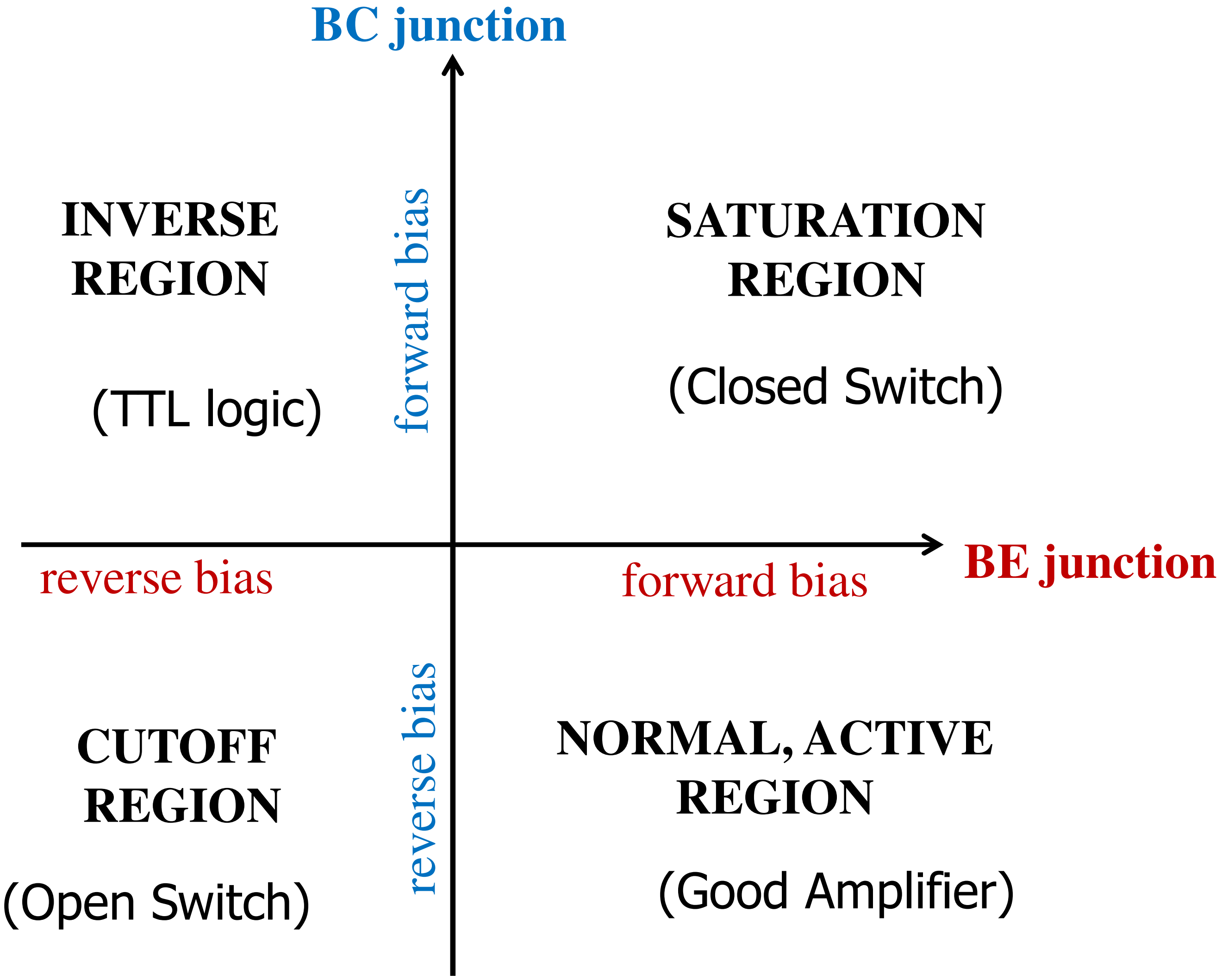


Substrate pnp structure



Minority carrier flow in the substrate *pnp* transistor

Operating regions of the BJT



BC junction

forward bias

reverse bias

BE junction

reverse bias

forward bias

INVERSE REGION

(TTL logic)

SATURATION REGION

(Closed Switch)

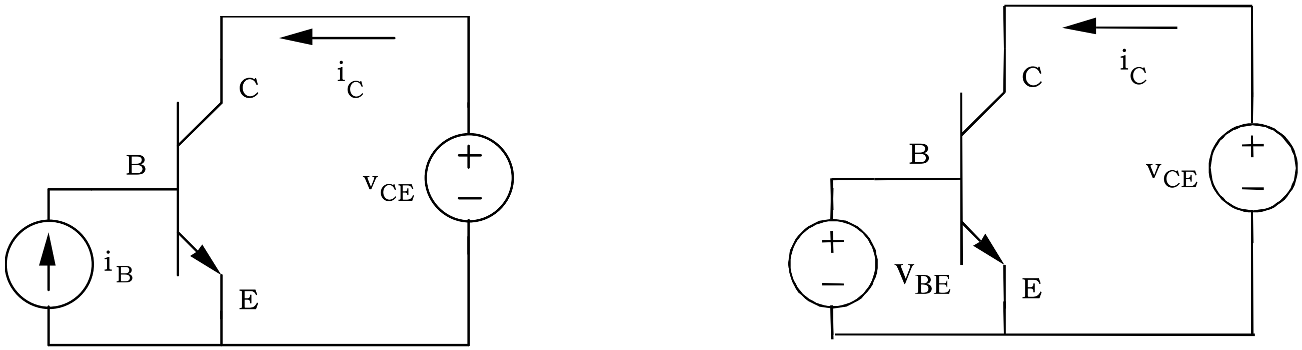
CUTOFF REGION

(Open Switch)

NORMAL, ACTIVE REGION

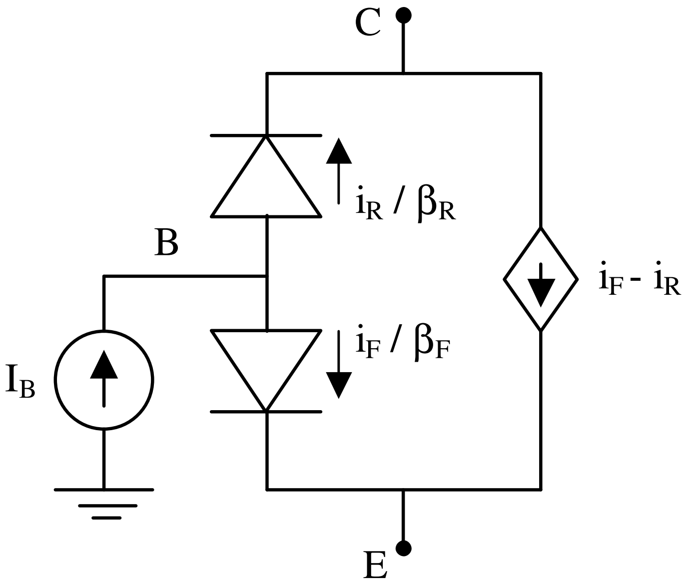
(Good Amplifier)

Graphical Representation of the BJT Characteristics



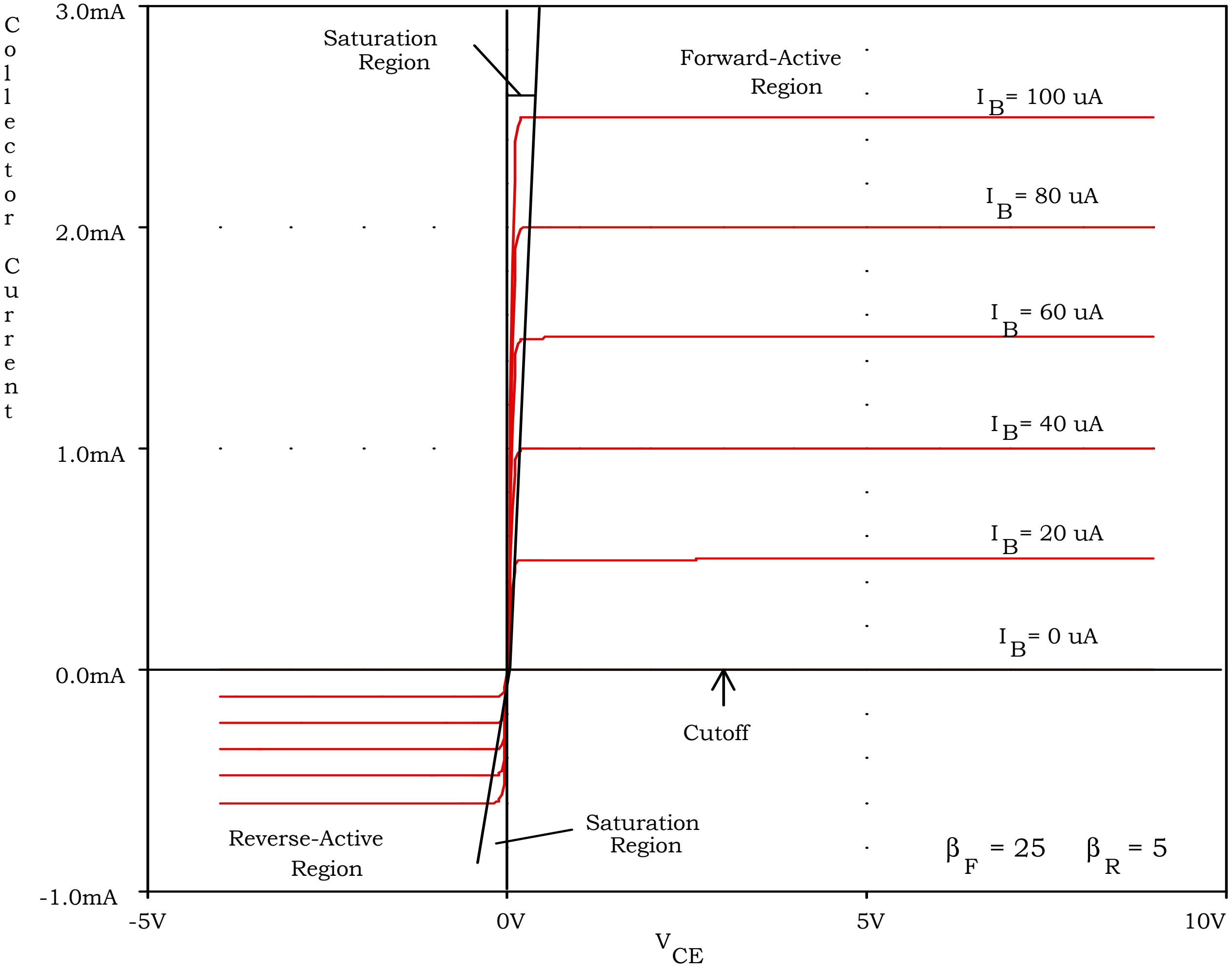
1st quadrant

Circuits for determining the common-emitter output characteristics



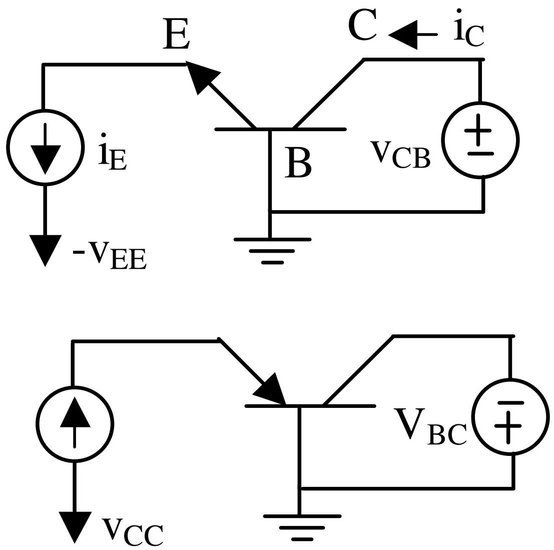
$$\boxed{i_B = \frac{I_S}{\beta_F}\left[\exp\left({}^{v_{BE}}\!/\!{}_{\phi_t}\right)-1\right] + \frac{I_S}{\beta_R}\left[\exp\left({}^{v_{BC}}\!/\!{}_{\phi_t}\right)-1\right]}$$

Graphical Representation of the BJT Characteristics

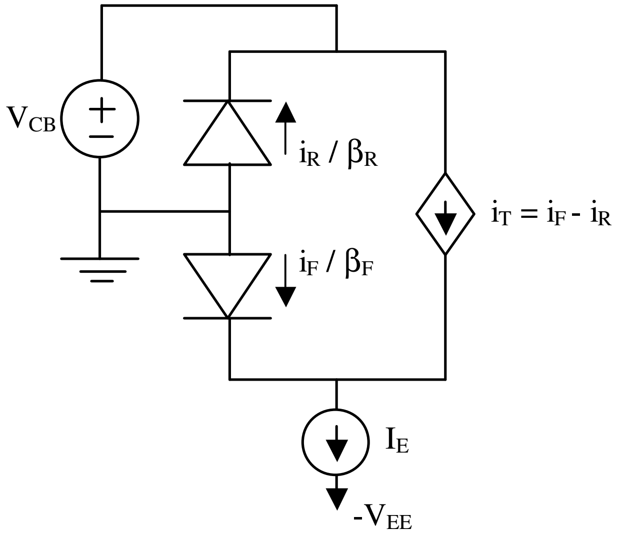


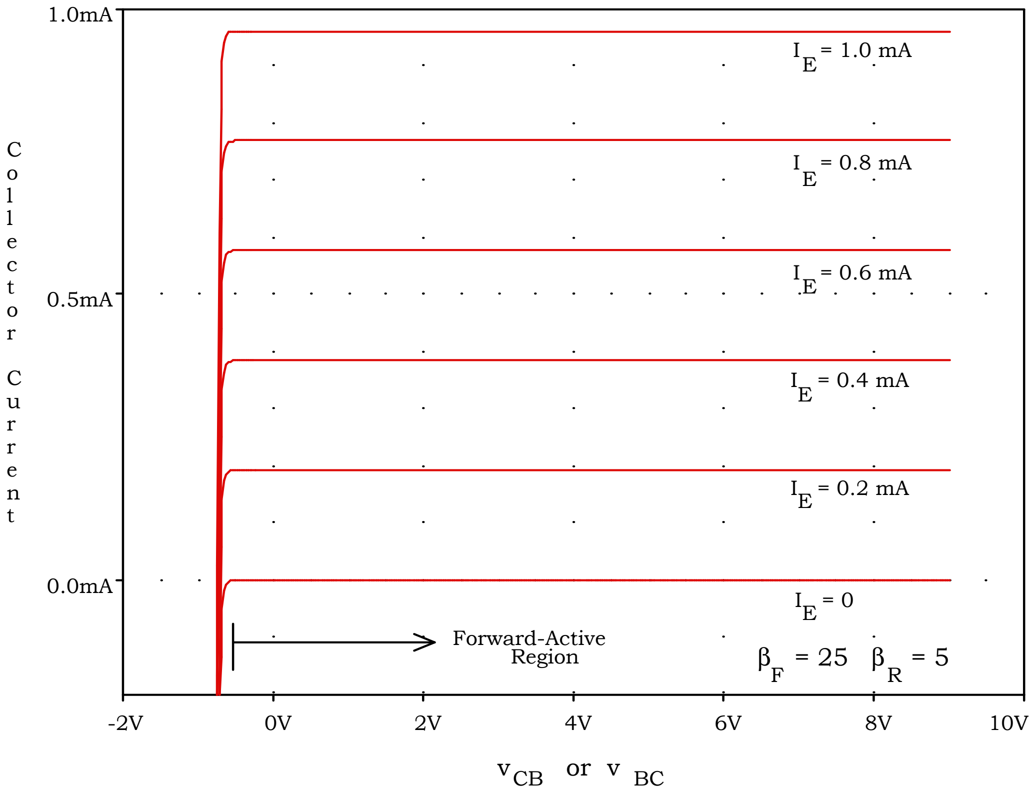
Commom-emitter output characteristics for the BJT

Graphical Representation of the BJT Characteristics



Circuit to determine common-base output characteristics

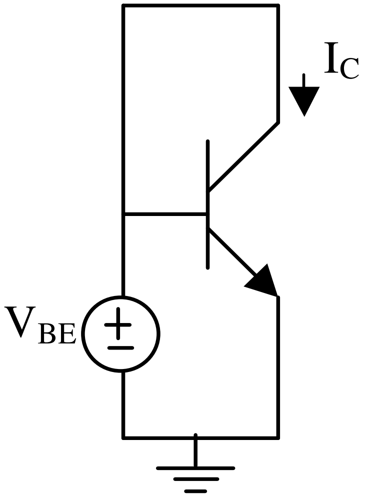


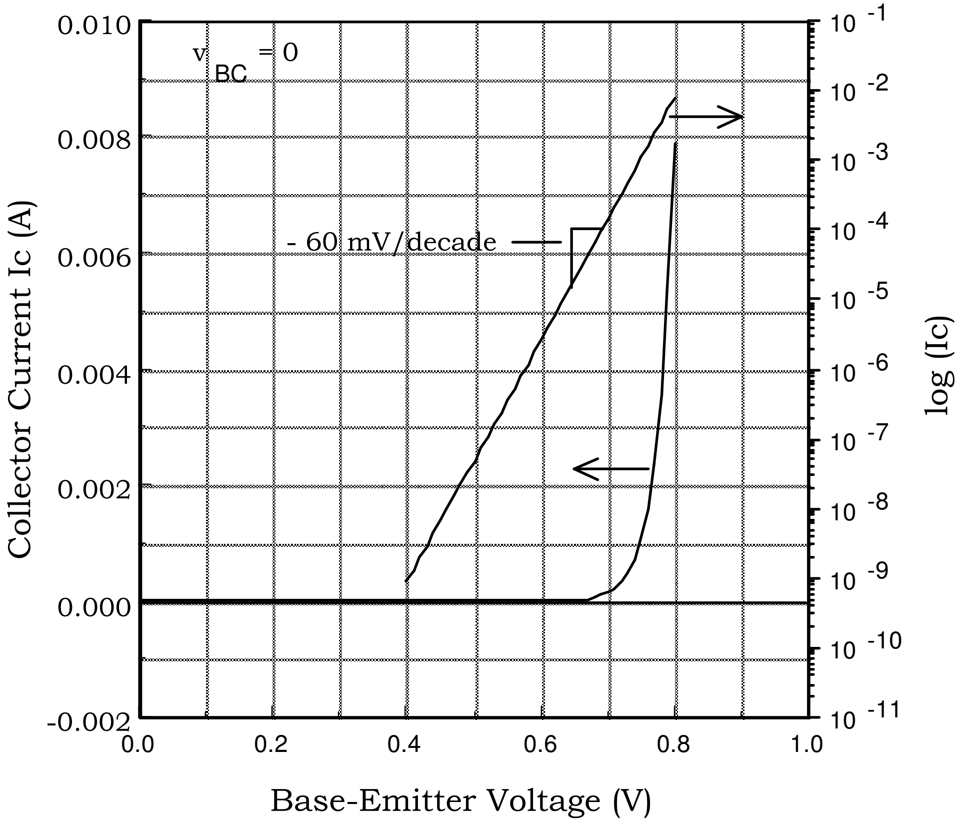


Common-base output characteristics for the BJT
(i_C vs. v_{CB} for npn BJT or i_C vs. v_{BC} for the pnp BJT

Graphical Representation of the BJT Characteristics

$$I_C = I_S\left[\exp\left(\frac{V_{BE}}{\phi_t}\right) - 1\right]$$

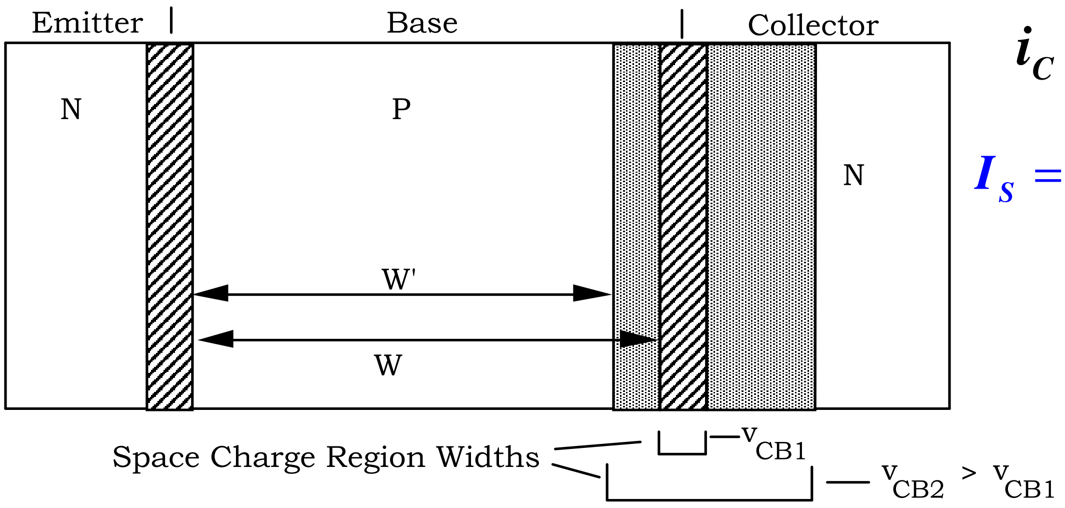




BJT transfer characteristic in the forward-active region

$$\left.\frac{\Delta V_{BE}}{\Delta T}\right|_{I_C} \approx -2 \text{ mV/°C} \longrightarrow$$ **Dependent of I_C**

The Early Effect



Base-width modulation or Early effect

Active mode

$$i_C = I_S \exp\left(v_{BE}/\phi_t\right)$$

$$I_S = \frac{qAD_n n_i^2}{\int_0^{W_B} N_{aB}\,dx}; \rightarrow I_S = \frac{qAD_n n_i^2}{N_{aB}W_B}$$

Uniform base doping

↓

Modulated by V_{CB} (or V_{CE})

Using linear approximation for W_B

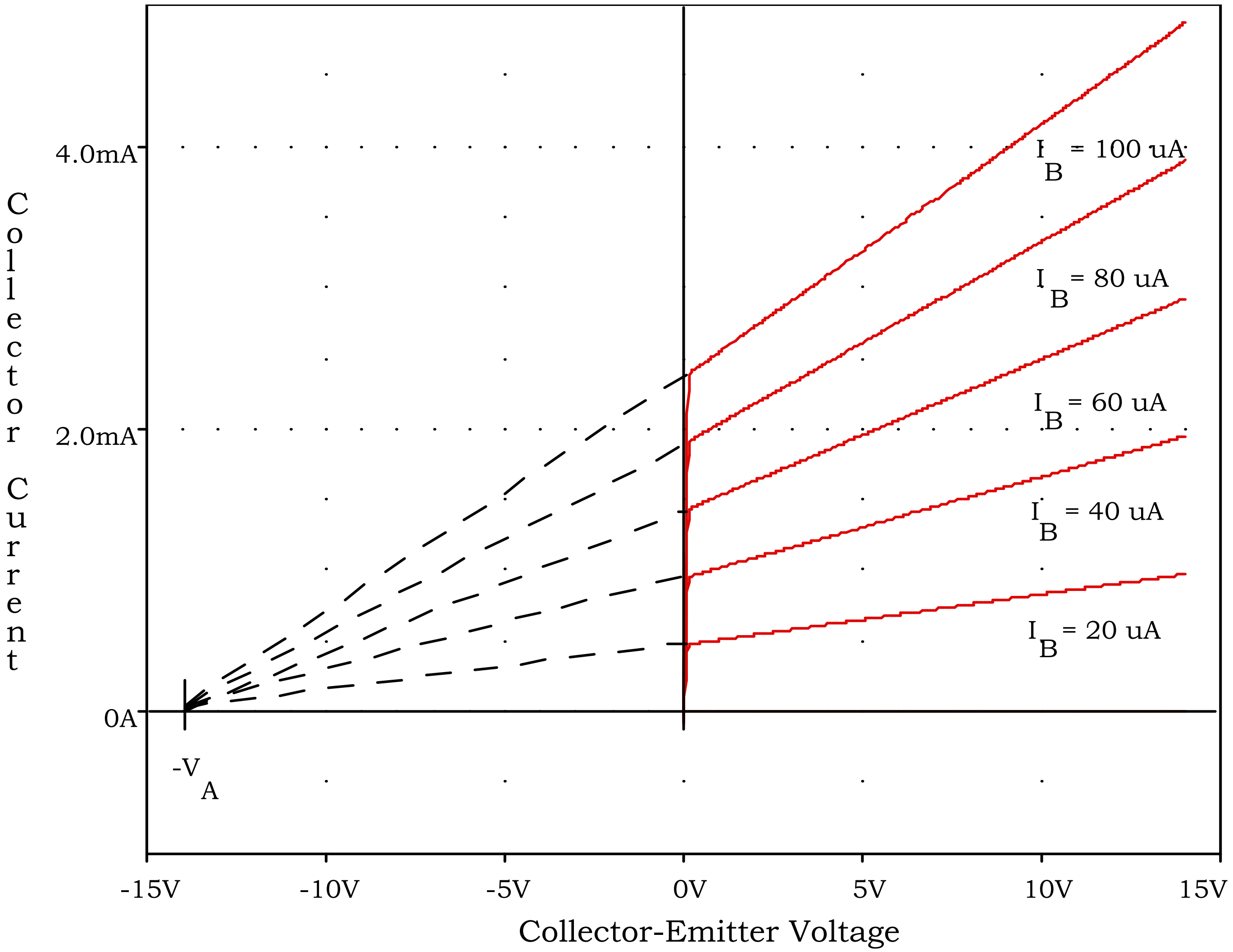
$$W_B = W_{B0}(1 - v_{CE}/V_A) \quad \text{yields}$$

$$i_C = \frac{I_{SO}}{(1 - v_{CE}/V_A)} \exp\left(\frac{v_{BE}}{\phi_t}\right) \cong I_{SO} \exp\left(\frac{v_{BE}}{\phi_t}\right)(1 + v_{CE}/V_A)$$

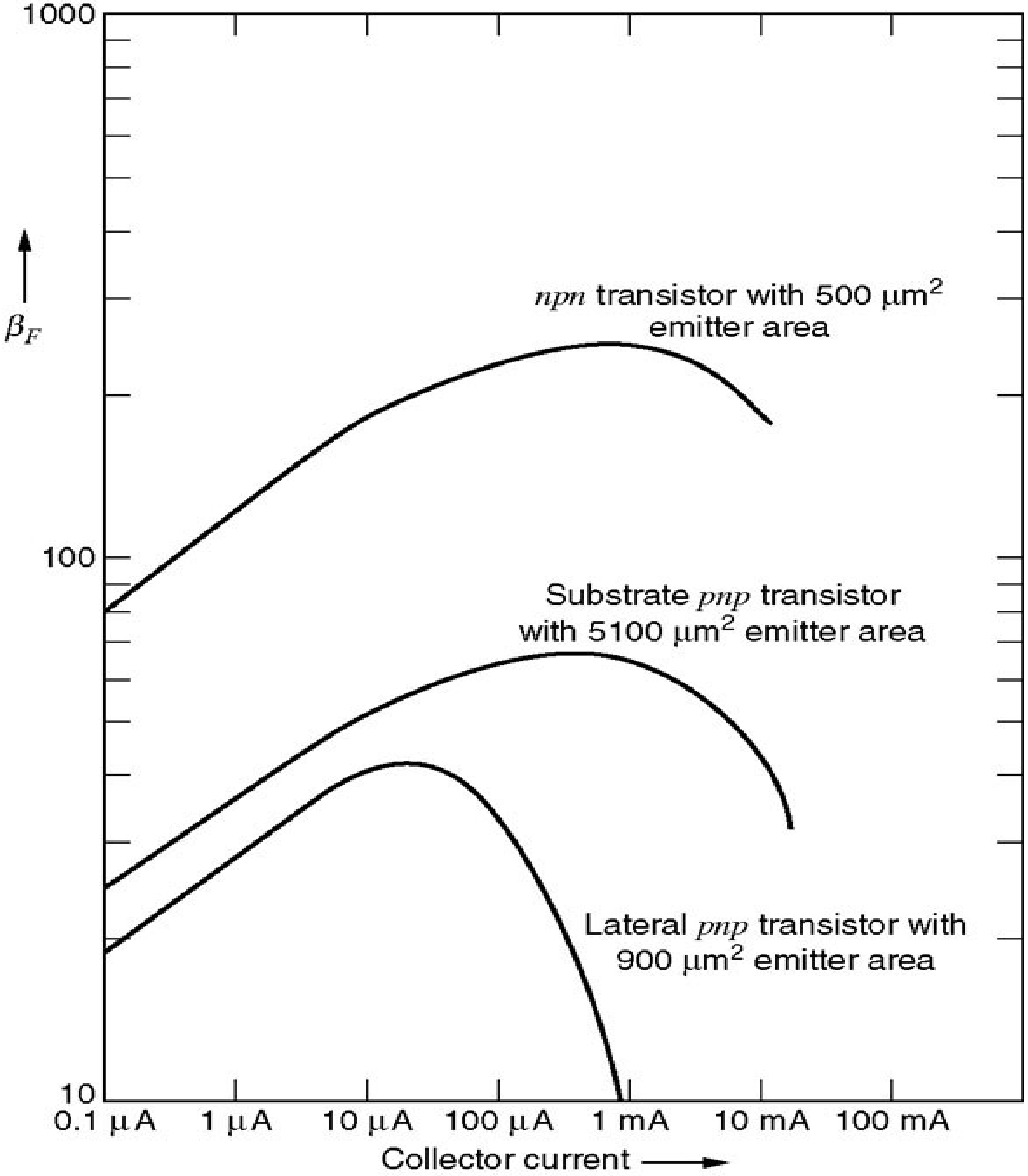
$v_{CE}/V_A \ll 1$

V_A : Early voltage

The Early Voltage



Transistor output characteristics identifying the Early voltage V_A


1000
100
10
β_F
0.1 μA
1 μA
10 μA
100 μA
1 mA
10 mA
100 mA
Collector current
npn transistor with 500 μm² emitter area
Substrate *pnp* transistor with 5100 μm² emitter area
Lateral *pnp* transistor with 900 μm² emitter area

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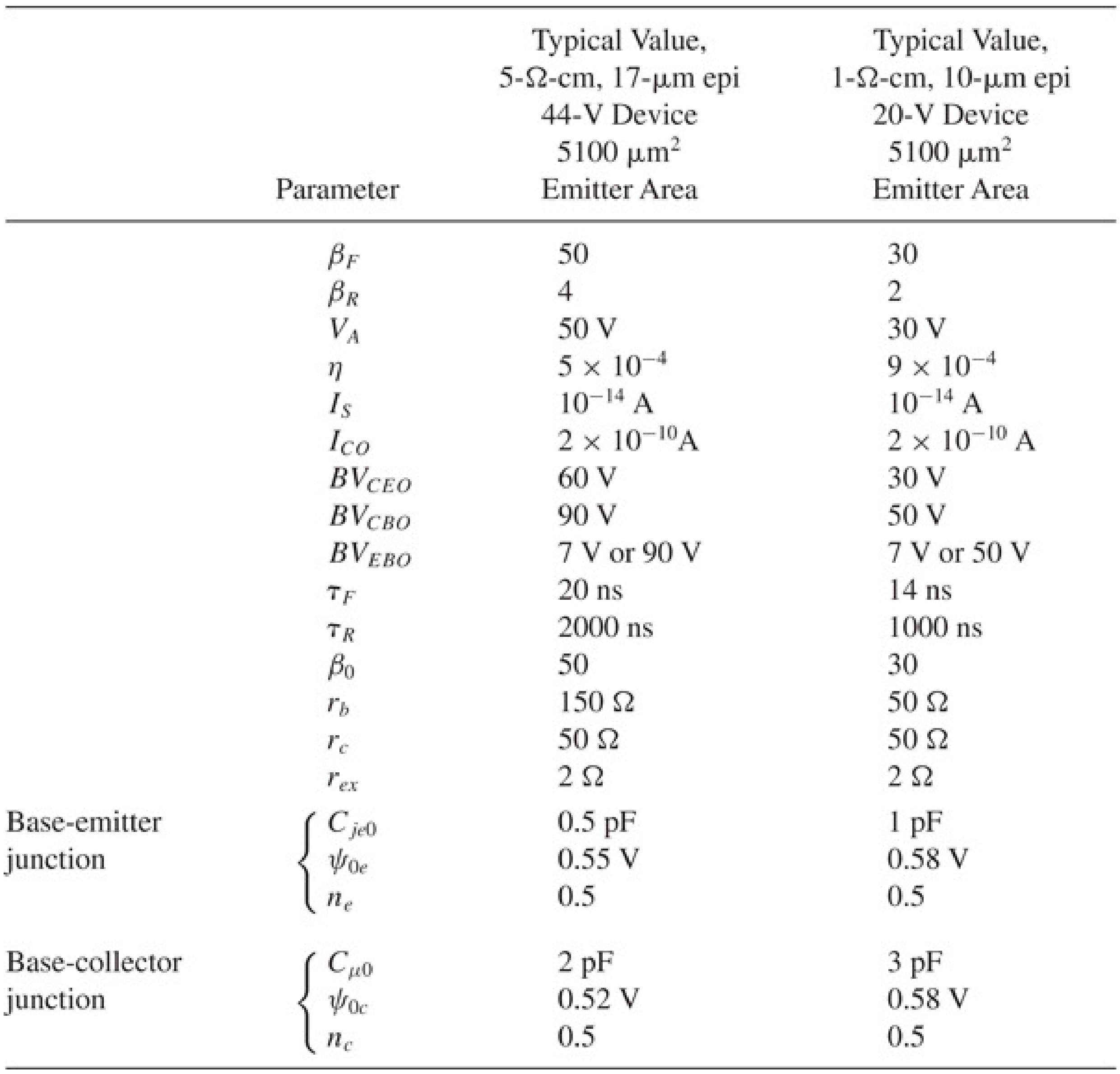
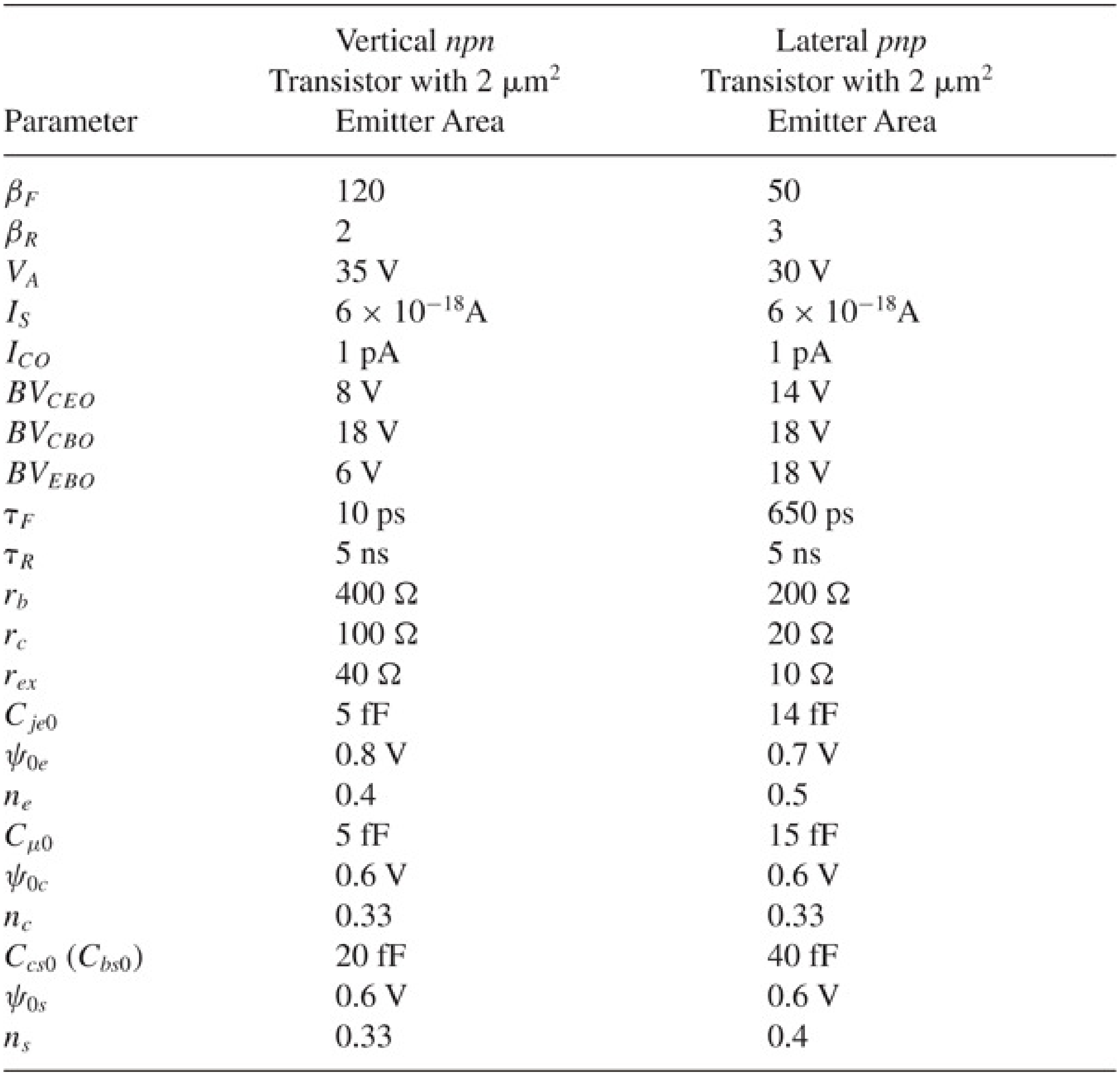


	Parameter	Typical Value, 5-Ω-cm, 17-μm epi 44-V Device 5100 μm^2 Emitter Area	Typical Value, 1-Ω-cm, 10-μm epi 20-V Device 5100 μm^2 Emitter Area
	β_F	50	30
	β_R	4	2
	V_A	50 V	30 V
	η	5×10^{-4}	9×10^{-4}
	I_S	10^{-14} A	10^{-14} A
	I_{CO}	2×10^{-10}A	2×10^{-10} A
	BV_{CEO}	60 V	30 V
	BV_{CBO}	90 V	50 V
	BV_{EBO}	7 V or 90 V	7 V or 50 V
	τ_F	20 ns	14 ns
	τ_R	2000 ns	1000 ns
	β_0	50	30
	r_b	150 Ω	50 Ω
	r_c	50 Ω	50 Ω
	r_{ex}	2 Ω	2 Ω
Base-emitter junction	C_{je0}	0.5 pF	1 pF
	ψ_{0e}	0.55 V	0.58 V
	n_e	0.5	0.5
Base-collector junction	$C_{\mu 0}$	2 pF	3 pF
	ψ_{0c}	0.52 V	0.58 V
	n_c	0.5	0.5



Parameter	Vertical *npn* Transistor with 2 μm^2 Emitter Area	Lateral *pnp* Transistor with 2 μm^2 Emitter Area
β_F	120	50
β_R	2	3
V_A	35 V	30 V
I_S	6×10^{-18}A	6×10^{-18}A
I_{CO}	1 pA	1 pA
BV_{CEO}	8 V	14 V
BV_{CBO}	18 V	18 V
BV_{EBO}	6 V	18 V
τ_F	10 ps	650 ps
τ_R	5 ns	5 ns
r_b	400 Ω	200 Ω
r_c	100 Ω	20 Ω
r_{ex}	40 Ω	10 Ω
C_{je0}	5 fF	14 fF
ψ_{0e}	0.8 V	0.7 V
n_e	0.4	0.5
$C_{\mu 0}$	5 fF	15 fF
ψ_{0c}	0.6 V	0.6 V
n_c	0.33	0.33
C_{cs0} (C_{bs0})	20 fF	40 fF
ψ_{0s}	0.6 V	0.6 V
n_s	0.33	0.4