TBJ DISPOSITIVO ELECTRONICOS
2016

Transistor Bipolar

Tipos de Transistores

- TRANSISTORES
  - BIPOLARES DE JUNTURA
    - NPN
    - PNP
  - EFECTO DE CAMPO FET
    - UNIÓN
      - CANAL N (JFET-N)
      - CANAL P (JFET-P)
    - METAL-OXIDO-SEMICONDUCTOR MOS
      - CANAL N (MOSFET-N)
      - CANAL P (MOSFET-P)

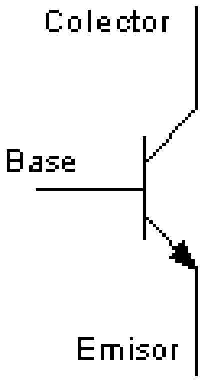
*** FET : Field Effect Transistor**

Definición Cualitativa

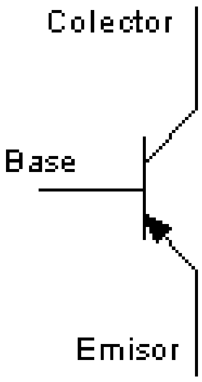
- **Dispositivo Semiconductor de 3 terminales**

- **Función en el circuito:**
  - **Amplificar Corriente**
  - **Fuente de Corriente**
  - **Llave Electrónica**

- **Tipos de Transistores:**
  - **NPN**
  - **PNP**



NPN



PNP

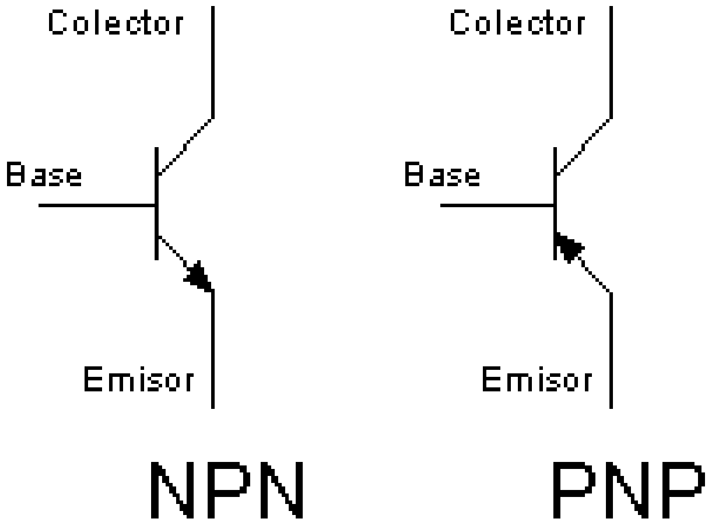
- **Símbolos que lo representan en el Circuito**

Definición

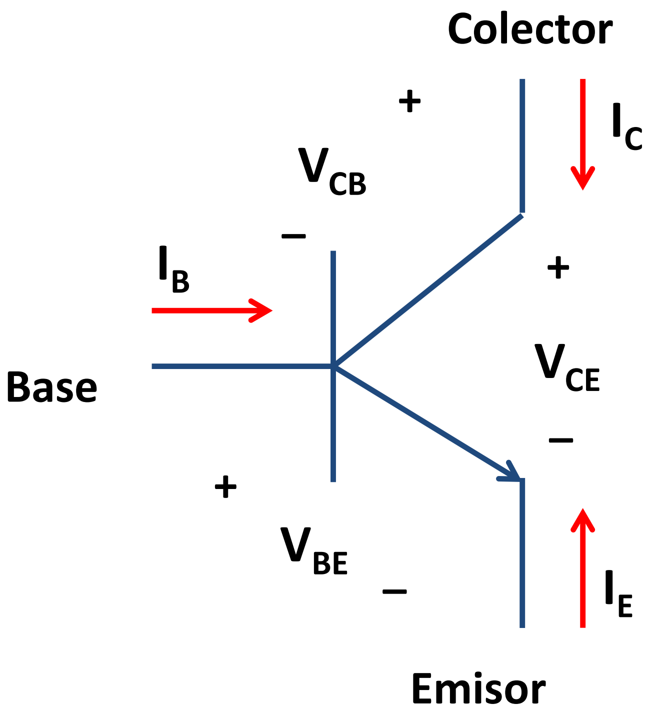
El transistor es un dispositivo de 3 terminales con los siguientes nombres: Base (B), Colector (C) y Emisor (E), coincidiendo siempre, el emisor, con el terminal que tiene la flecha en el gráfico de transistor.

El transistor es un Amplificador de Corriente, esto quiere decir que si le introducimos una corriente por el terminal de Base (IB), entregará por el terminal de Colector (IC), una corriente mayor en un factor que se llama ganancia de corriente en emisor común (β) - IC = β IB

El factor β (Beta) es un parámetro del transistor.

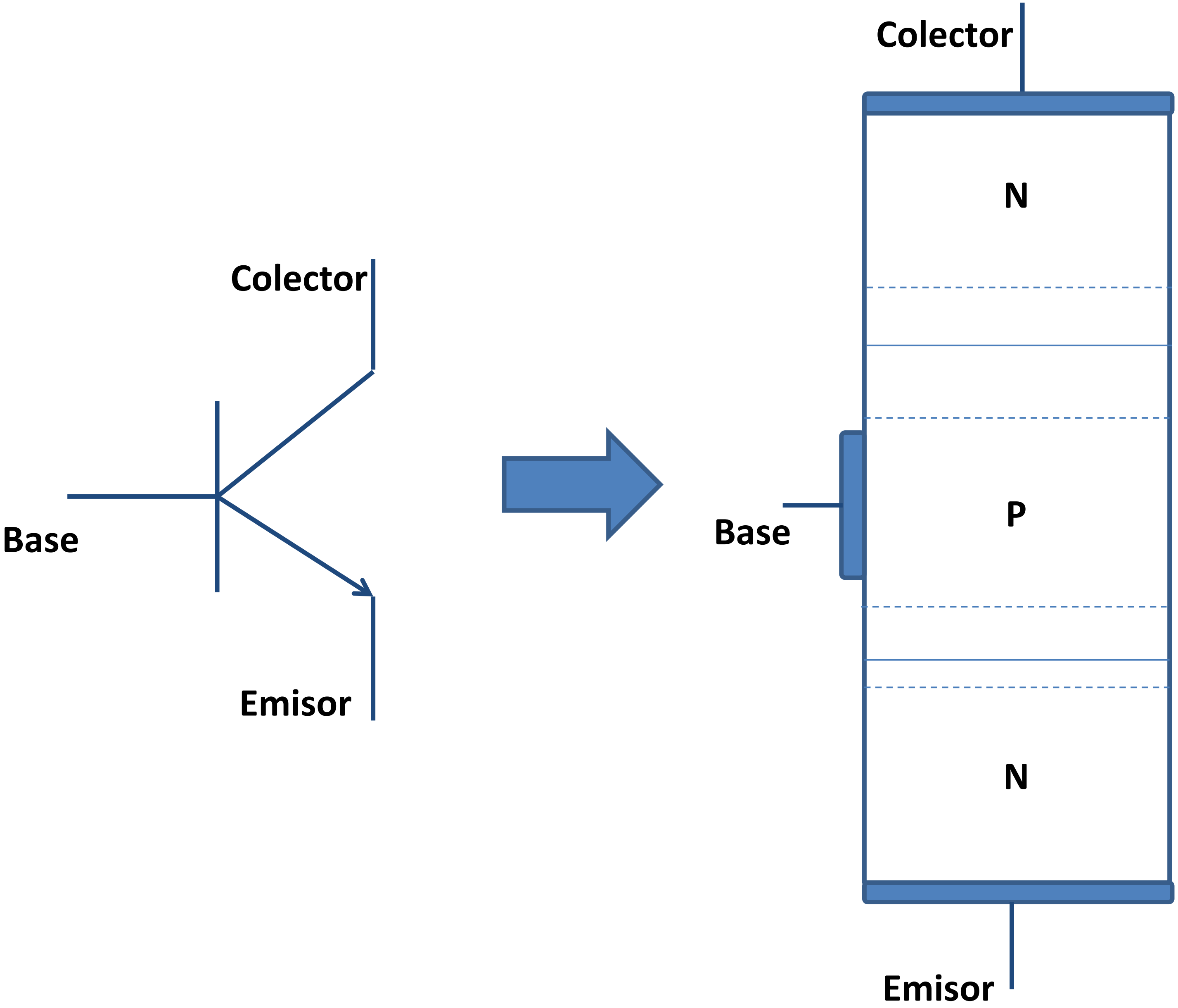


Convenciones V-I

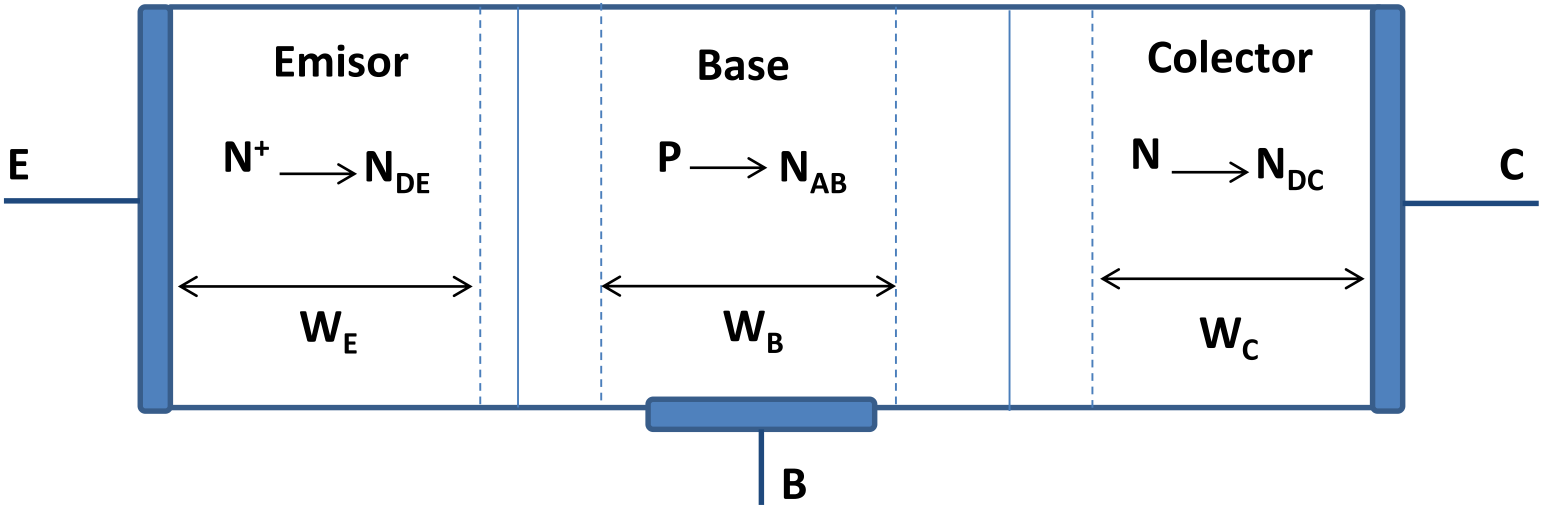


- Corrientes positivas cuando entran al dispositivo
- Tensiones indicadas por subíndices

Estructura Física



Estructura Física



E

Emisor

$N^{+} \longrightarrow N_{DE}$

W_E

Base

$P \longrightarrow N_{AB}$

W_B

Colector

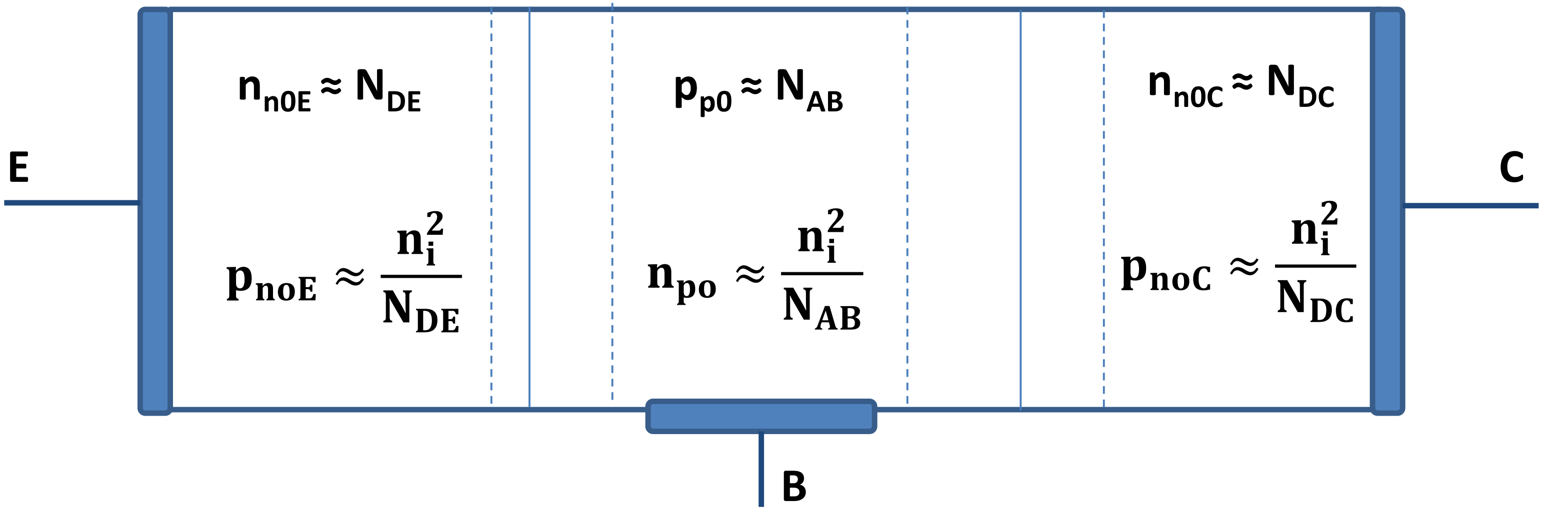
$N \longrightarrow N_{DC}$

W_C

C

B

Concentración de portadores



E

$n_{n0E} \approx N_{DE}$

$$p_{noE} \approx \frac{n_i^2}{N_{DE}}$$

$p_{p0} \approx N_{AB}$

$$n_{po} \approx \frac{n_i^2}{N_{AB}}$$

$n_{n0C} \approx N_{DC}$

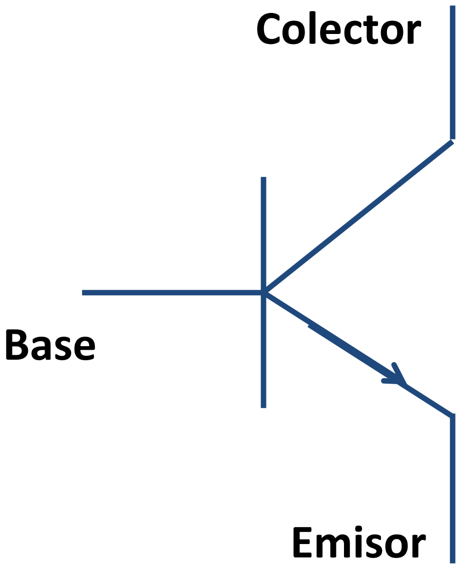
$$p_{noC} \approx \frac{n_i^2}{N_{DC}}$$

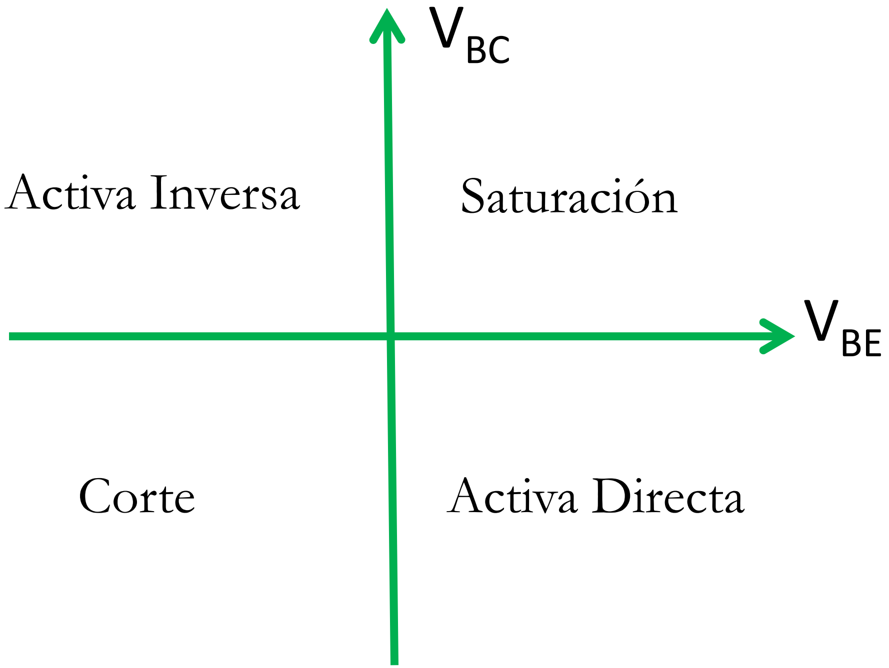
C

B

Zonas de Operación

Juntura B-E	Juntura B-C	Zona de Operación
Directa	Inversa	**Activa Directa**
Directa	Directa	**Saturación**
Inversa	Inversa	**Corte**
Inversa	Directa	**Activa Inversa**

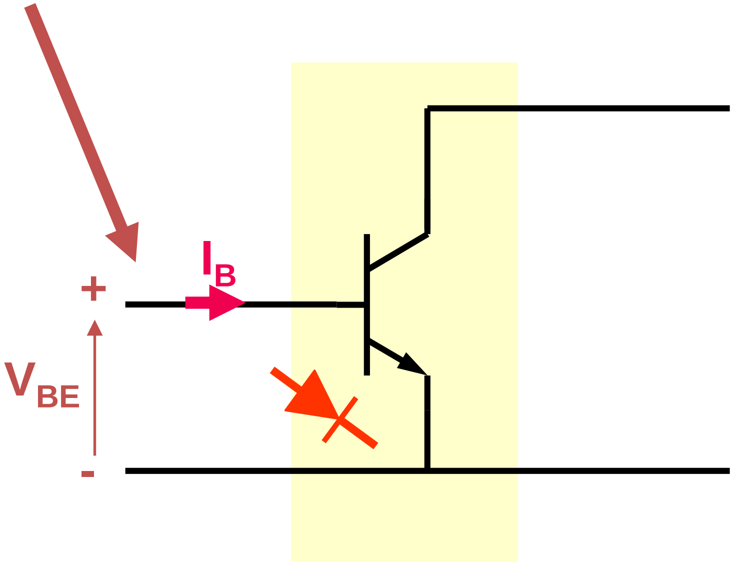


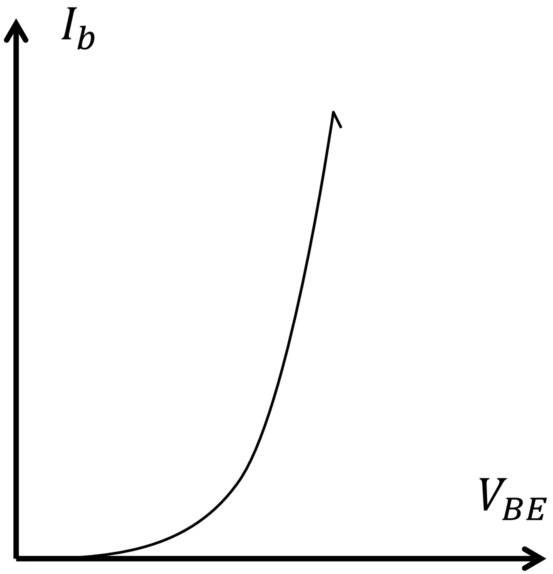


Características V-I de Base

Transistor NPN

$I_B = f(V_{BE}, V_{CE})$ Característica de entrada

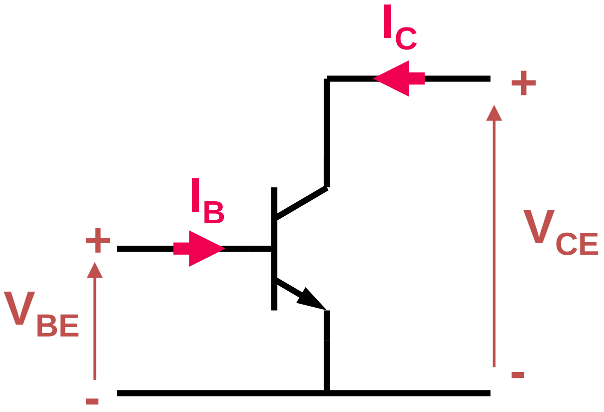


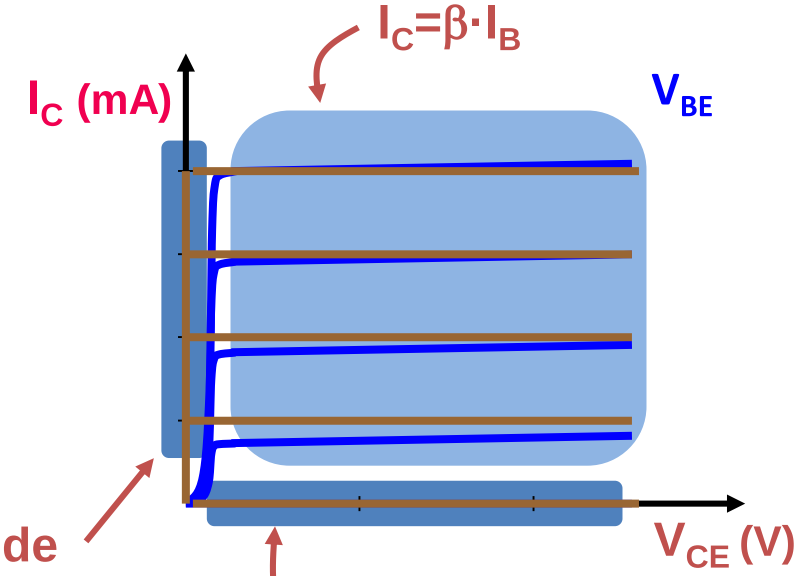


Entre base y emisor el transistor se comporta como un diodo.

Características V-I de Colector

Transistor NPN



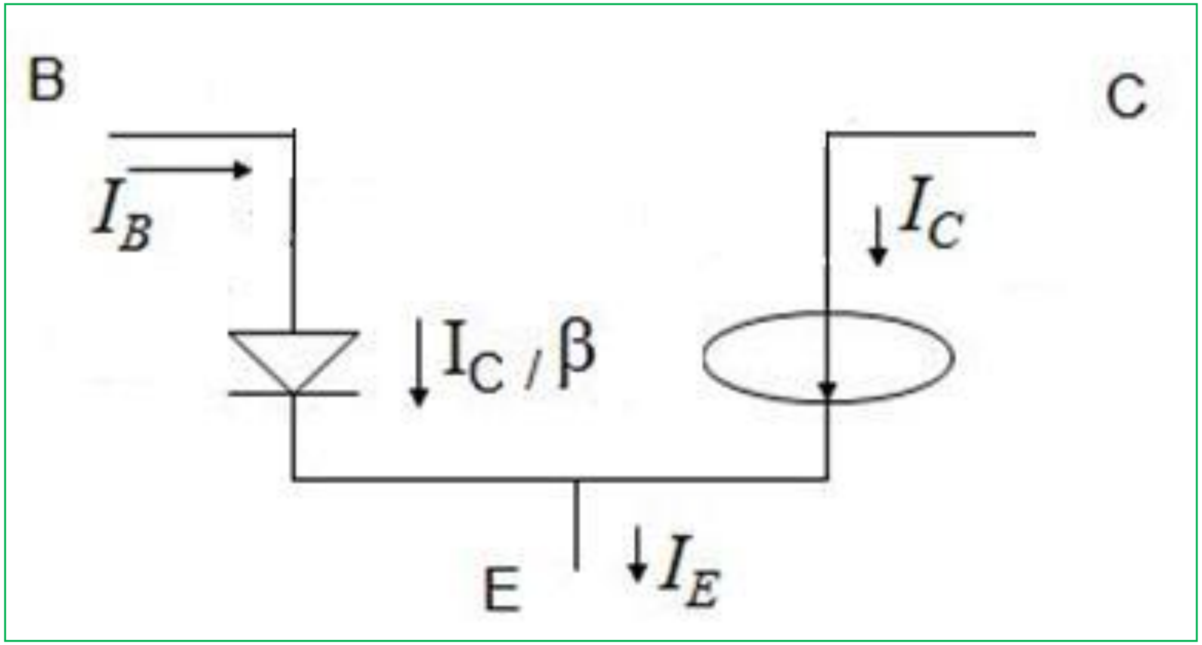


$I_C=\beta\cdot I_B$

Zona de saturación

Zona de corte

Modelo para Zona Activa Directa

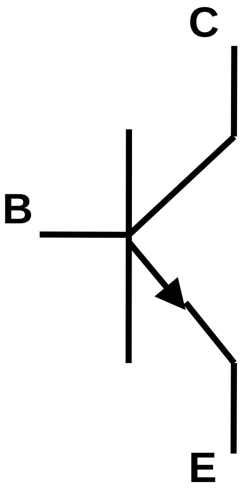


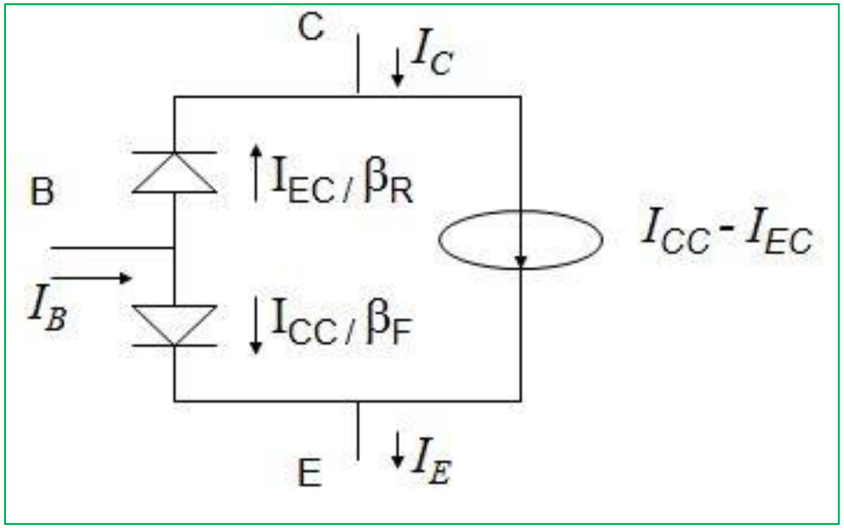
$$I_B = \frac{I_C}{\beta}$$

$$I_C = I_S\ e^{\left(V_{BE}/U_T\right)}$$

Parámetros I_s y β

Modelo de Eber & Moll





$$I_{CC} = I_S\,[\exp\,(V_{BE}/U_T) - 1] \qquad I_{EC} = I_S\,[\exp\,(V_{BC}/U_T) - 1]$$

$$I_B = I_{EC}/\beta_R + I_{CC}/\beta_F$$

Parametros

$I_S - \beta_F - \beta_R$

Características del Modelo de Eber & Moll

Parámetros
- I_S
- β_F
- β_R

→ Determinados por la fabricación

Validez del modelo → Todos los modos de operación

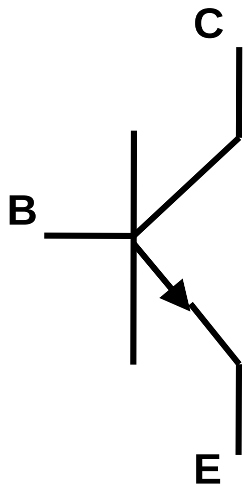
Funcionamiento del modelo → Generador de corriente entre Colector – Emisor controlado por V_{BC} y V_{BE}

MODELO UTILIZADO POR LOS SIMULADORES

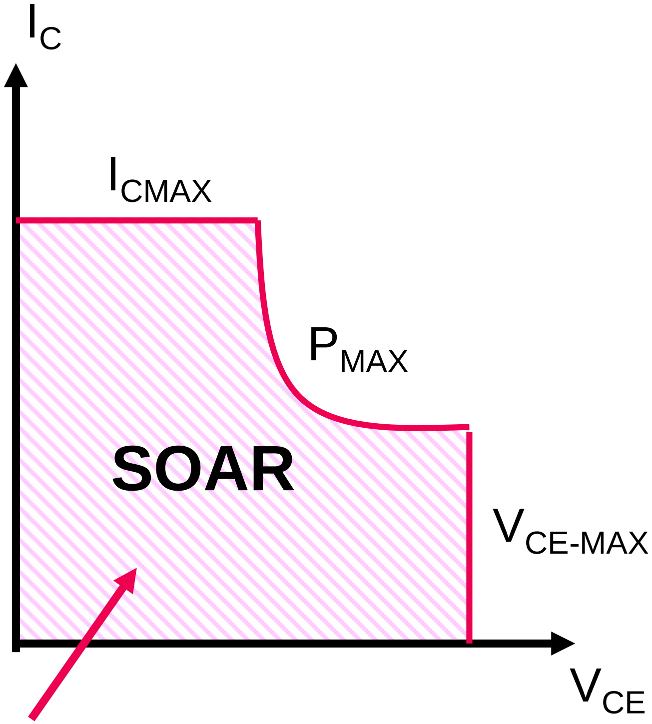
Limitaciones del Modelo

- No contempla Máximas Tensiones, Corrientes y Potencia

(Zona de Operación Segura SOAR)



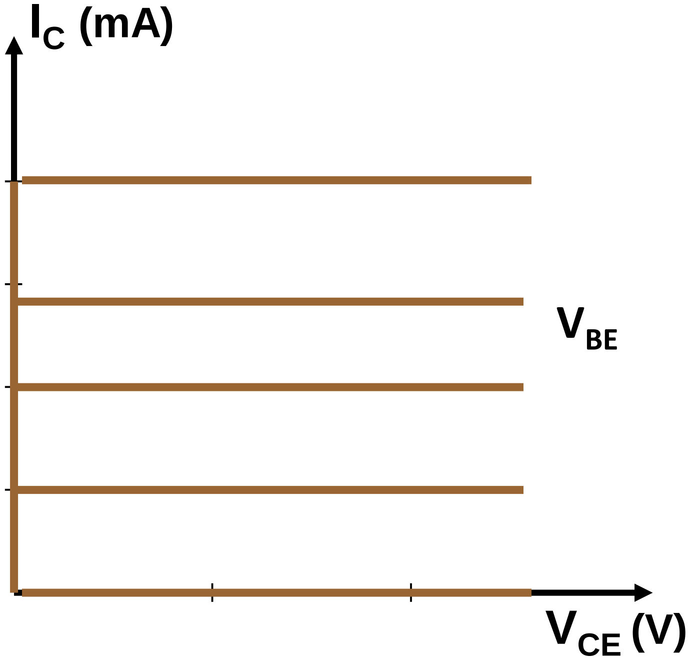
$I_{C\text{-}MAX}$	Corriente máxima de colector
$V_{CE\text{-}MAX}$	Tensión máxima CE
P_{MAX}	Potencia máxima

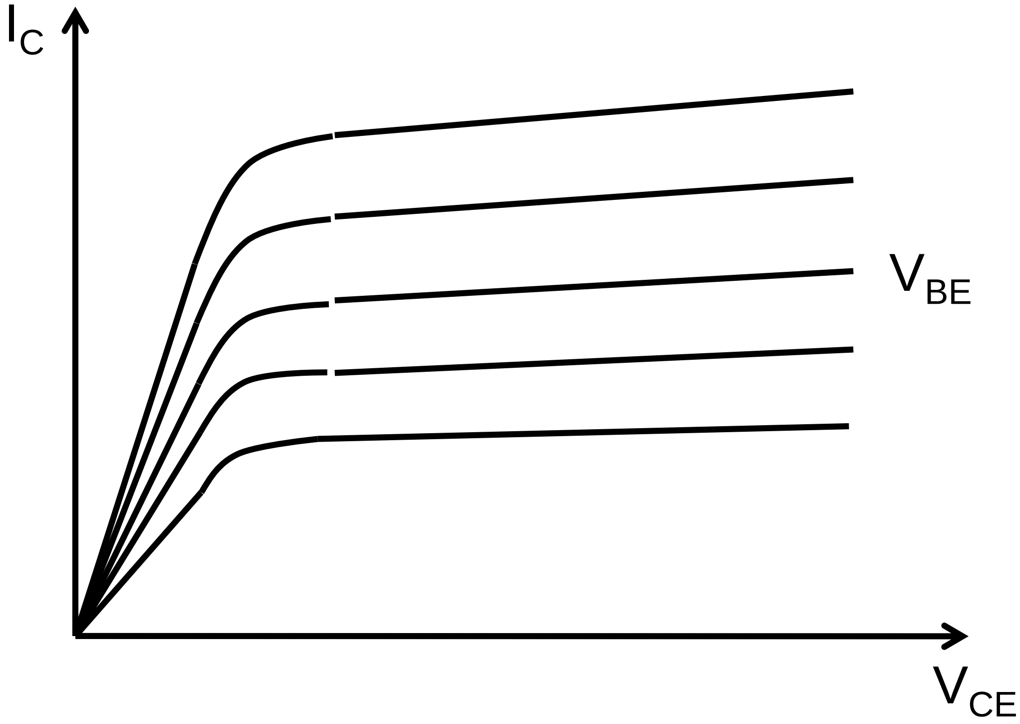


Área de operación segura
(Safety Operation Area)

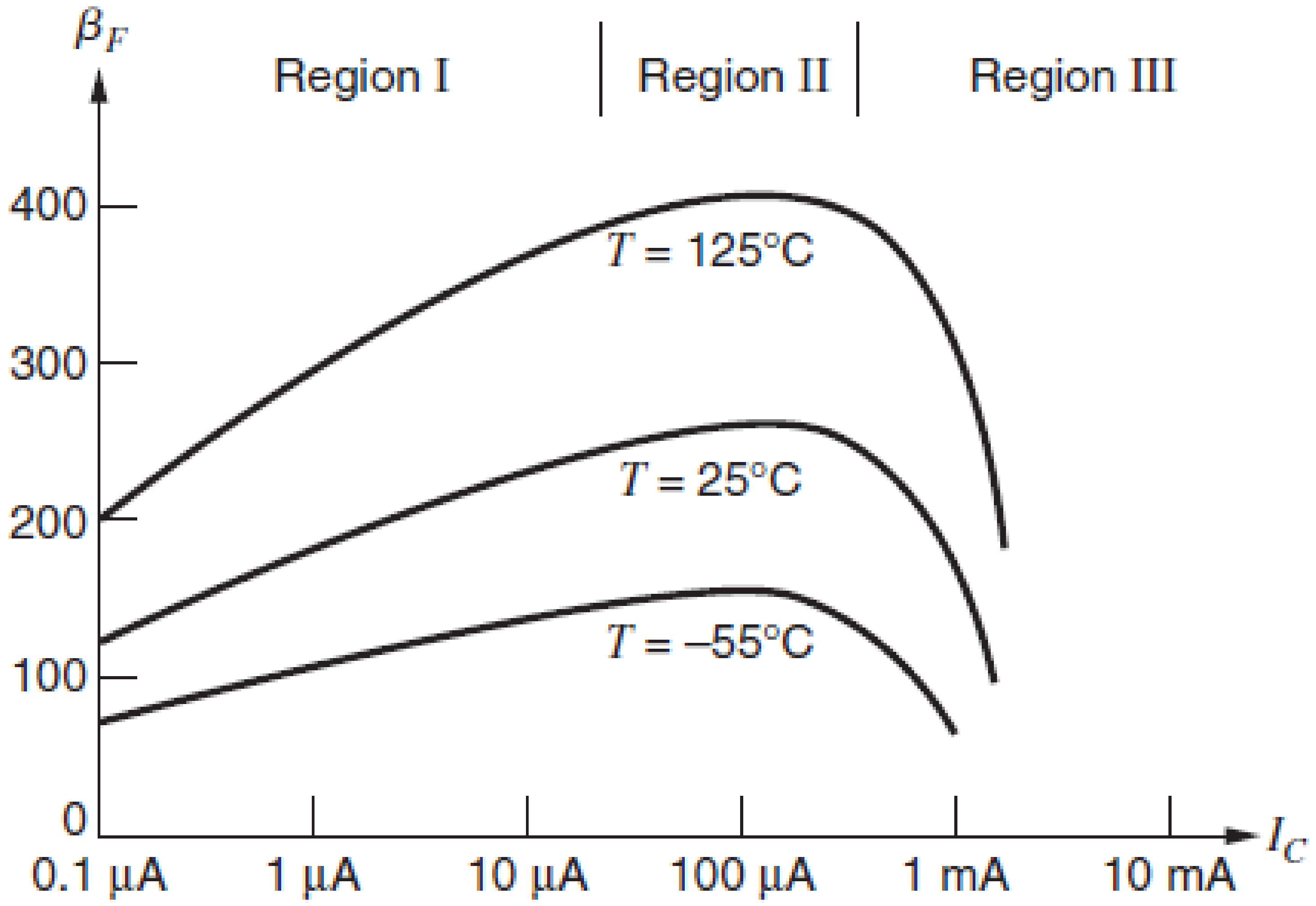
- **No representa la variación de la corriente IC con la tensión VCE**

(Modulación del ancho de la base)



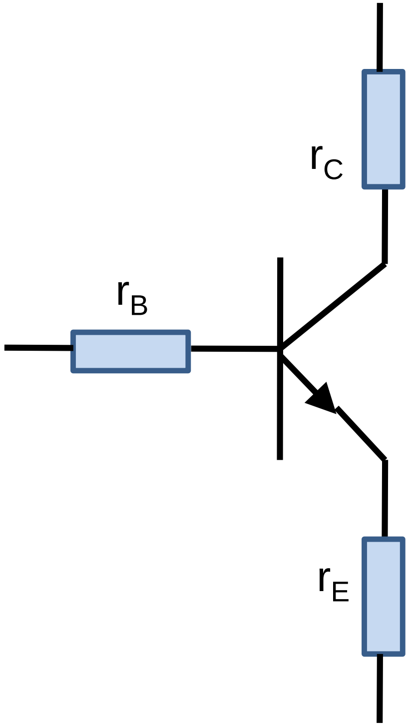


- No representa la dependencia del valor de β con la corriente IC.
- No contempla la dependencia de β con la temperatura

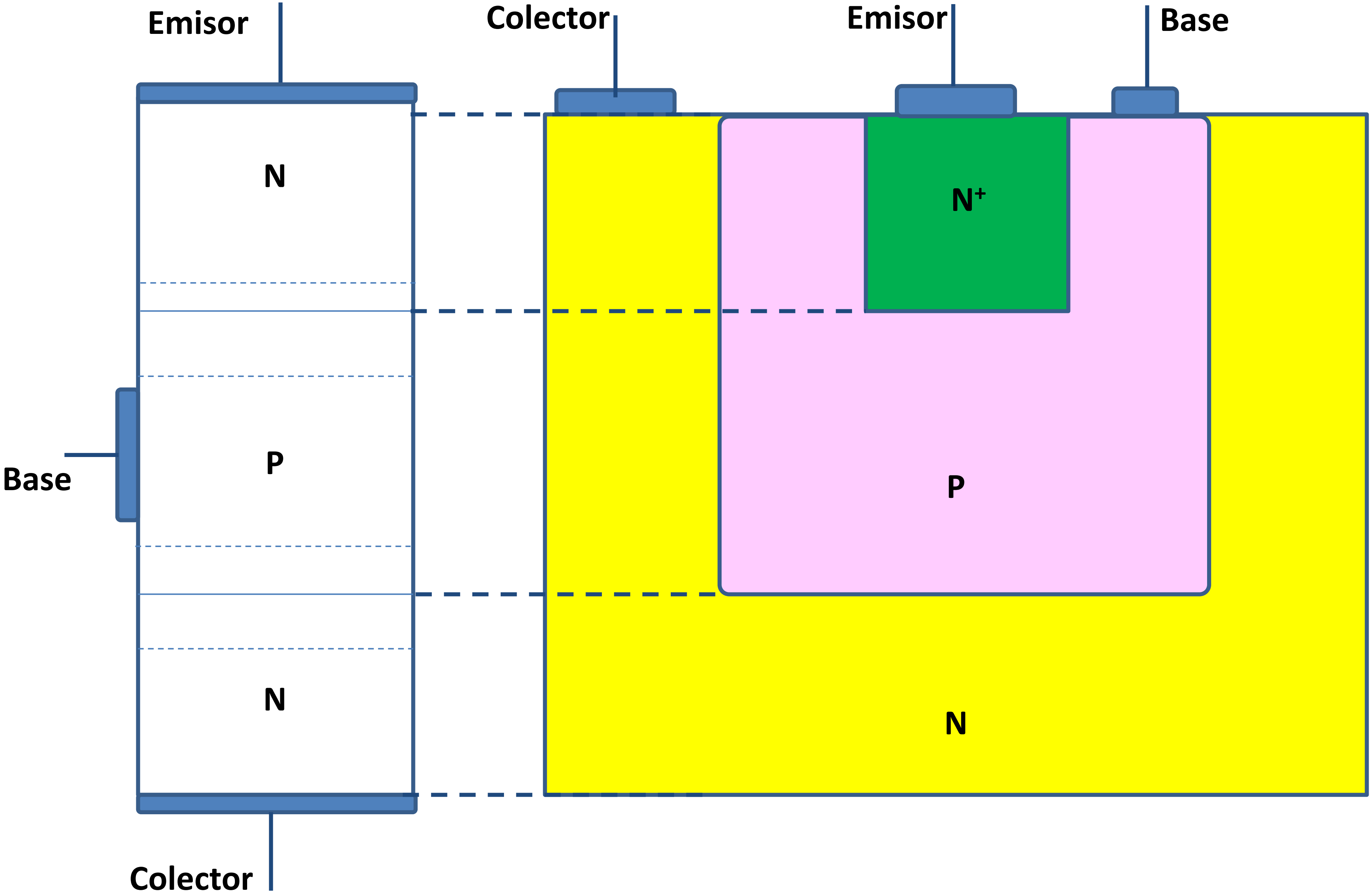


- No contempla los Efectos Capacitivos de las junturas que afecta al funcionamiento en altas frecuencias
  - Capacidades de juntura C_{JC} (Colector –Base) C_{jE} (Emisor – Base)
  - Capacidades de difusión C_{DC} (Colector – Base) C_{DE} (Emisor – Base)

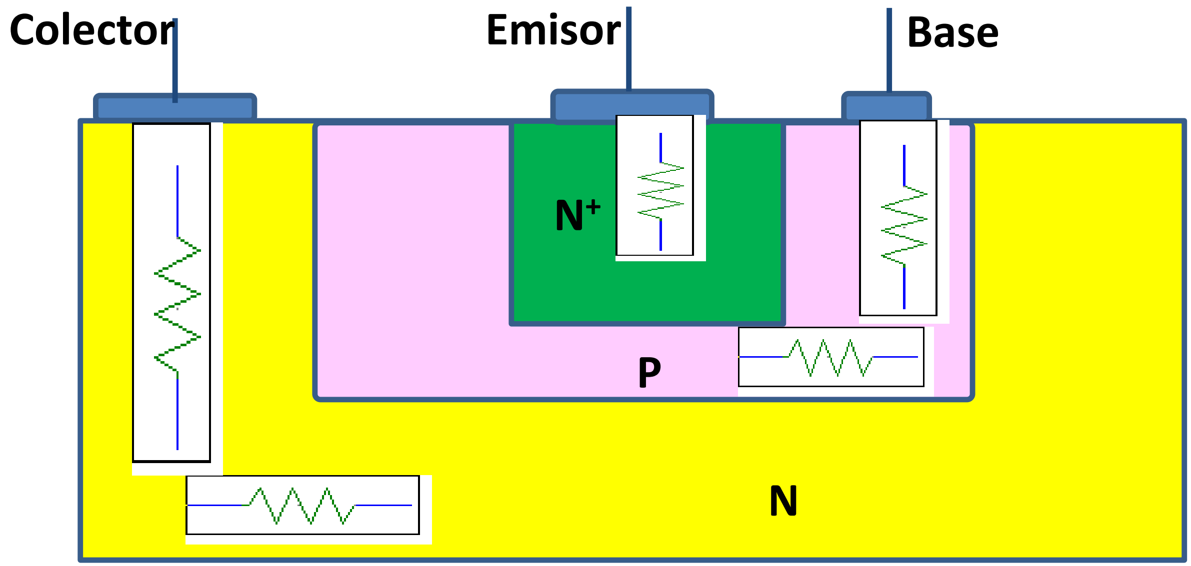
- La tecnología de fabricación de los TBJ introduce Resistencias Parásitas en serie con los terminales
  - Base (r_B),
  - Colector (r_C)
  - Emisor (r_E).

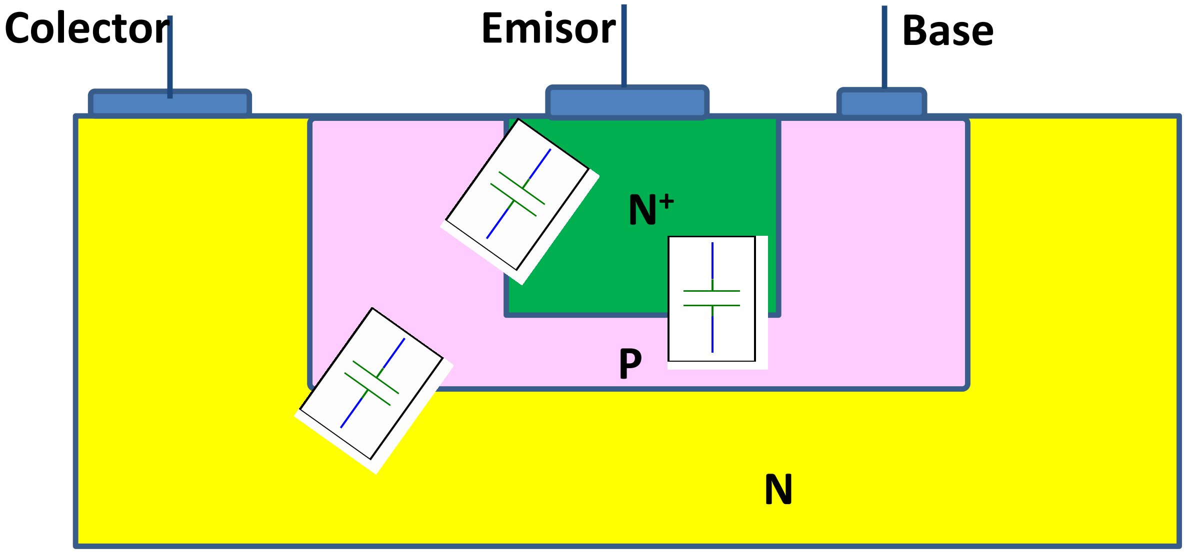


Corte Transversal de un TBJ NPN

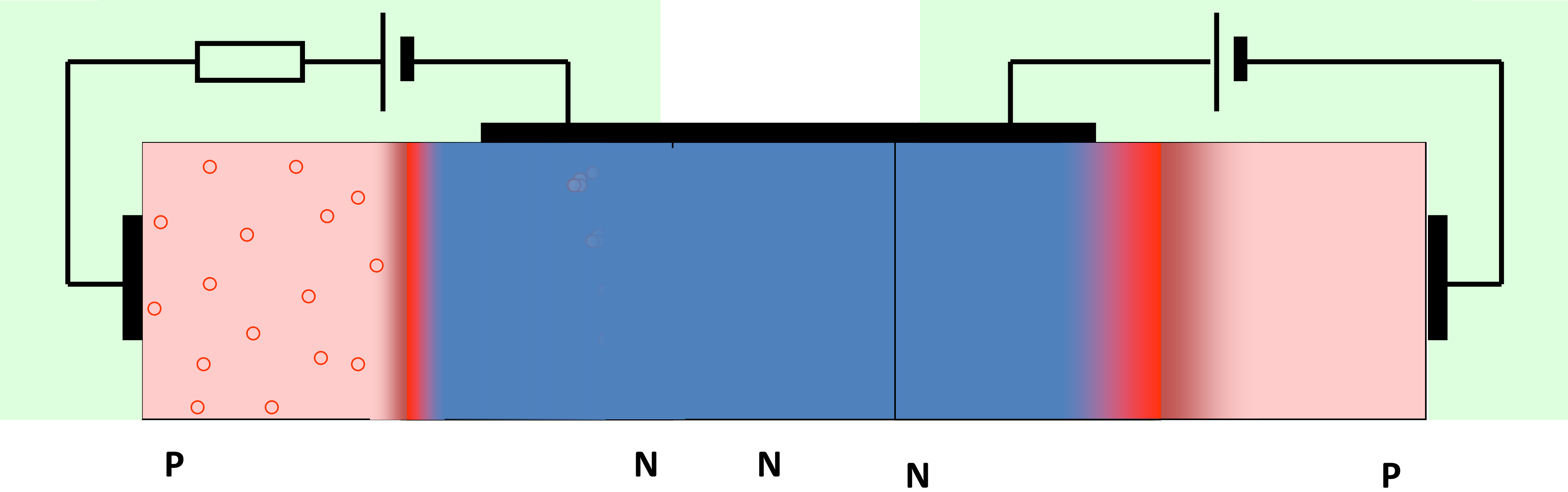


Elementos parásitos



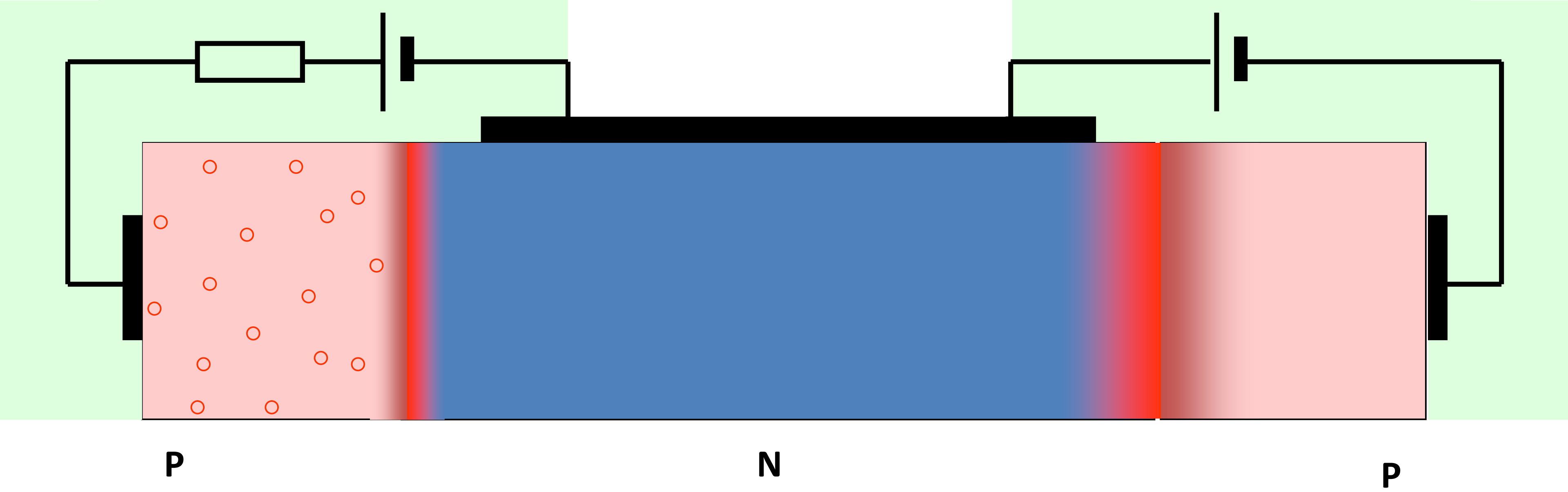


Principio de Funcionamiento del Transistor Bipolar

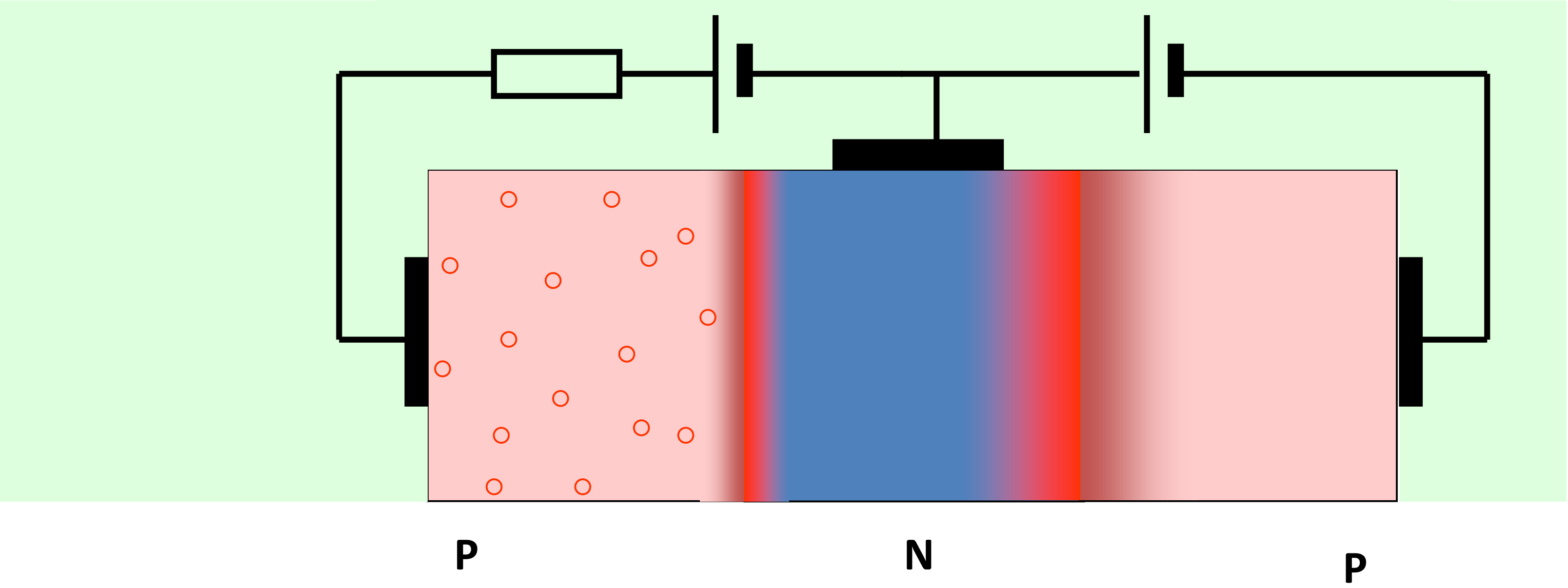


Si la zona central es muy ancha el comportamiento es el de dos diodos en serie: el funcionamiento de la primera unión no afecta al de la segunda

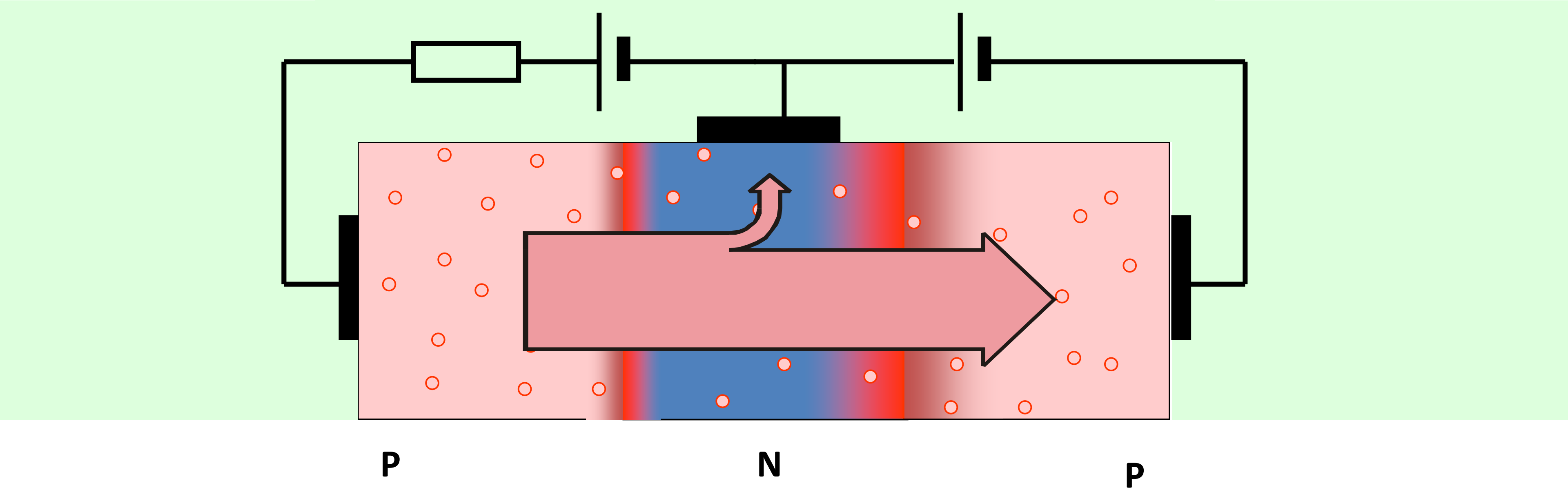
Principio de Funcionamiento del Transistor Bipolar



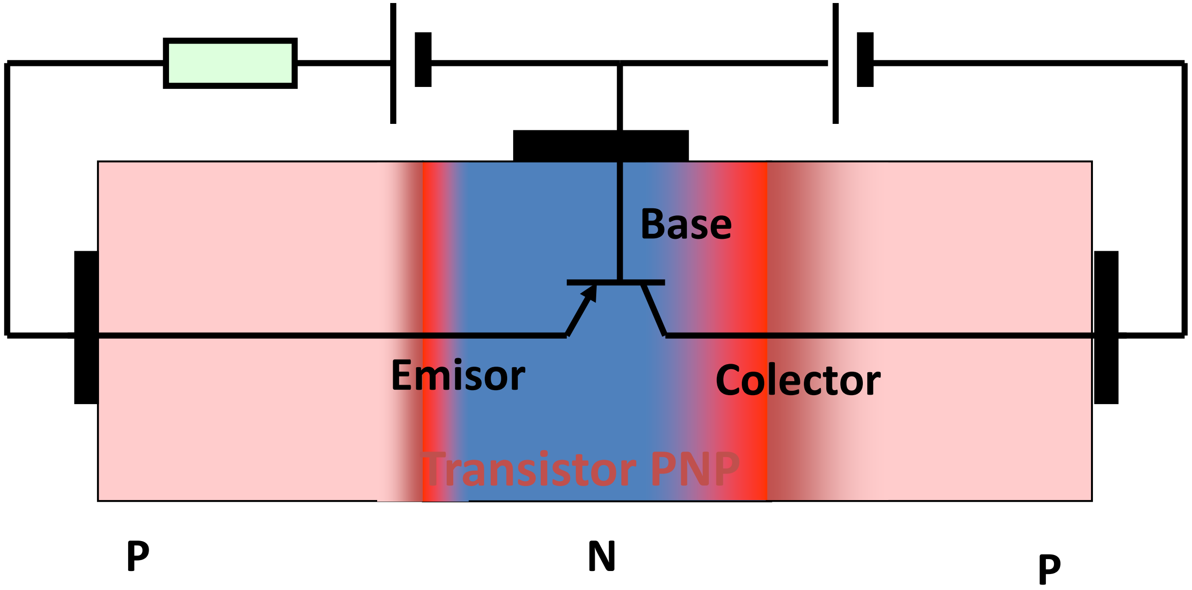
Principio de Funcionamiento del Transistor Bipolar



Principio de Funcionamiento del Transistor Bipolar



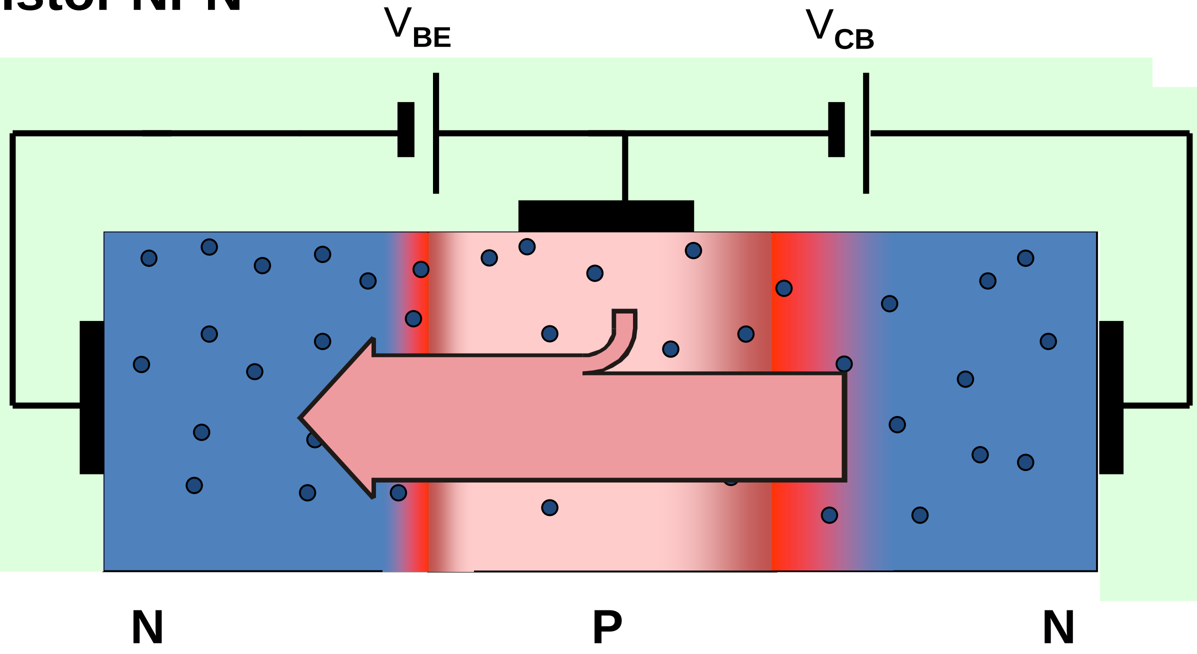
Principio de Funcionamiento del Transistor Bipolar



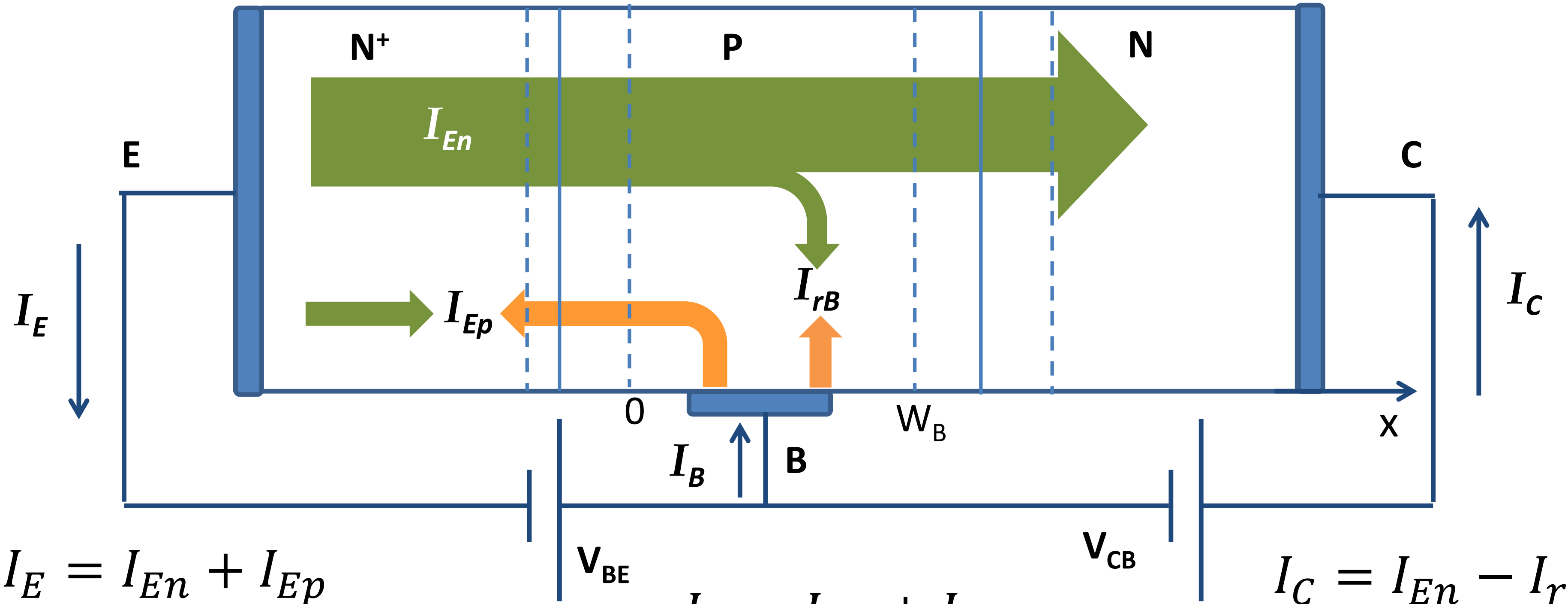
El terminal de base actúa como terminal de control manejando una fracción de la corriente mucho menor a la de emisor y el colector.

Principio de Funcionamiento del Transistor Bipolar

Transistor NPN



Desplazamiento de portadores en Zona Activa Directa



$$I_E = I_{En} + I_{Ep}$$

$$I_B = I_{Ep} + I_{rB}$$

$$I_C = I_{En} - I_{rB}$$

$$\beta = \frac{I_C}{I_B} \qquad \beta = \frac{I_{En} - I_{rB}}{I_{Ep} + I_{rB}}$$

$$\alpha = \frac{I_C}{I_E} \qquad \alpha = \frac{I_{En} - I_{rB}}{I_{Ep} + I_{En}} \qquad \alpha = \left(\frac{I_{En}}{I_{Ep} + I_{En}}\right)\left(\frac{I_{En} - I_{rB}}{I_{En}}\right)$$

$$\frac{Corriente\ de\ electrones\ en\ la\ juntura\ B-E}{Corriente\ total\ en\ la\ juntura\ B-E}$$

γ_E → Eficiencia de inyección

$$\alpha = \left(\frac{I_{En}}{I_{Ep}+I_{En}}\right)\left(\frac{I_{En}-I_{rB}}{I_{En}}\right)$$

$$\frac{Corriente\ de\ electrones\ que\ llega\ a\ la\ juntura\ B-C}{Corriente\ de\ electrones\ que\ pasa\ por\ la\ juntura\ B-E}$$

α_T → Factor de transporte de base

$$\alpha = \gamma_E \alpha_T$$

$$\beta = \frac{\alpha}{1-\alpha}$$

β *alto* $\Rightarrow \alpha \approx 1$

$$\alpha = \frac{\beta}{1+\beta}$$

$\alpha \approx 1$

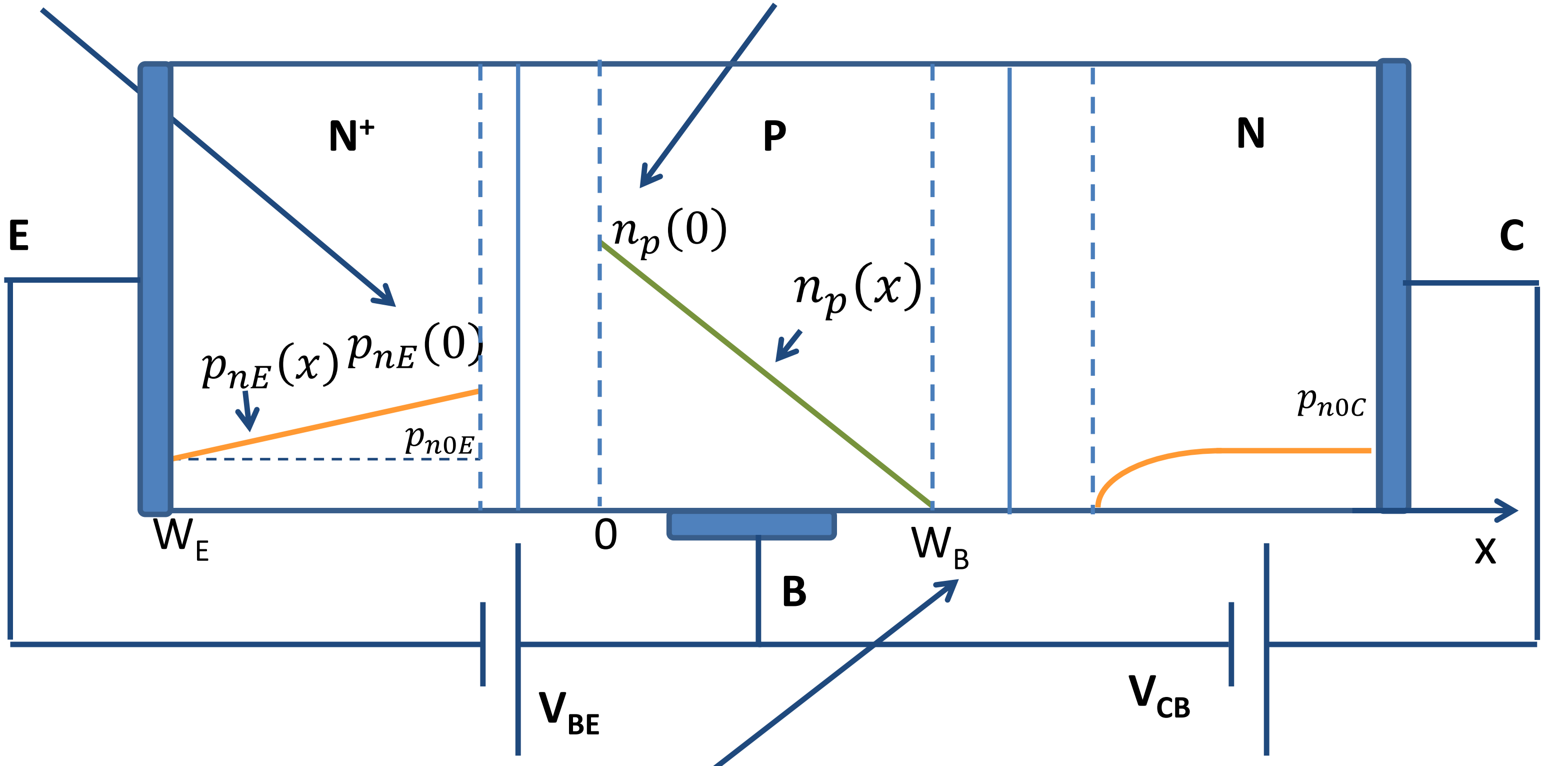
$\gamma_E \approx 1$

$\alpha_T \approx 1$

Concentraciones de portadores en Zona Activa Directa

$$p_{nE}(0) = p_{n0E}\, e^{\frac{V_{BE}}{U_T}}$$

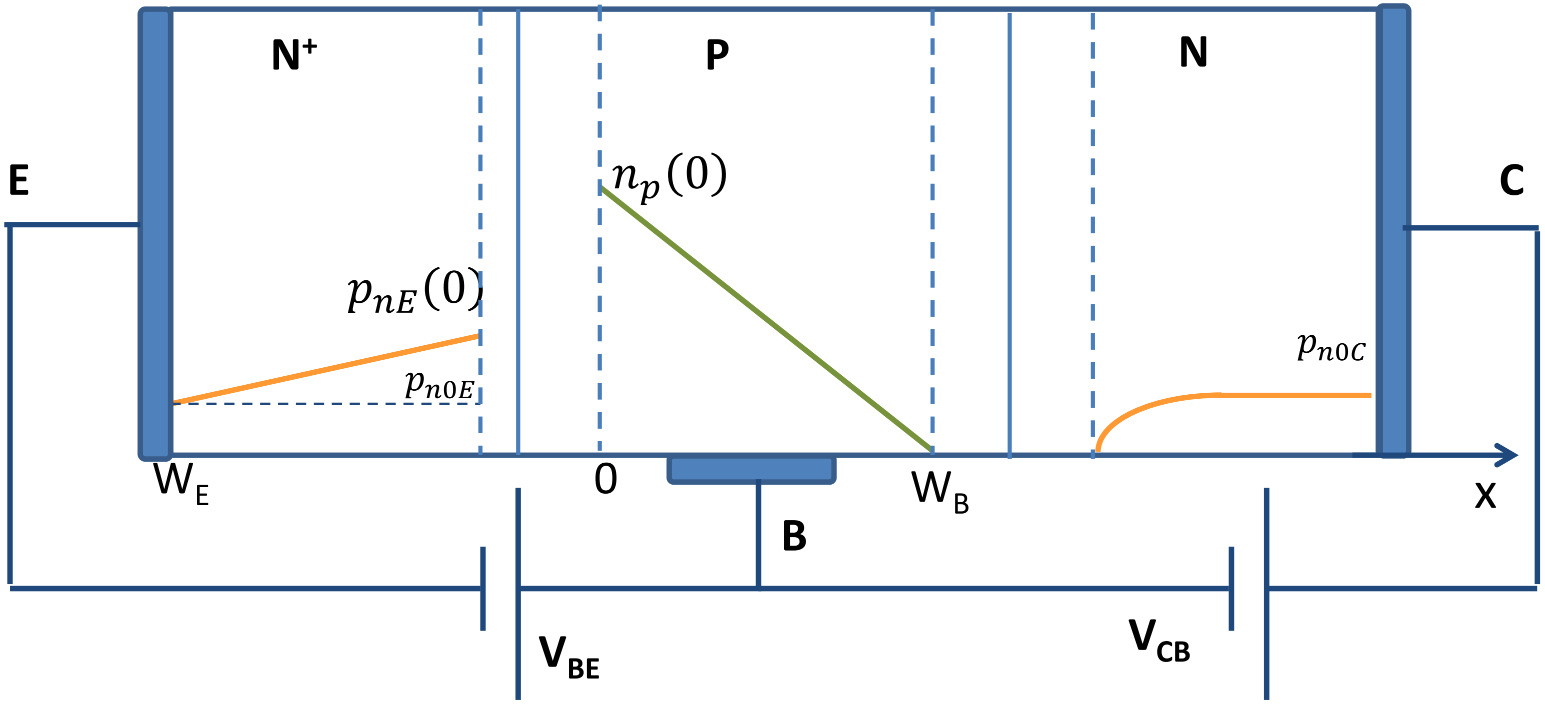
$$n_p(0) = n_{p0}\, e^{\frac{V_{BE}}{U_T}}$$



$V_{BC} < 0$

$$n_p(W_B) = n_{p0}\, e^{\frac{V_{BC}}{U_T}} \quad \Rightarrow \quad n_p(W_B) \approx 0$$

Corrientes en Zona Activa Directa



$$I_{En} = qA_E D_n \left.\frac{dn_p(x)}{dx}\right|_{x=0}$$

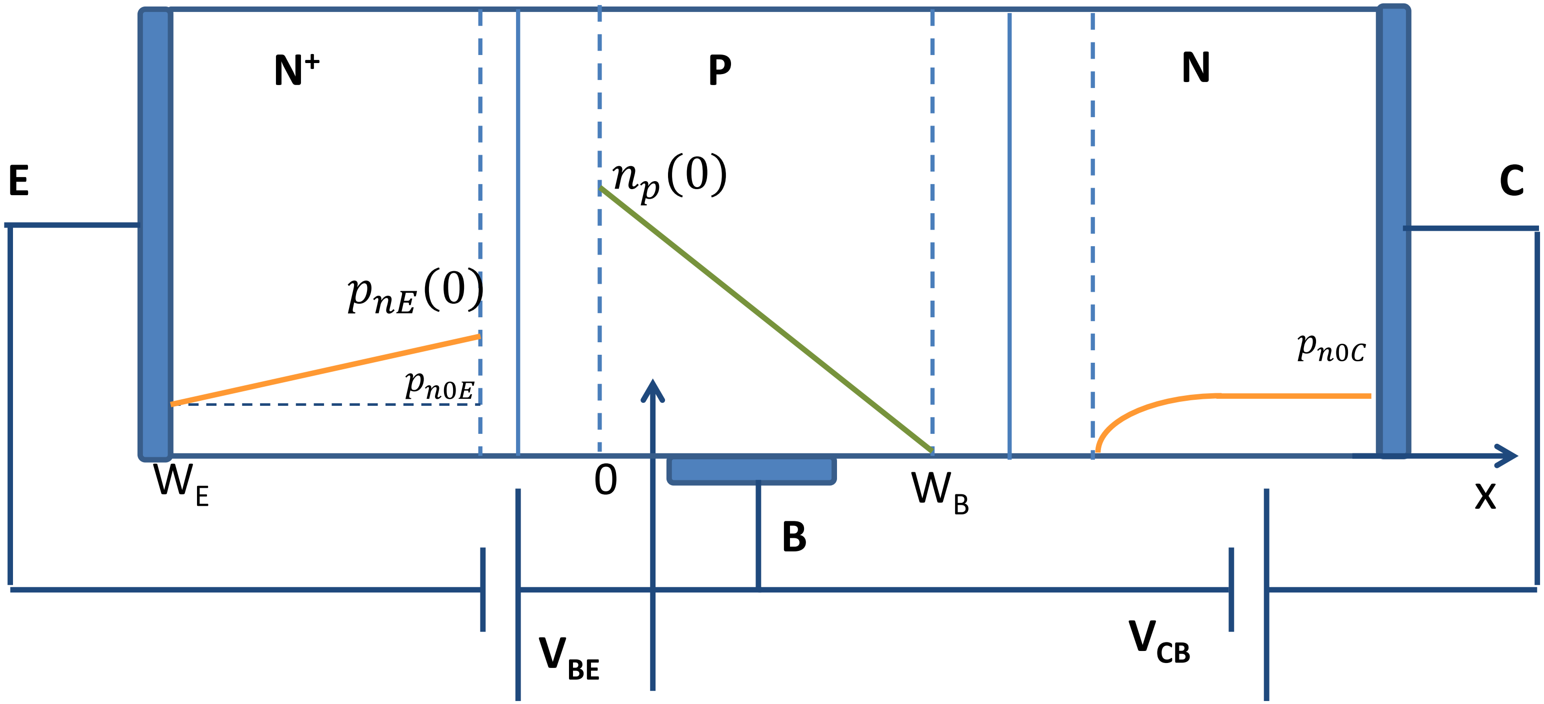
$$\left.\frac{dn_p(x)}{dx}\right|_{x=0} = -\frac{n_p(0)}{W_B}$$

$$I_{En} = -qA_E D_n \frac{n_p(0)}{W_B}$$

$$I_{Ep} = -qA_E D_p \left.\frac{dp_{nE}(x)}{dx}\right|_{x=0}$$

$$\left.\frac{dp_{nE}(x)}{dx}\right|_{x=0} = \frac{p_{nE}(0)}{W_E}$$

$$I_{Ep} = -qA_E D_p \frac{p_{nE}(0)}{W_E}$$



$$I_{rB} = \frac{Q_B}{\tau_n}$$

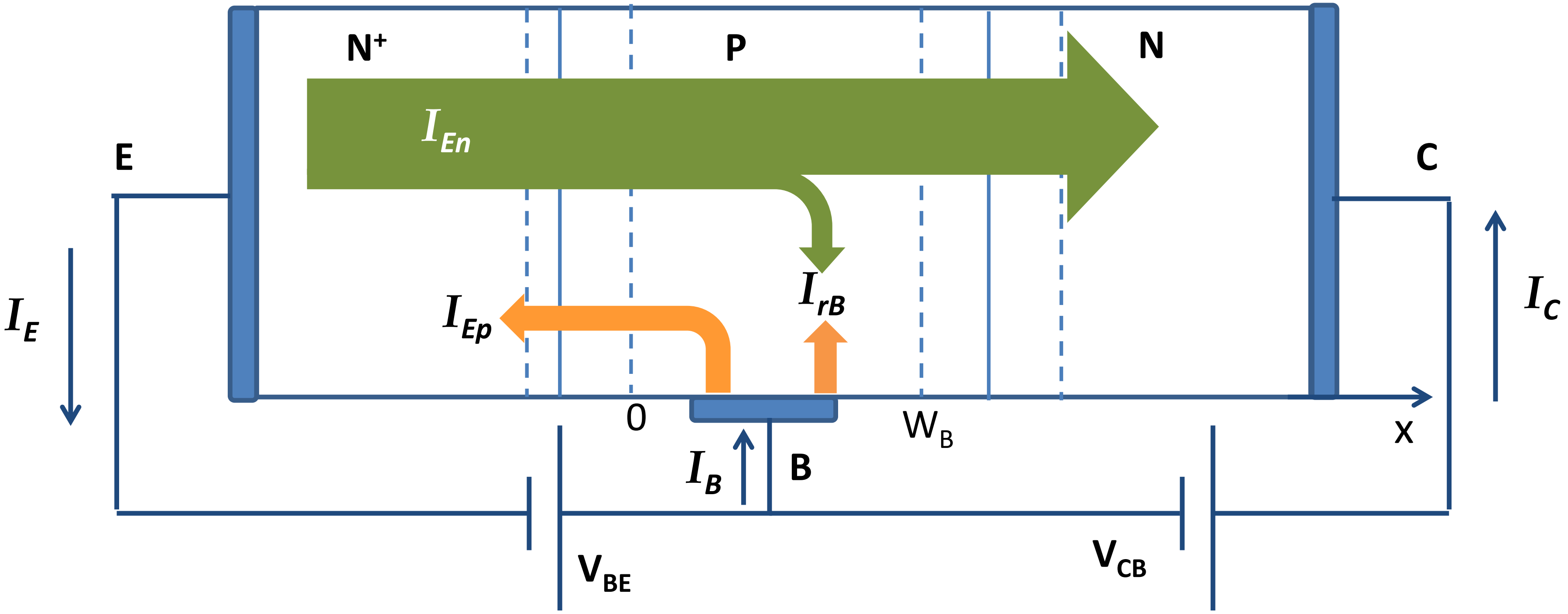
$Q_B \rightarrow$ *Carga almacenada en base*

$\tau_n \rightarrow$ *Tiempo de vida medio de electrones en base*

$$Q_B = \frac{1}{2} q A_E W_B n_p(0)$$

$$I_{rB} = -\frac{1}{2}\frac{q A_E W_B}{\tau_n} n_p(0)$$

RELACION I_C vs V_{BE}



$$I_C = I_{En} - I_{rB}$$

si $I_{rB} \ll I_{En}$

$$I_C \approx -I_{En}$$

$$I_{En} = -qA_E D_n \frac{n_p(0)}{W_B}$$

$$n_p(0) = n_{p0} e^{\frac{V_{BE}}{U_T}}$$

$$I_C = \frac{qA_E D_n n_{p0}}{W_B} e^{\frac{V_{BE}}{U_T}}$$

$$\boxed{I_C = I_S e^{\frac{V_{BE}}{U_T}}}$$

$$\boxed{I_S = \frac{qA_E D_n n_{p0}}{W_B}}$$

Ganancia de Corriente β

$$\beta = \frac{\alpha}{1-\alpha} \qquad \beta = \frac{1}{\frac{1}{\alpha}-1} \qquad \alpha = \gamma_E \alpha_T$$

$$\alpha = \left(\frac{I_{En}}{I_{Ep}+I_{En}}\right)\left(\frac{I_{En}-I_{rB}}{I_{En}}\right) \qquad \alpha = \left(\frac{1}{\frac{I_{Ep}}{I_{En}}+1}\right)\left(1-\frac{I_{rB}}{I_{En}}\right)$$

$$\gamma_E = \left(\frac{1}{\frac{I_{Ep}}{I_{En}}+1}\right) \qquad \frac{I_{Ep}}{I_{En}} = \frac{D_p p_{n0E} W_B}{D_n n_{p0} W_E}$$

$$\boxed{I_{Ep} = -qA_E D_p \frac{p_{nE}(0)}{W_E}}$$

$$\boxed{I_{En} = -qA_E D_n \frac{n_p(0)}{W_B}}$$

$$\alpha_T = \left(1-\frac{I_{rB}}{I_{En}}\right) \qquad \frac{I_{rB}}{I_{En}} = \frac{W_B^2}{2\,D_n \tau_n}$$

$$\boxed{I_{rB} = \frac{1}{2}\frac{qA_E W_B}{\tau_n} n_p(0)}$$

$$\alpha = \gamma_E \alpha_T$$

$$\downarrow$$

Si $\alpha_T \approx 1$ $\nearrow$ $\alpha \approx \gamma_E$ $\longrightarrow$ $\beta \approx \dfrac{1}{\dfrac{1}{\gamma_E} - 1}$

$$\gamma_E = \left(\frac{1}{\frac{I_{Ep}}{I_{En}} + 1} \right)$$

$$\frac{1}{\gamma_E} = 1 + \frac{I_{Ep}}{I_{En}}$$

$$\frac{1}{\gamma_E} - 1 = \frac{I_{Ep}}{I_{En}}$$

$$\beta \approx \frac{I_{En}}{I_{Ep}}$$

$$\frac{I_{En}}{I_{Ep}} = \frac{D_n n_{p0} W_E}{D_p p_{n0E} W_B}$$

$$\beta \approx \frac{D_n W_E n_{p0}}{D_p W_B p_{n0E}}$$

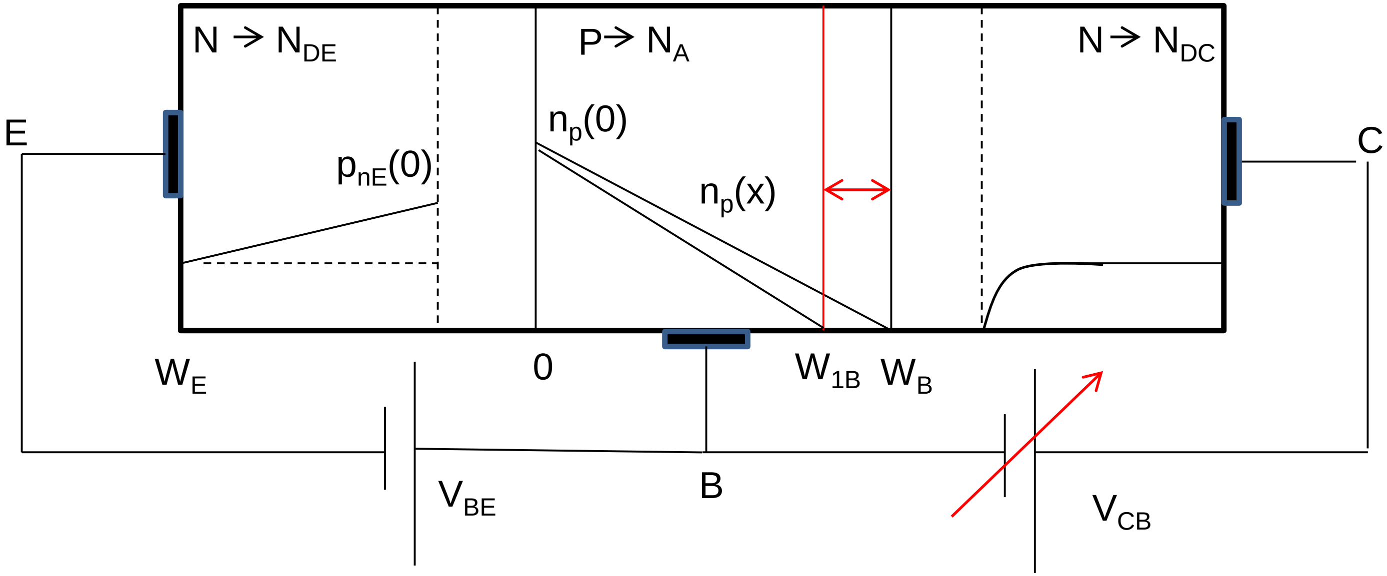
$\nearrow$ $n_{p0} = \dfrac{n_i^2}{N_{AB}}$

$\searrow$ $p_{n0E} = \dfrac{n_i^2}{N_{DE}}$

$$\beta \approx \frac{D_n N_{DE} W_E}{D_p N_{AB} W_B}$$

Modulación del ancho de la base

(Efecto EARLY)



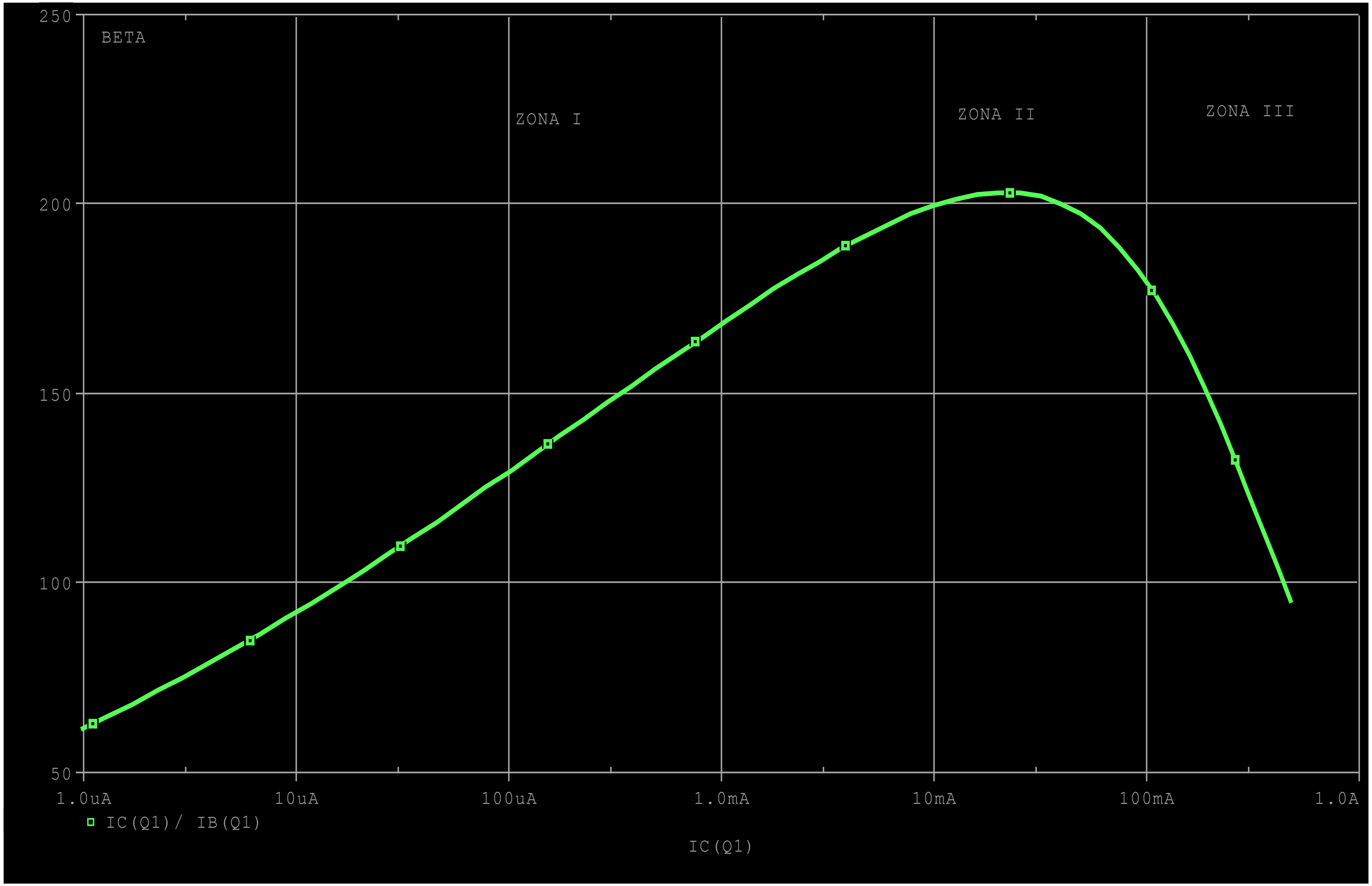
$$\frac{dn_p(x)}{dx} = -\frac{n_p(0)}{W_B}$$

$$I_{En} = \mathrm{q}\, D_n\, A_E \left.\frac{dn_p(x)}{dx}\right|_{x=}$$

$$\frac{dn1_p(x)}{dx} = -\frac{n_p(0)}{W_{1B}}$$

$$I_C = (1+V_{CE}/V_A)\, I_S \exp\,(V_{BE}/U_T)$$

β vs IC

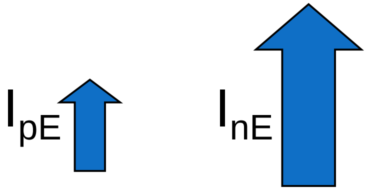

250
BETA
ZONA I
ZONA II
ZONA III
200
150
100
50
1.0uA
10uA
100uA
1.0mA
10mA
100mA
1.0A
IC(Q1)/ IB(Q1)
IC(Q1)

$$\beta = \frac{I_C}{I_B}$$

$I_C \simeq I_{nE}$

$I_B = I_{pE} + I_{rB}$

$$\beta = \frac{I_{nE}}{I_{pE} + I_{rB}}$$



Zona I • La corriente I_{rB} es del orden de I_{pE} por lo que no puede despreciarse

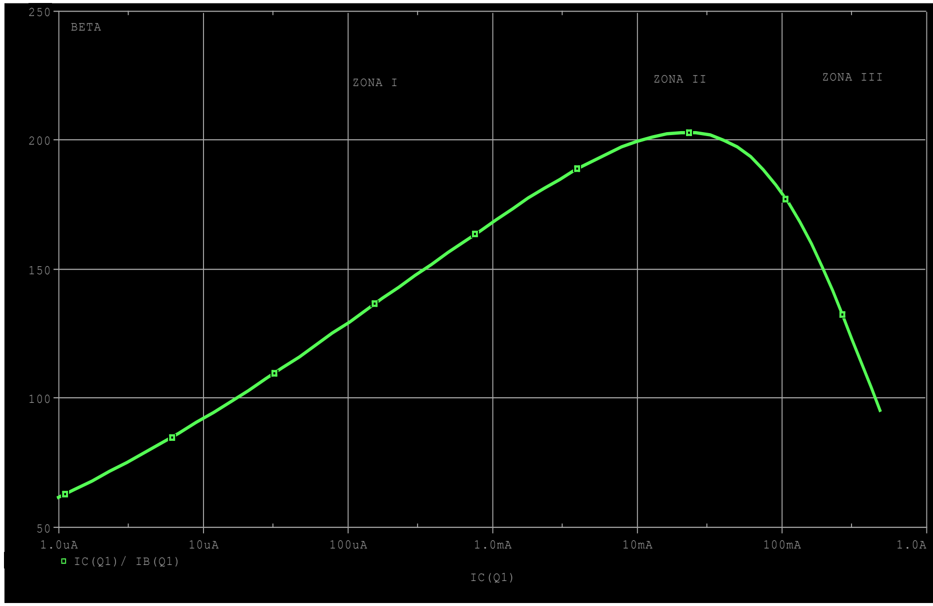
I_{rB}	I_{pE}	I_{nE}	β
1 µA	1 µA	100 µA	50
1 µA	10 µA	1000 µA	90
1 µA	100 µA	10000 uA	99

Zona II

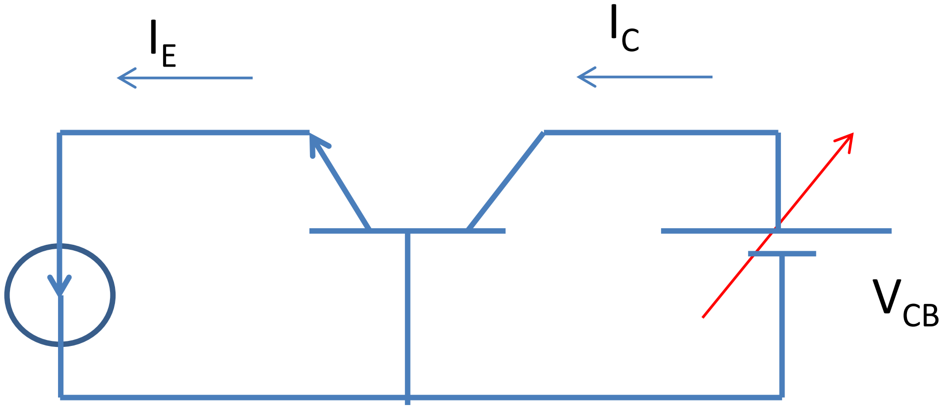
- La corriente I_{rB} puede despreciarse

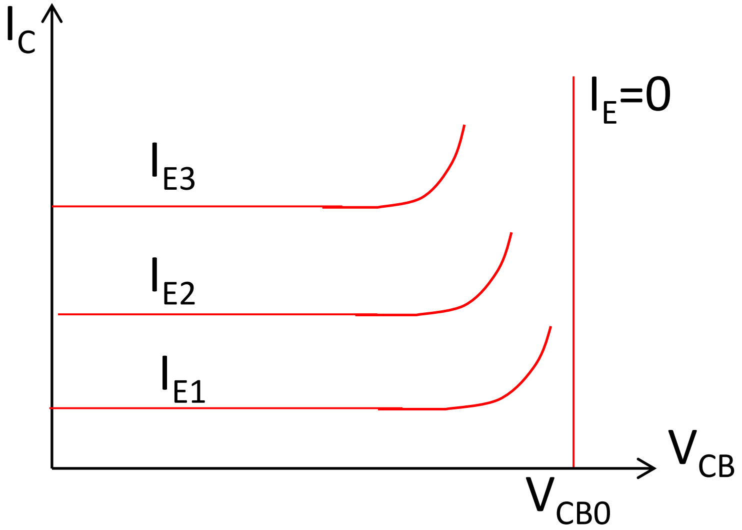
Zona III

- Inyeccion de alto nivel



Tensión de ruptura V_{CB}





$$I_C = -\alpha * M * I_E$$

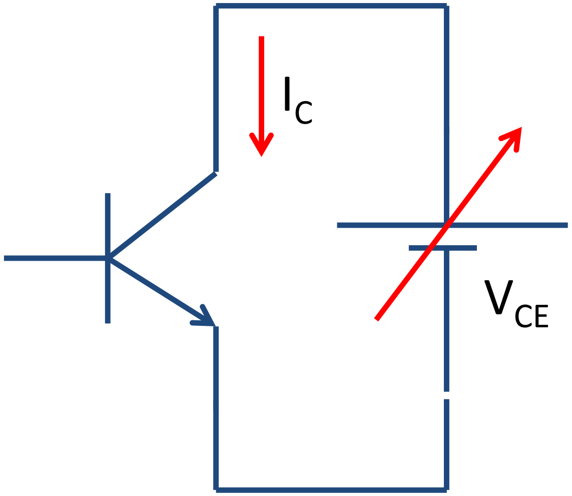
Cuando llega a la ruptura αM >1

M: Factor de Multiplicación

$$M = \frac{1}{1-(\frac{V_{CB}}{V_{CBO}})^n}$$

V_{CBO}: Parámetro del TBJ

Tensión de ruptura V_{CE}



$$I_C = \beta I_B \qquad \beta = \frac{\alpha}{1-\alpha} \qquad I_C = \frac{\alpha M}{1-\alpha M} I_B$$

$$Cuando \;\; \alpha M = 1 \qquad I_C \to \infty$$

$$\alpha M = \frac{\alpha}{1-\left(\frac{V_{CB}}{V_{CB0}}\right)^n} = 1 \qquad \alpha = 1-\left(\frac{V_{CB}}{V_{CB0}}\right)^n$$

$$\frac{V_{CB}}{V_{CB0}} = \sqrt[n]{1-\alpha} \qquad V_{CB} = V_{CB0}\sqrt[n]{1-\alpha} \qquad V_{CB} \approx V_{CE} \qquad V_{CE} = V_{CB0}\sqrt[n]{1-\alpha}$$

Multiplico y divido el segundo miembro por $\boldsymbol{\alpha}$

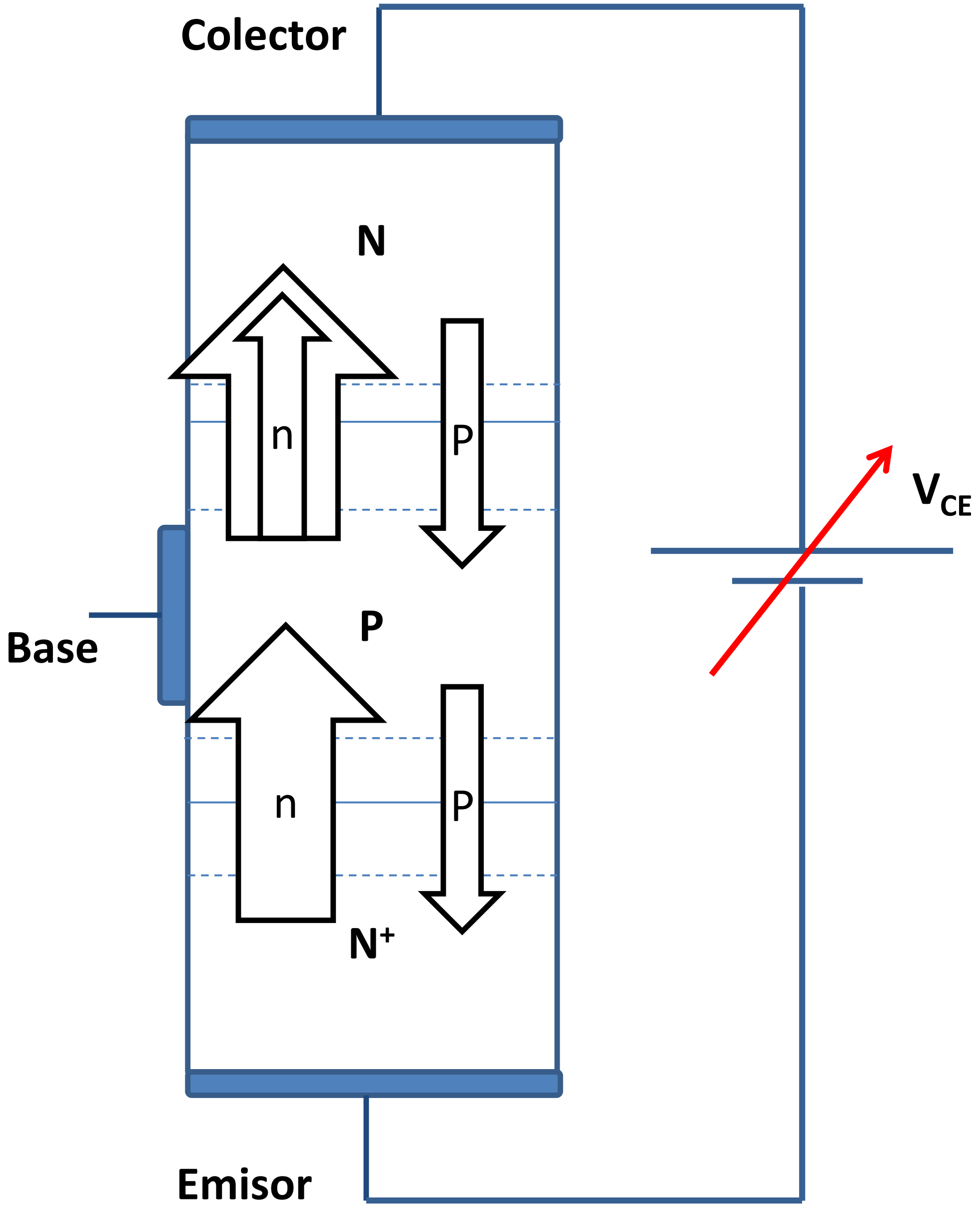
$$\boldsymbol{\alpha \approx 1}$$

$$V_{CE} = V_{CB0}\sqrt[n]{\frac{1-\alpha}{\alpha}}$$

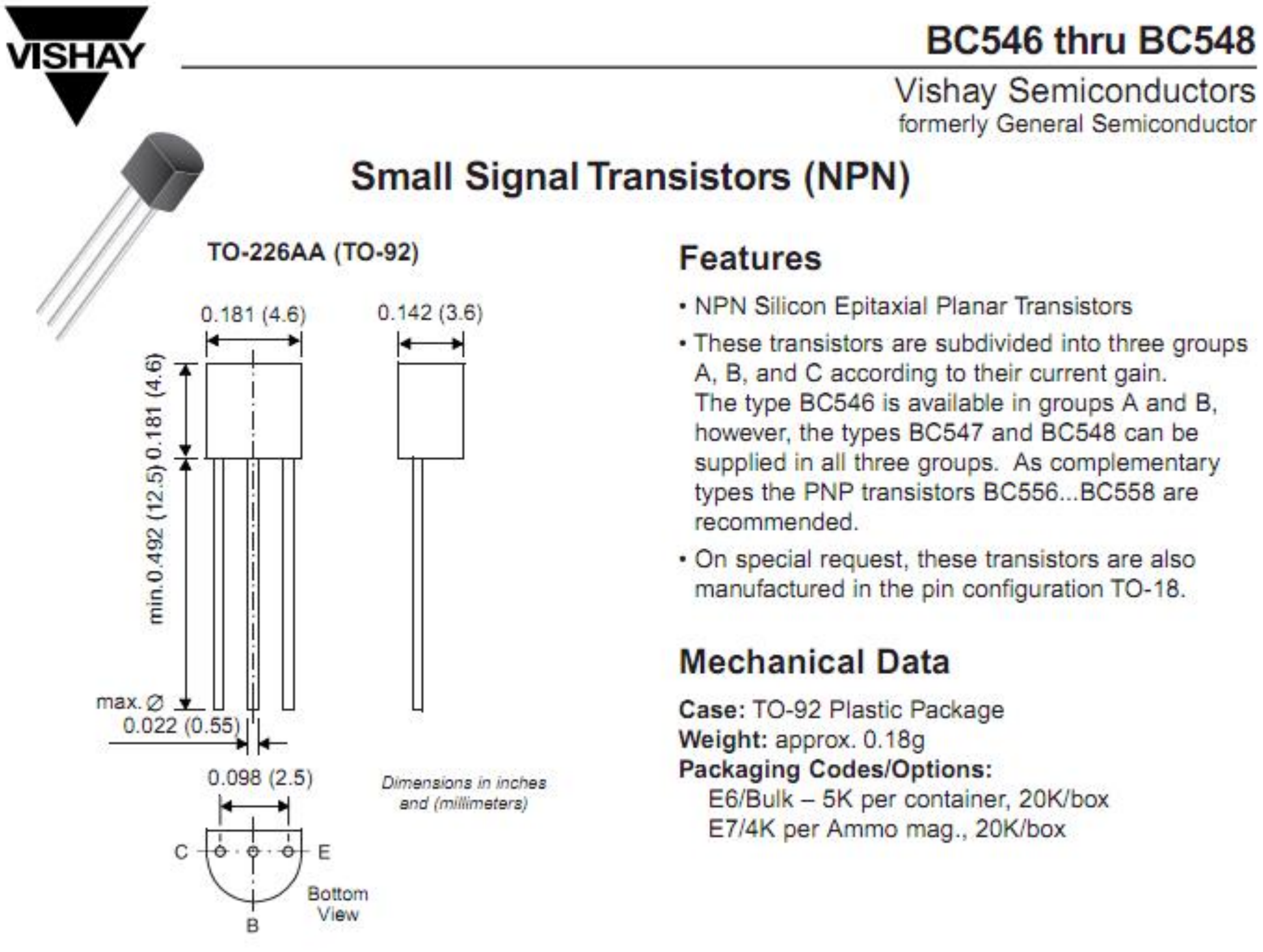
$$V_{CE} = \frac{V_{CB0}}{\sqrt[n]{\beta}}$$

Cuanto más grande sea el valor de β menor es la ruptura V_{CEO}

Tensión de ruptura V_{CE}



Máximos Absolutos



VISHAY

BC546 thru BC548

Vishay Semiconductors
formerly General Semiconductor

Small Signal Transistors (NPN)

TO-226AA (TO-92)

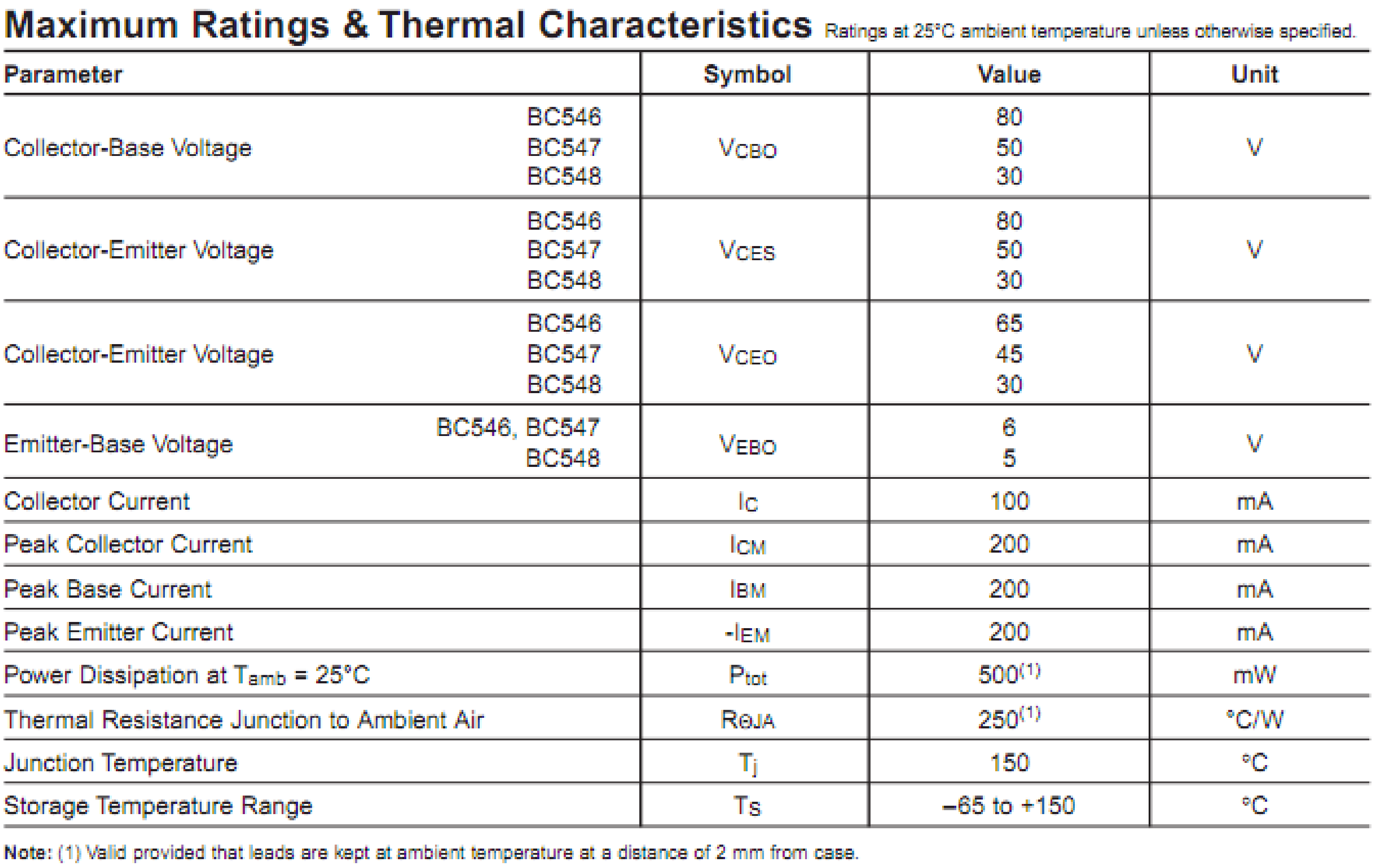
Dimensions in inches and (millimeters)

Features

- NPN Silicon Epitaxial Planar Transistors
- These transistors are subdivided into three groups A, B, and C according to their current gain. The type BC546 is available in groups A and B, however, the types BC547 and BC548 can be supplied in all three groups. As complementary types the PNP transistors BC556...BC558 are recommended.
- On special request, these transistors are also manufactured in the pin configuration TO-18.

Mechanical Data

Case: TO-92 Plastic Package
Weight: approx. 0.18g
Packaging Codes/Options:
E6/Bulk – 5K per container, 20K/box
E7/4K per Ammo mag., 20K/box

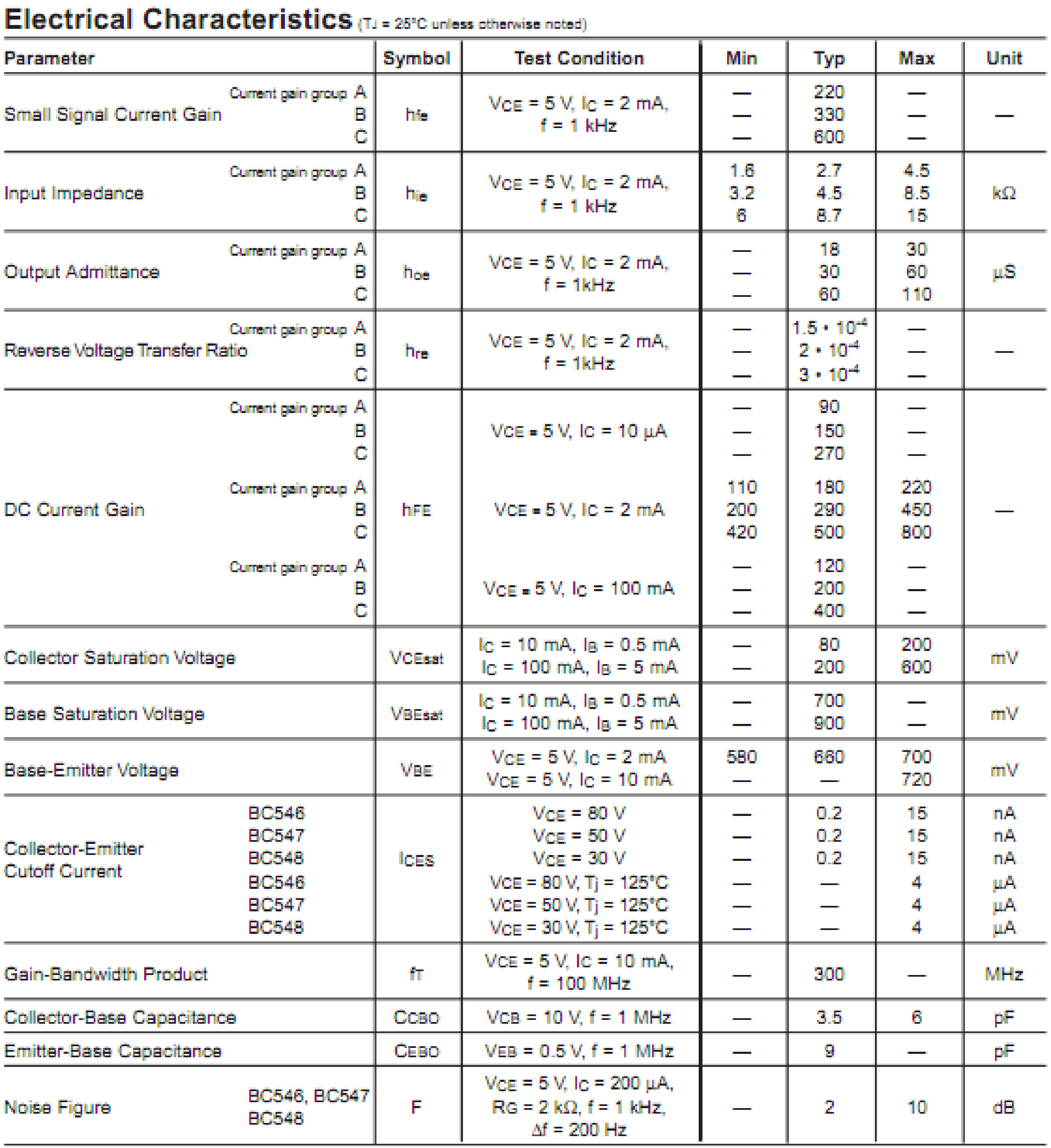


Maximum Ratings & Thermal Characteristics

Ratings at 25°C ambient temperature unless otherwise specified.

Parameter		Symbol	Value	Unit
Collector-Base Voltage	BC546 BC547 BC548	V_{CBO}	80 50 30	V
Collector-Emitter Voltage	BC546 BC547 BC548	V_{CES}	80 50 30	V
Collector-Emitter Voltage	BC546 BC547 BC548	V_{CEO}	65 45 30	V
Emitter-Base Voltage	BC546, BC547 BC548	V_{EBO}	6 5	V
Collector Current		I_C	100	mA
Peak Collector Current		I_{CM}	200	mA
Peak Base Current		I_{BM}	200	mA
Peak Emitter Current		$-I_{EM}$	200	mA
Power Dissipation at T_{amb} = 25°C		P_{tot}	500(1)	mW
Thermal Resistance Junction to Ambient Air		$R_{\Theta JA}$	250(1)	°C/W
Junction Temperature		T_j	150	°C
Storage Temperature Range		T_S	–65 to +150	°C

Note: (1) Valid provided that leads are kept at ambient temperature at a distance of 2 mm from case.



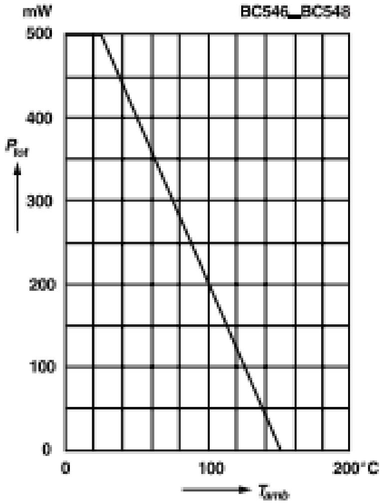
Electrical Characteristics (T_J = 25°C unless otherwise noted)

Parameter		Symbol	Test Condition	Min	Typ	Max	Unit
Small Signal Current Gain	Current gain group A	h_{fe}	V_{CE} = 5 V, I_C = 2 mA, f = 1 kHz	—	220	—	—
	B			—	330	—	
	C			—	600	—	
Input Impedance	Current gain group A	h_{ie}	V_{CE} = 5 V, I_C = 2 mA, f = 1 kHz	1.6	2.7	4.5	kΩ
	B			3.2	4.5	8.5	
	C			6	8.7	15	
Output Admittance	Current gain group A	h_{oe}	V_{CE} = 5 V, I_C = 2 mA, f = 1kHz	—	18	30	µS
	B			—	30	60	
	C			—	60	110	
Reverse Voltage Transfer Ratio	Current gain group A	h_{re}	V_{CE} = 5 V, I_C = 2 mA, f = 1kHz	—	$1.5 \cdot 10^{-4}$	—	—
	B			—	$2 \cdot 10^{-4}$	—	
	C			—	$3 \cdot 10^{-4}$	—	
DC Current Gain	Current gain group A	h_{FE}	V_{CE} = 5 V, I_C = 10 µA	—	90	—	—
	B			—	150	—	
	C			—	270	—	
	Current gain group A		V_{CE} = 5 V, I_C = 2 mA	110	180	220	
	B			200	290	450	
	C			420	500	800	
	Current gain group A		V_{CE} = 5 V, I_C = 100 mA	—	120	—	
	B			—	200	—	
	C			—	400	—	
Collector Saturation Voltage		V_{CEsat}	I_C = 10 mA, I_B = 0.5 mA	—	80	200	mV
			I_C = 100 mA, I_B = 5 mA	—	200	600	
Base Saturation Voltage		V_{BEsat}	I_C = 10 mA, I_B = 0.5 mA	—	700	—	mV
			I_C = 100 mA, I_B = 5 mA	—	900	—	
Base-Emitter Voltage		V_{BE}	V_{CE} = 5 V, I_C = 2 mA	580	660	700	mV
			V_{CE} = 5 V, I_C = 10 mA	—	—	720	
Collector-Emitter Cutoff Current	BC546	I_{CES}	V_{CE} = 80 V	—	0.2	15	nA
	BC547		V_{CE} = 50 V	—	0.2	15	nA
	BC548		V_{CE} = 30 V	—	0.2	15	nA
	BC546		V_{CE} = 80 V, T_j = 125°C	—	—	4	µA
	BC547		V_{CE} = 50 V, T_j = 125°C	—	—	4	µA
	BC548		V_{CE} = 30 V, T_j = 125°C	—	—	4	µA
Gain-Bandwidth Product		f_T	V_{CE} = 5 V, I_C = 10 mA, f = 100 MHz	—	300	—	MHz
Collector-Base Capacitance		C_{CBO}	V_{CB} = 10 V, f = 1 MHz	—	3.5	6	pF
Emitter-Base Capacitance		C_{EBO}	V_{EB} = 0.5 V, f = 1 MHz	—	9	—	pF
Noise Figure	BC546, BC547	F	V_{CE} = 5 V, I_C = 200 µA, R_G = 2 kΩ, f = 1 kHz, Δf = 200 Hz	—	2	10	dB
	BC548						

Ratings and Characteristic Curves (T_A = 25°C unless otherwise noted)

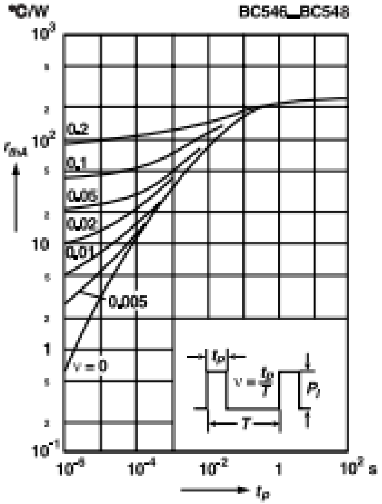
Admissible power dissipation versus temperature

Valid provided that leads are kept at ambient temperature at a distance of 2 mm from case

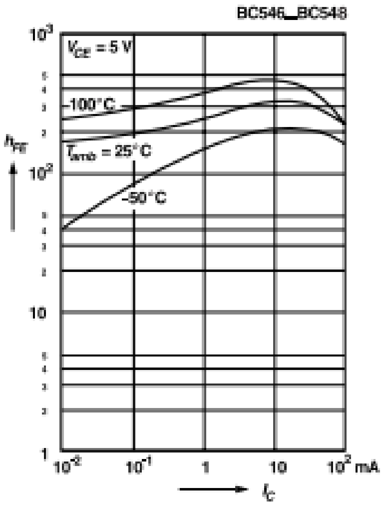


Pulse thermal resistance versus pulse duration

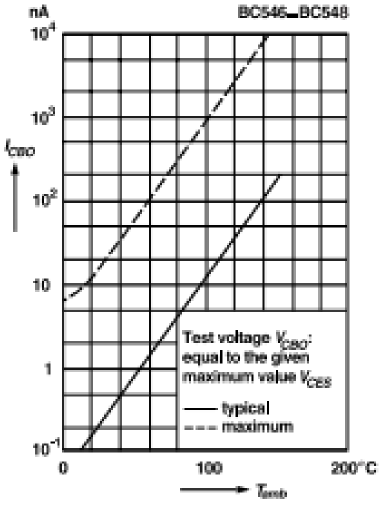
Valid provided that leads are kept at ambient temperature at a distance of 2 mm from case



DC current gain versus collector current

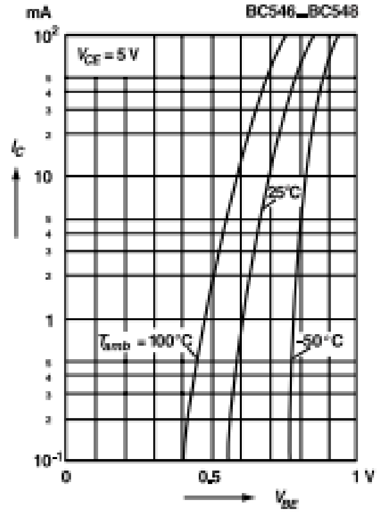


Collector-base cutoff current versus ambient temperature

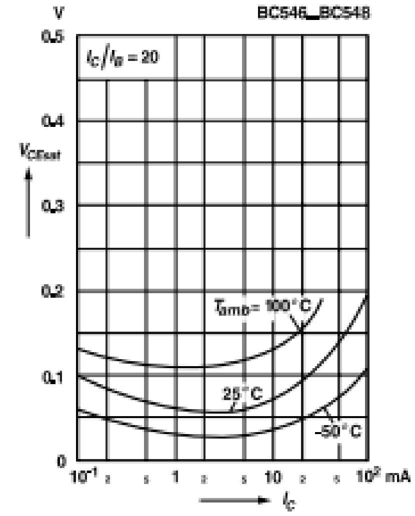


Ratings and Characteristic Curves (T_A = 25°C unless otherwise noted)

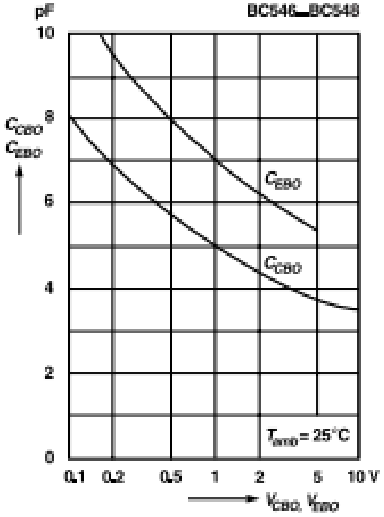
Collector current versus base-emitter voltage



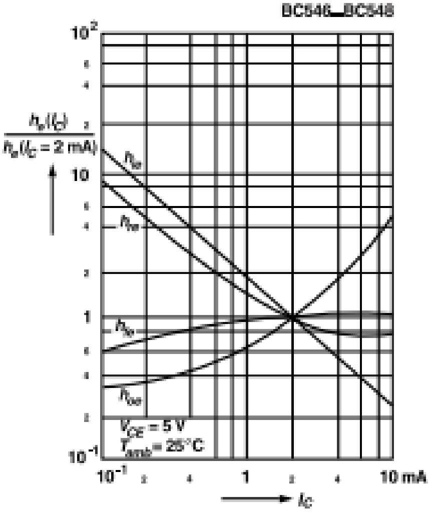
Collector saturation voltage versus collector current



Collector-base capacitance, Emitter-base capacitance versus reverse bias voltage

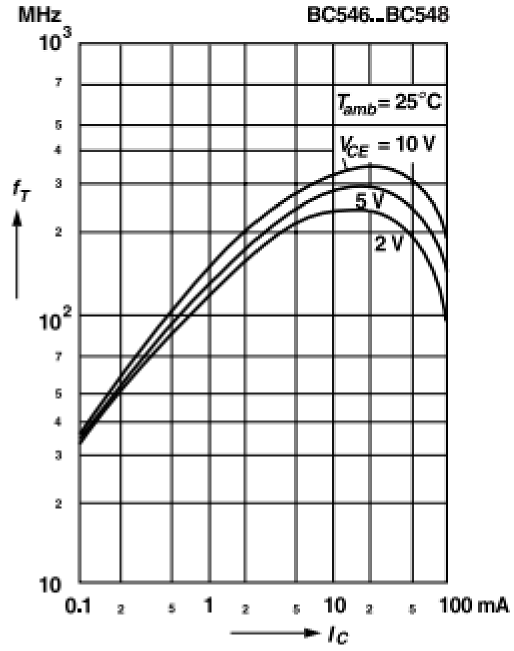


Relative h-parameters versus collector current

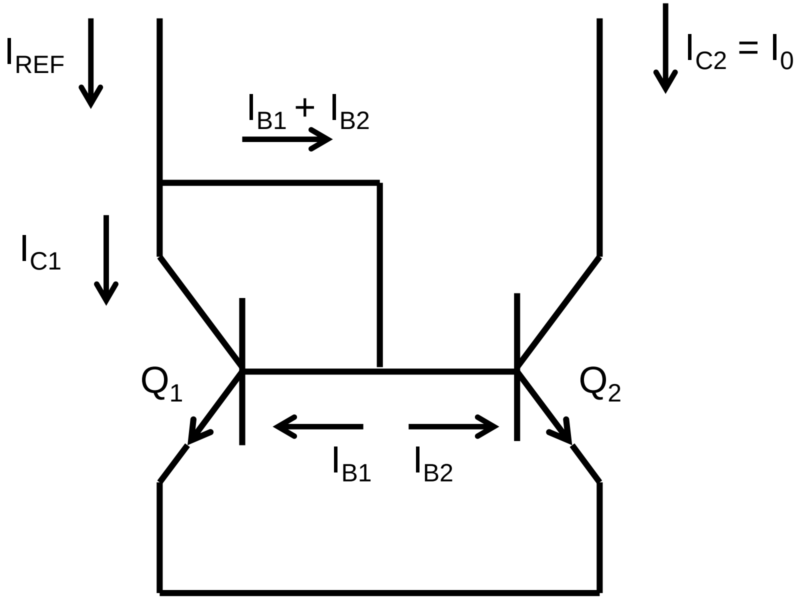


Ratings and Characteristic Curves (T_A = 25°C unless otherwise noted)

Gain-bandwidth product versus collector current



Fuente Espejo



$$I_{C1} = I_{S1} e^{\frac{V_{BE1}}{U_T}}$$

$$I_{C2} = I_{S2} e^{\frac{V_{BE2}}{U_T}}$$

$$V_{BE1} = V_{BE2} \qquad \frac{I_{C1}}{I_{C2}} = \frac{I_{S1}}{I_{S2}}$$

$$Q_1 = Q_2$$

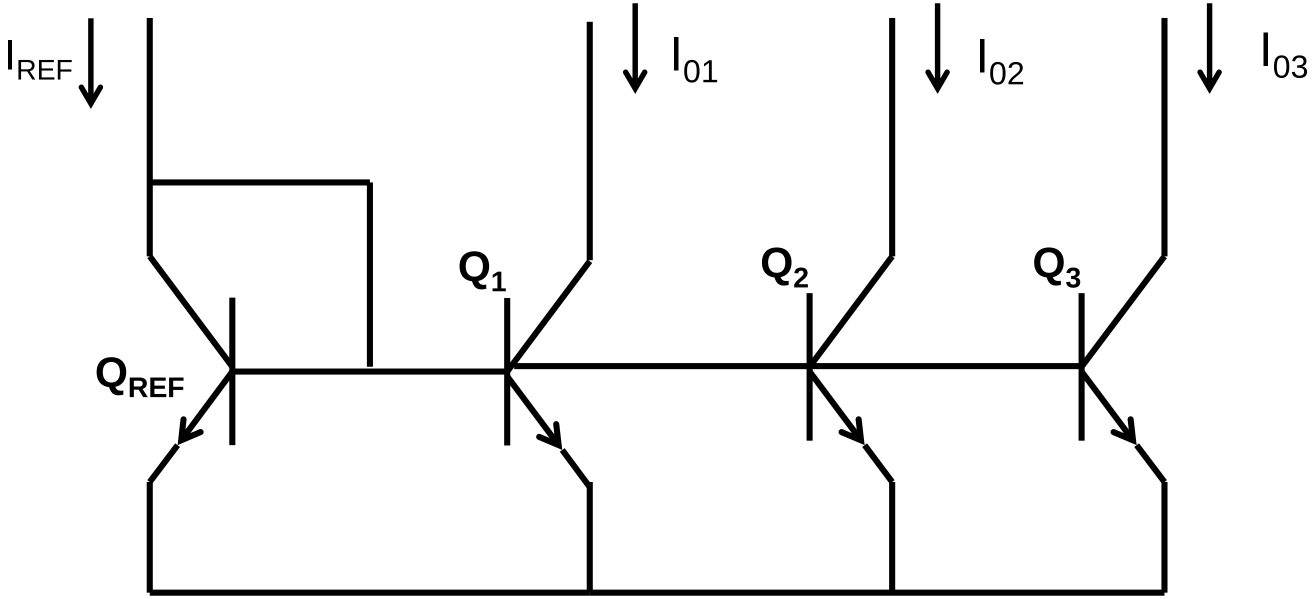
$$I_{REF} = I_{C1} + I_{B1} + I_{B2} \qquad I_{B1} = I_{B2} = I_B \qquad I_{REF} = I_{C1} + 2I_B \qquad I_{C1} = I_{C2}$$

$$I_{REF} = I_{C2} + 2I_B \qquad I_{C2} = I_0 \qquad I_{REF} = I_0 + 2I_B \qquad I_B = \frac{I_{C1,2}}{\beta} = \frac{I_0}{\beta}$$

$$I_{REF} = I_0 + 2\frac{I_0}{\beta}$$

$$\boxed{I_0 = \frac{I_{REF}}{1 + \frac{2}{\beta}}}$$

Fuente Espejo

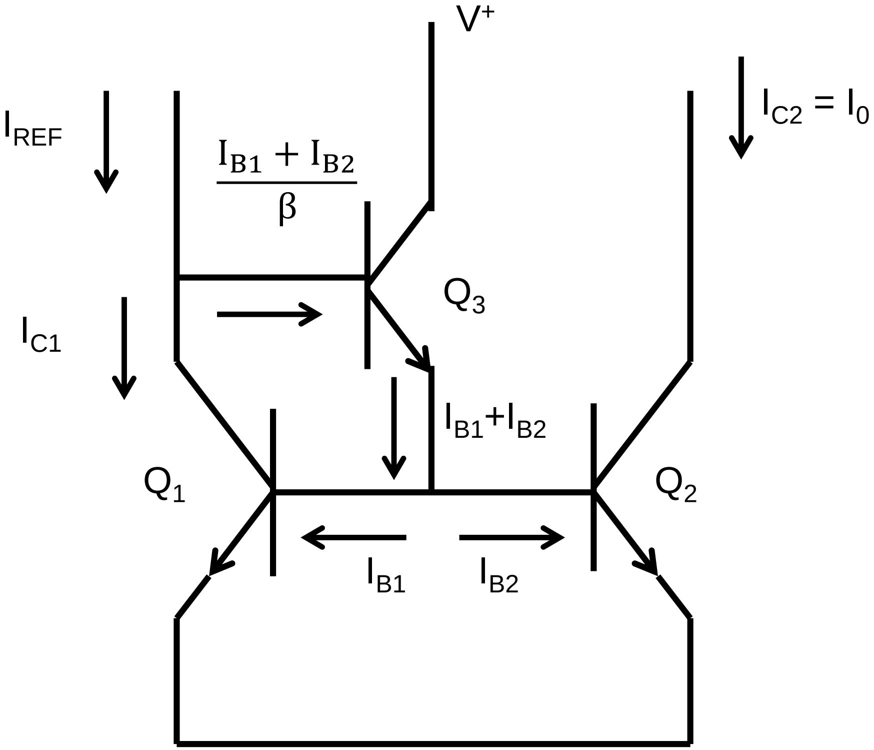


$I_{S1} = I_{SREF}$ ➡ $I_{01} = I_{REF}$

$I_{S2} = 2\ I_{SREF}$ ➡ $I_{02} = 2\ I_{REF}$

$I_{S3} = 4\ I_{SREF}$ ➡ $I_{03} = 4\ I_{REF}$

Fuente Espejo de 3 Transistores



$$\mathrm{I_{REF}} = \mathrm{I_{C1}} + \frac{\mathrm{I_{B1}} + \mathrm{I_{B2}}}{\beta}$$

$$\mathrm{I_{C1}} = \mathrm{I_{C2}} = \mathrm{I_0}$$

$$\mathrm{I_{B1}} = \mathrm{I_{B2}} = \frac{\mathrm{I_{C1}}}{\beta}$$

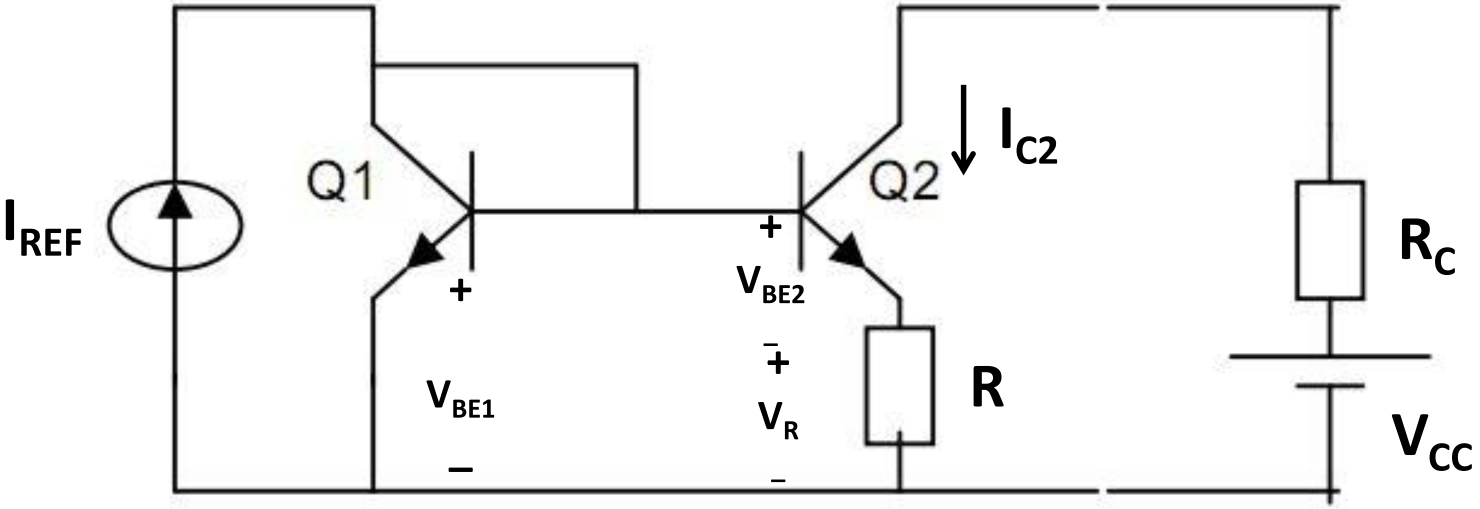
$$\mathrm{I_{REF}} = \mathrm{I_{C1}} + \frac{2I_{C1}}{\beta^2}$$

$$\mathrm{I_{REF}} = I_{C1}\left(1 + \frac{2}{\beta^2}\right)$$

$$\mathrm{I_{REF}} = I_0\left(1 + \frac{2}{\beta^2}\right)$$

$$\mathbf{I_0} = \frac{\mathbf{I_{REF}}}{\left(\mathbf{1} + \frac{\mathbf{2}}{\boldsymbol{\beta}^{\mathbf{2}}}\right)}$$

Fuente Espejo Desequilibrada



$$I_{C1} = I_{S1} e^{\frac{V_{BE1}}{U_T}}$$

$$I_{C2} = I_{S2} e^{\frac{V_{BE2}}{U_T}}$$

$$\frac{I_{C1}}{I_{C2}} = \frac{I_{S1}}{I_{S2}} e^{\frac{V_{BE1}-V_{BE2}}{U_T}}$$

$$Q_1 \equiv Q_2$$

$$I_{S1} \equiv I_{S2}$$

$$\frac{I_{C1}}{I_{C2}} = e^{\frac{V_{BE1}-V_{BE2}}{U_T}}$$

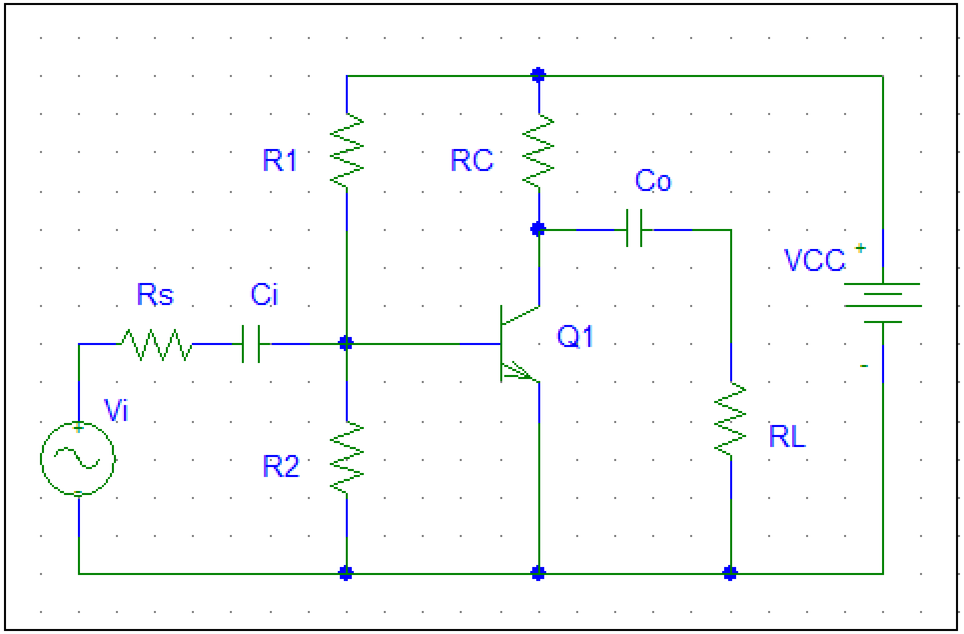
$$V_{BE1} - V_{BE2} = I_{C2} \times R$$

Despreciando las corrientes de base $I_{REF} \approx I_{C1}$

$$\frac{I_{REF}}{I_{C2}} = e^{\frac{I_{C2} \times R}{U_T}}$$

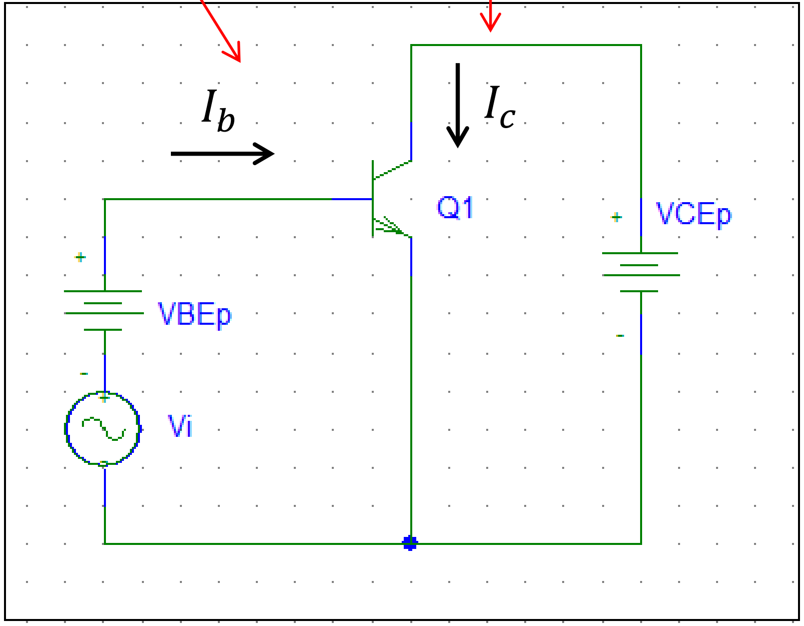
$$\boldsymbol{I_{REF} = I_{C2} e^{\frac{I_{C2} \times R}{U_T}}}$$

El Transistor como Amplificador



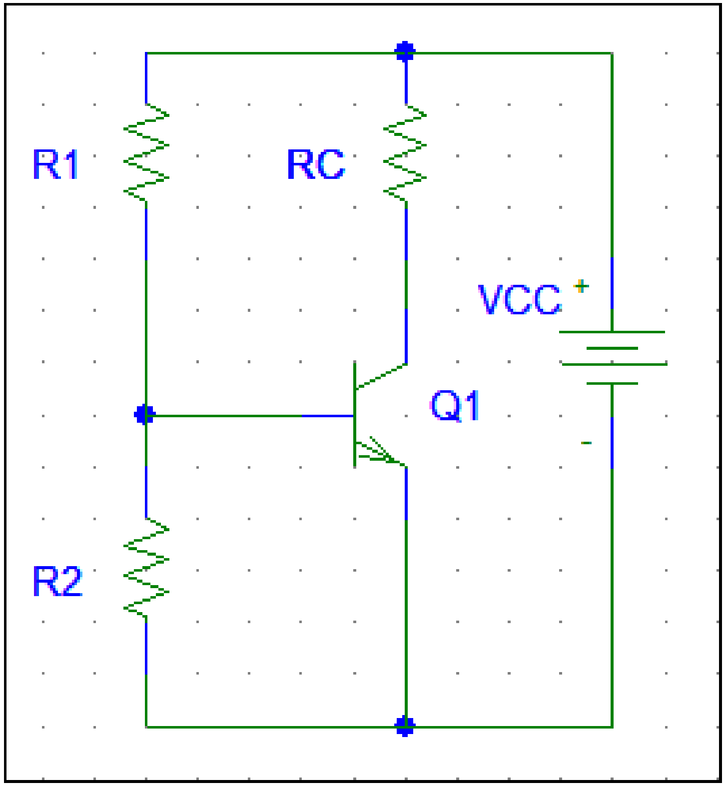
$$I_c = I_{CP} + i_c$$

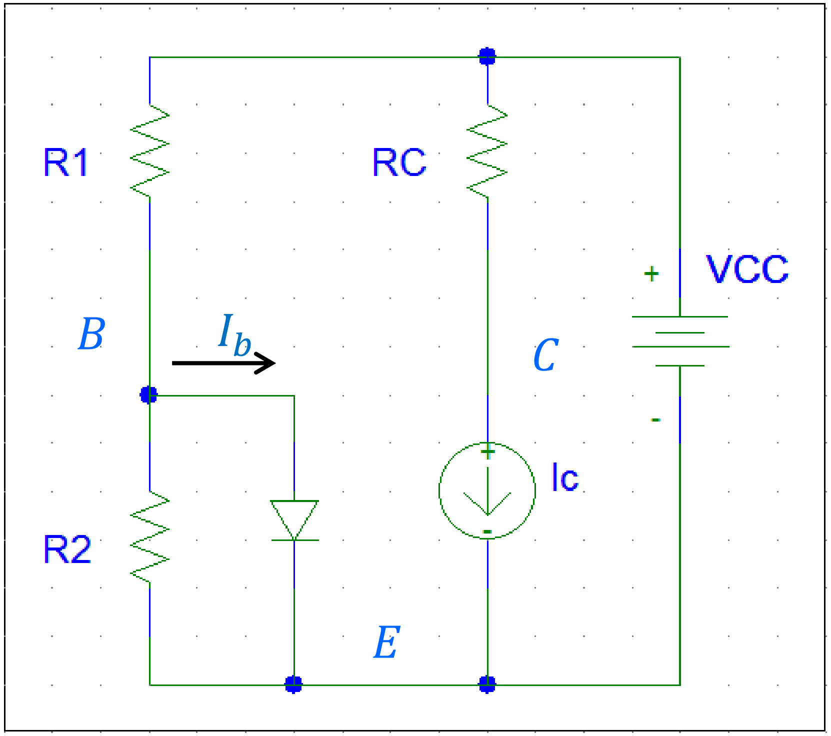
$$I_b = I_{Bp} + i_b$$

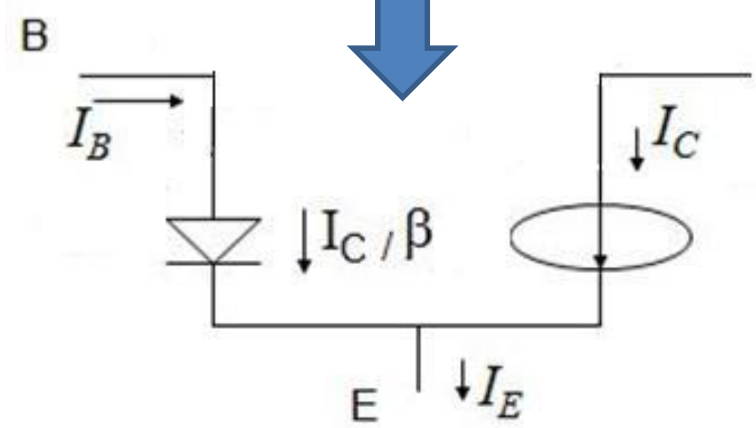


$$V_{be} = V_{BEp} + v_i$$

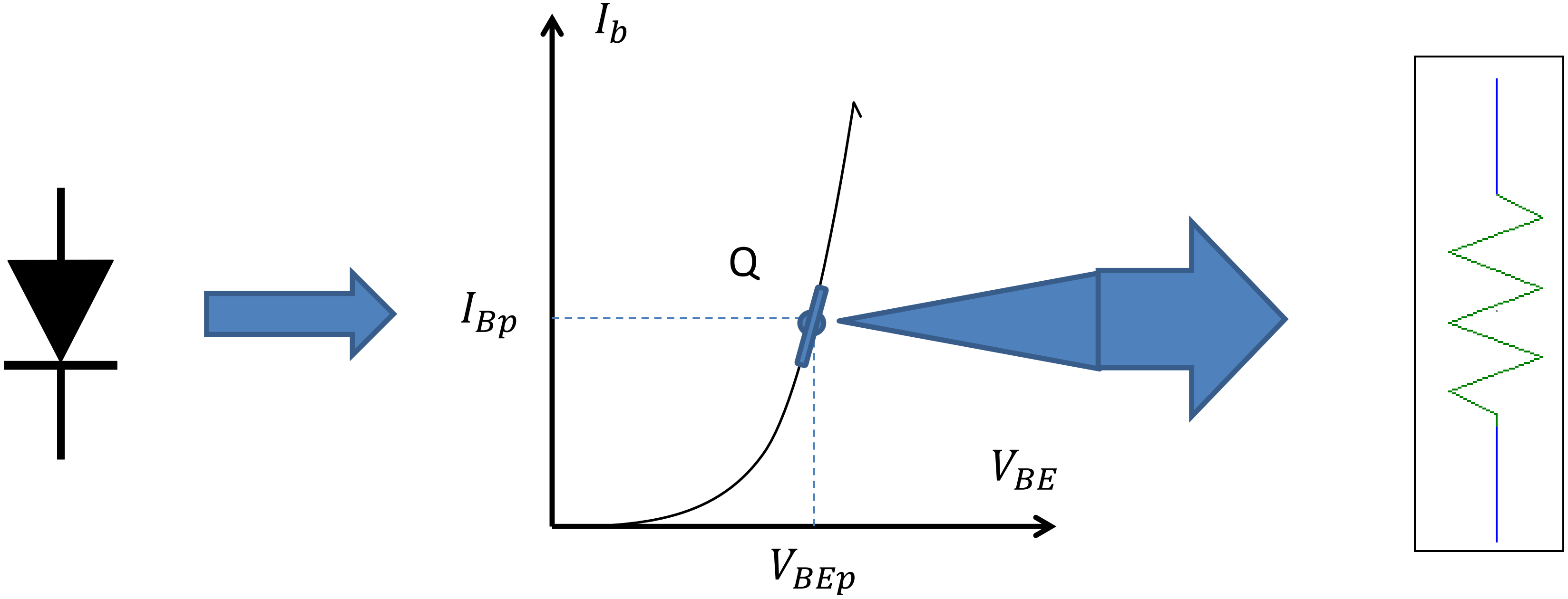
Circuito de Polarización







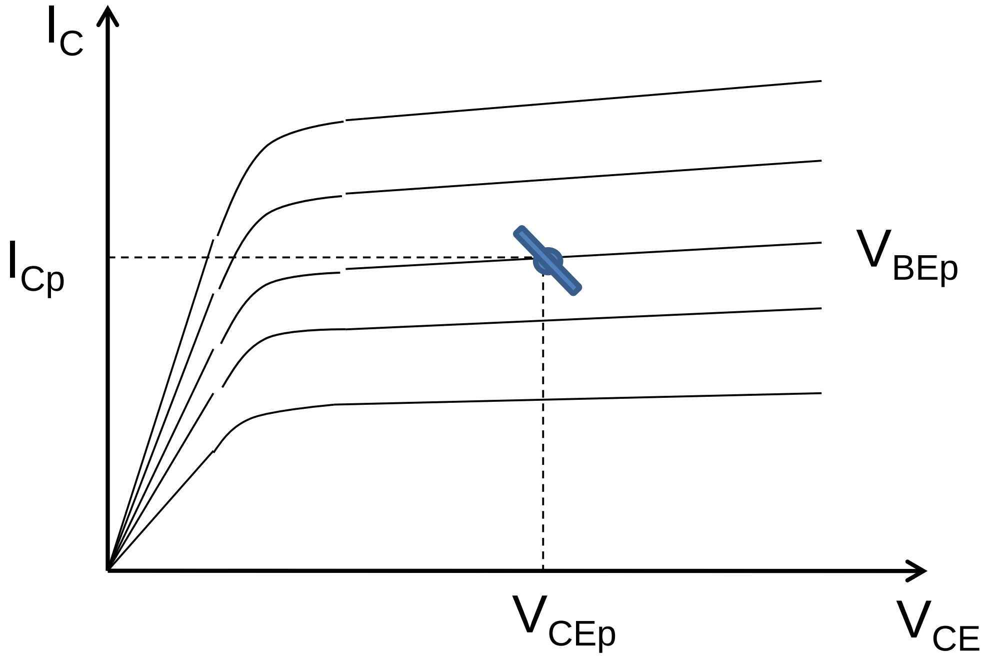
$$I_C = \left(1+\frac{V_{CE}}{V_A}\right) I_S e^{\frac{V_{BEp}}{U_T}}$$



Cuando Vi es pequeño puedo linealizar la exponencial

El diodo puedo reemplazarlo por un resistor (r_π)

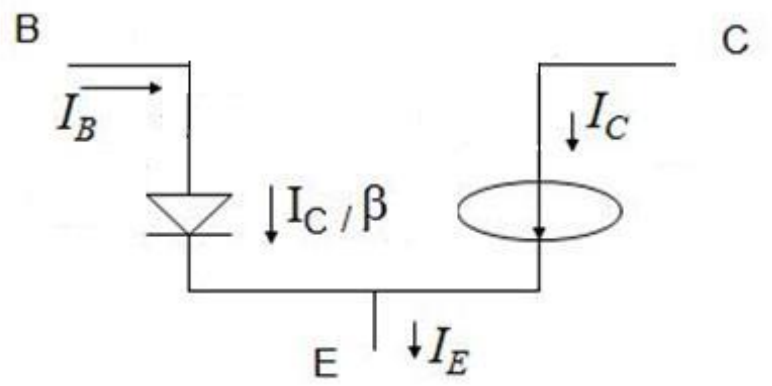
El valor del resistor se calcula como $r_\pi = \left.\frac{dV_{BE}}{dI_B}\right|_{\text{Calculado en Q}}$



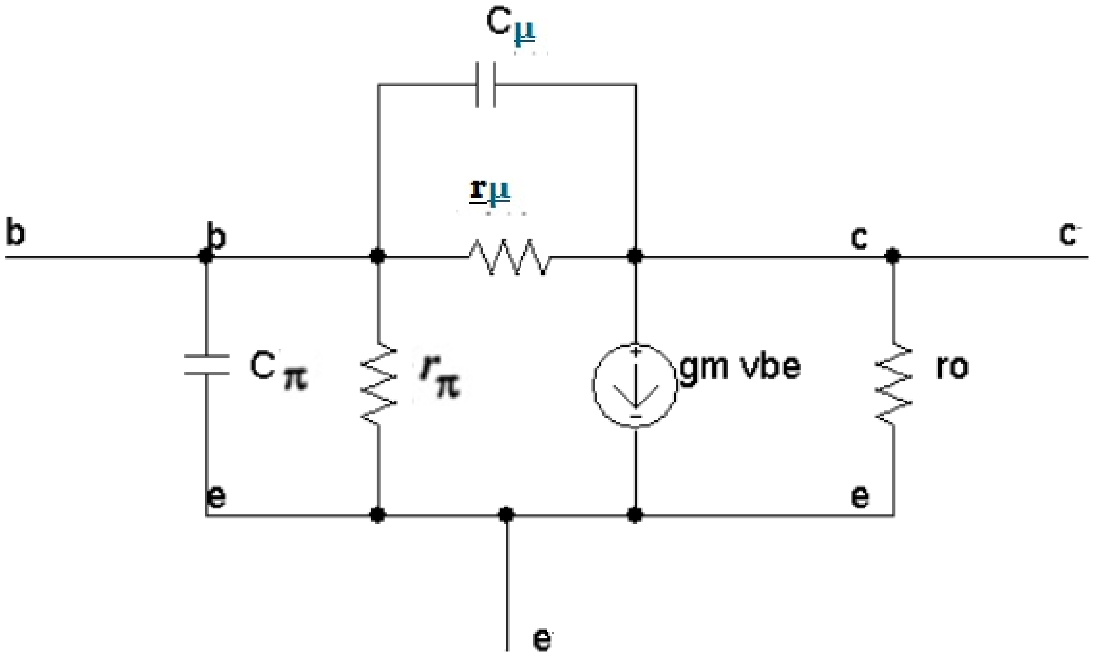
Cuando Vi es pequeño puedo linealizar la relación entre I_c y V_{BE}

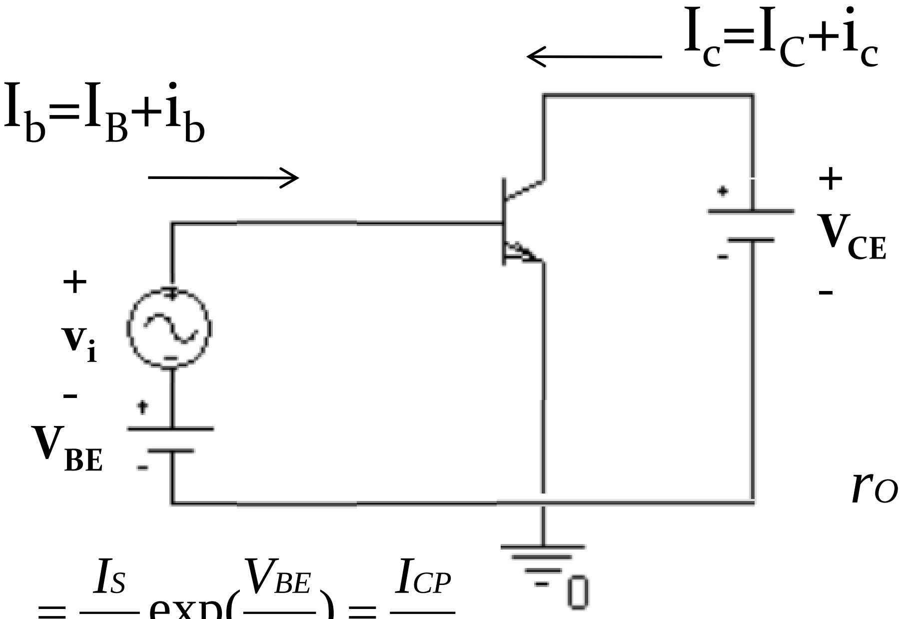
$$i_C = I_S e^{\frac{V_i}{U_T}} \qquad i_c = g_m v_i \qquad g_m = \left.\frac{dI_C}{dV_{BE}}\right|_{Calculado\ en\ Q}$$

Modelo de Pequeña Señal configuración Emisor Común



$$I_{S}, \beta, V_{A}, V_{CBO} \Rightarrow \begin{array}{l} V_{CEp} \\ I_{Cp} \\ V_{BEp} \end{array}$$





$$g_m = \left.\frac{dI_C}{dV_{BE}}\right|_{VBE} = \frac{I_S}{U_T}\exp\left(\frac{V_{BE}}{U_T}\right) = \frac{I_{CP}}{U_T}$$

$$r_\pi = \left.\frac{dV_{BE}}{dI_B}\right|_{VBE} = \beta\frac{U_T}{I_{CP}}$$

$$I_B = \frac{I_s}{\beta}\exp\left(\frac{V_{BE}}{U_T}\right)$$

$$\frac{dI_B}{dV_{BE}} = \frac{I_S}{\beta U_T}\exp\left(\frac{V_{BE}}{U_T}\right)$$

$$r_O = \frac{dV_{CE}}{dI_C} = \frac{V_A}{I_{Cp}}$$

$$I_C = I_S\left(1 + \frac{V_{CE}}{V_A}\right)\exp\left(\frac{V_{BE}}{U_T}\right)$$

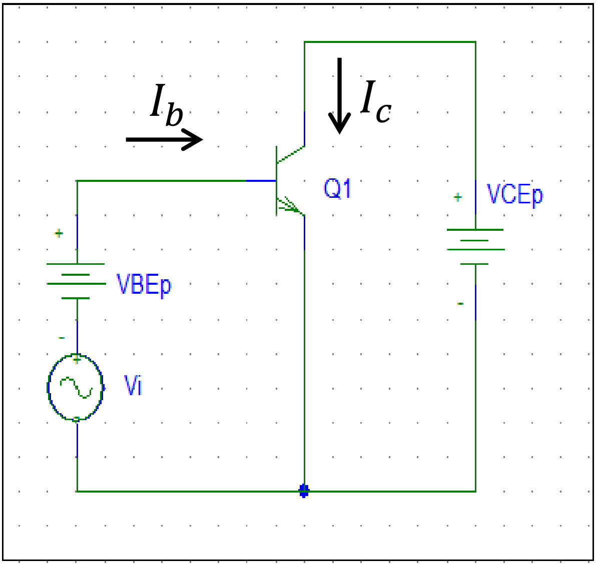
$$\frac{dI_C}{dV_{CE}} = \frac{I_S}{V_A}\exp\left(\frac{V_{BE}}{U_T}\right)$$

$$r_\mu = \frac{dV_{CE}}{dI_B} = \frac{dV_{CE}}{dI_C} * \frac{dIc}{dI_B} = r_O\beta$$

Validez del Modelo

$$\boxed{I_c = I_{CP} + i_c}$$

$$\boxed{V_{be} = V_{BEp} + v_i}$$



$$I_c = I_S e^{\left(\frac{V_{BEp}+v_i}{U_T}\right)}$$

$$I_c = I_S e^{\left(\frac{V_{BEp}}{U_T}\right)} * \; e^{\left(\frac{v_i}{U_T}\right)}$$

$$I_c = I_{CP} * e^{\left(\frac{v_i}{U_T}\right)}$$

$$I_c = I_{CP} * \left(1 + \frac{v_i}{U_T}\right)$$

$$I_c - I_{CP} = i_c$$

$$i_c = I_{CP}\frac{v_i}{U_T}$$

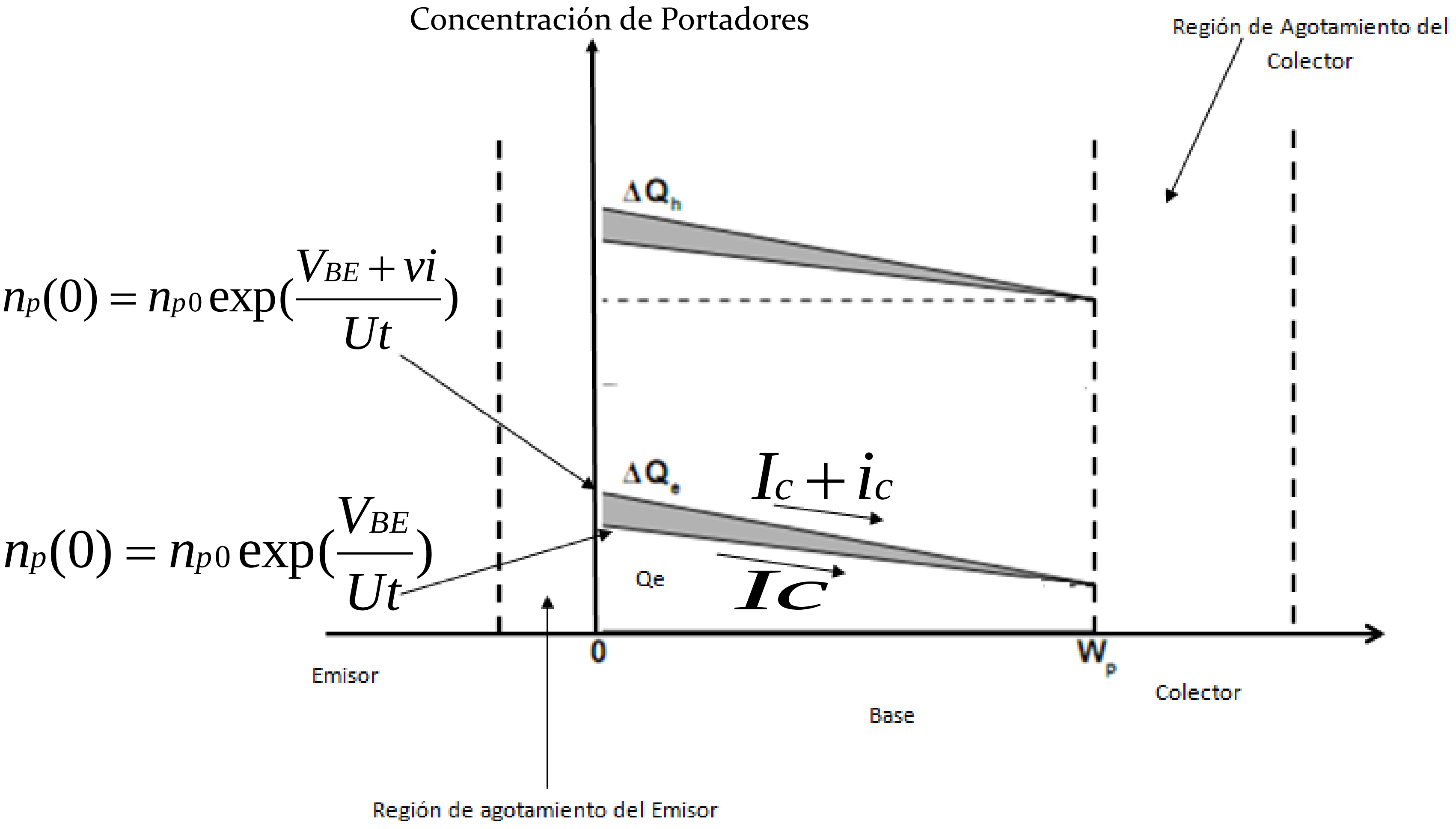
$$\frac{i_c}{v_i} = \frac{I_{CP}}{U_T} \quad \Rightarrow \quad g_m = \frac{I_{CP}}{U_T}$$

$$Si \; \frac{v_i}{U_T} < 1 \quad \Rightarrow \quad e^{\left(\frac{v_i}{U_T}\right)} = 1 + \frac{v_i}{U_T} + \frac{1}{2}\left(\frac{v_i}{U_T}\right)^2 + \frac{1}{3}\left(\frac{v_i}{U_T}\right)^3 + \cdots\cdots$$

$$Si \; \frac{v_i}{U_T} \ll 1 \quad \Rightarrow \quad e^{\left(\frac{v_i}{U_T}\right)} \sim 1 + \frac{v_i}{U_T}$$

$$U_T = 26mV \;\Rightarrow\; v_i \sim 2.6\,mV$$

Capacitancias del Modelo



$$n_p(0) = n_{p0}\exp(\frac{V_{BE} + vi}{Ut})$$

$$n_p(0) = n_{p0}\exp(\frac{V_{BE}}{Ut})$$

$$\Delta V_{BE} \rightarrow \ v_i \rightarrow \Delta Q_E \rightarrow \Delta Q_h$$

Capacitancias del Modelo

$$\Delta V_{BE} \rightarrow \; v_i \rightarrow \underset{\substack{\downarrow \\ \text{Corriente}}}{\Delta Q_E} \rightarrow \underset{\substack{\downarrow \\ \text{Neutralidad}}}{\Delta Q_h}$$

$$v_i \rightarrow q_h \Rightarrow \textit{Capacidad } C_b = \frac{q_h}{v_i}$$

$$\frac{Q_E}{I_C} = \tau_F = \frac{W_B}{2D_n}^{2} \rightarrow \textit{Tiempo de Tránsito}$$

$$Si\ \Delta Q_E = \Delta Q_h$$

$$\frac{\Delta Q_E}{\Delta I_C} = \frac{\Delta Q_h}{\Delta I_C} = \tau_F$$

$$q_h = \tau_F i_c$$

$$\frac{q_h}{v_i} = \tau_F * g_m$$

$$\Rightarrow \quad C_b = \tau_F * g_m$$

Capacitancias del Modelo

$$C_{\pi} = C_{jBE} + C_{b}$$

Capacidad de Juntura
Base-Emisor

$$C_{jBE} = \frac{C_{jBE0}}{\sqrt{1 - \frac{V_{BE}}{V_{j0BE}}}}$$

Capacidad de Difusión
Base-Emisor

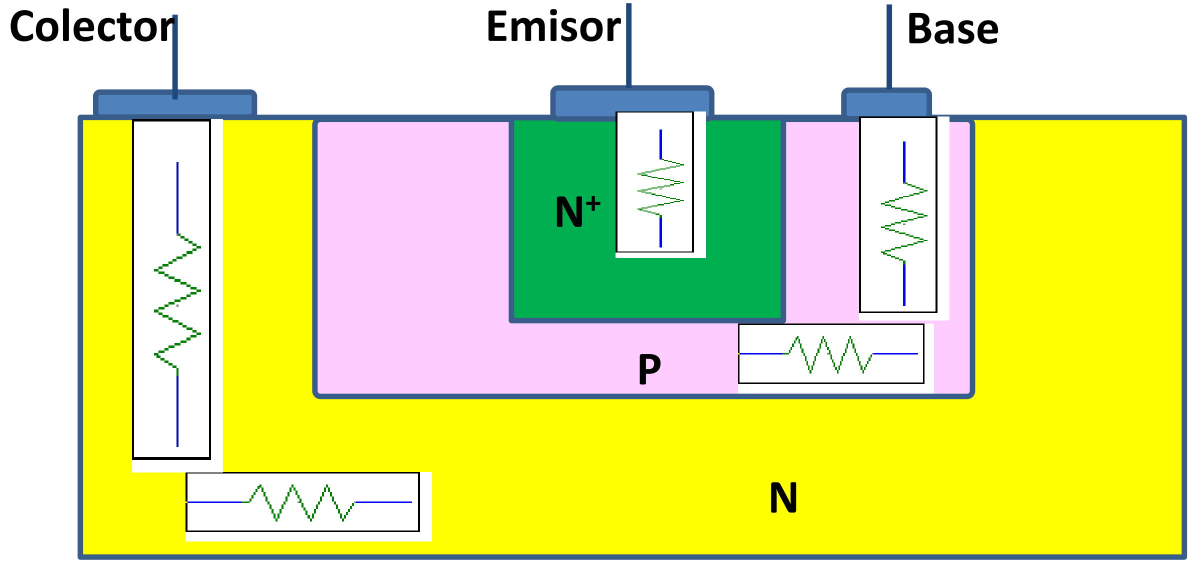
$$C_{b} = \tau_{F} \times g_{m}$$

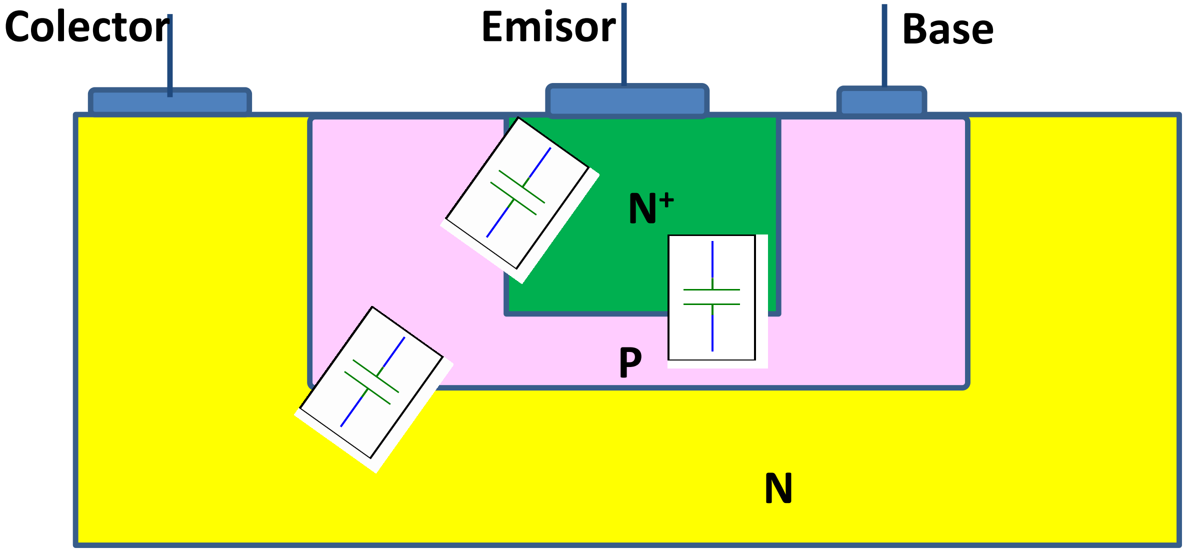
$$C_{\mu} = C_{jBC}$$

Capacidad de Juntura
Base-Colector

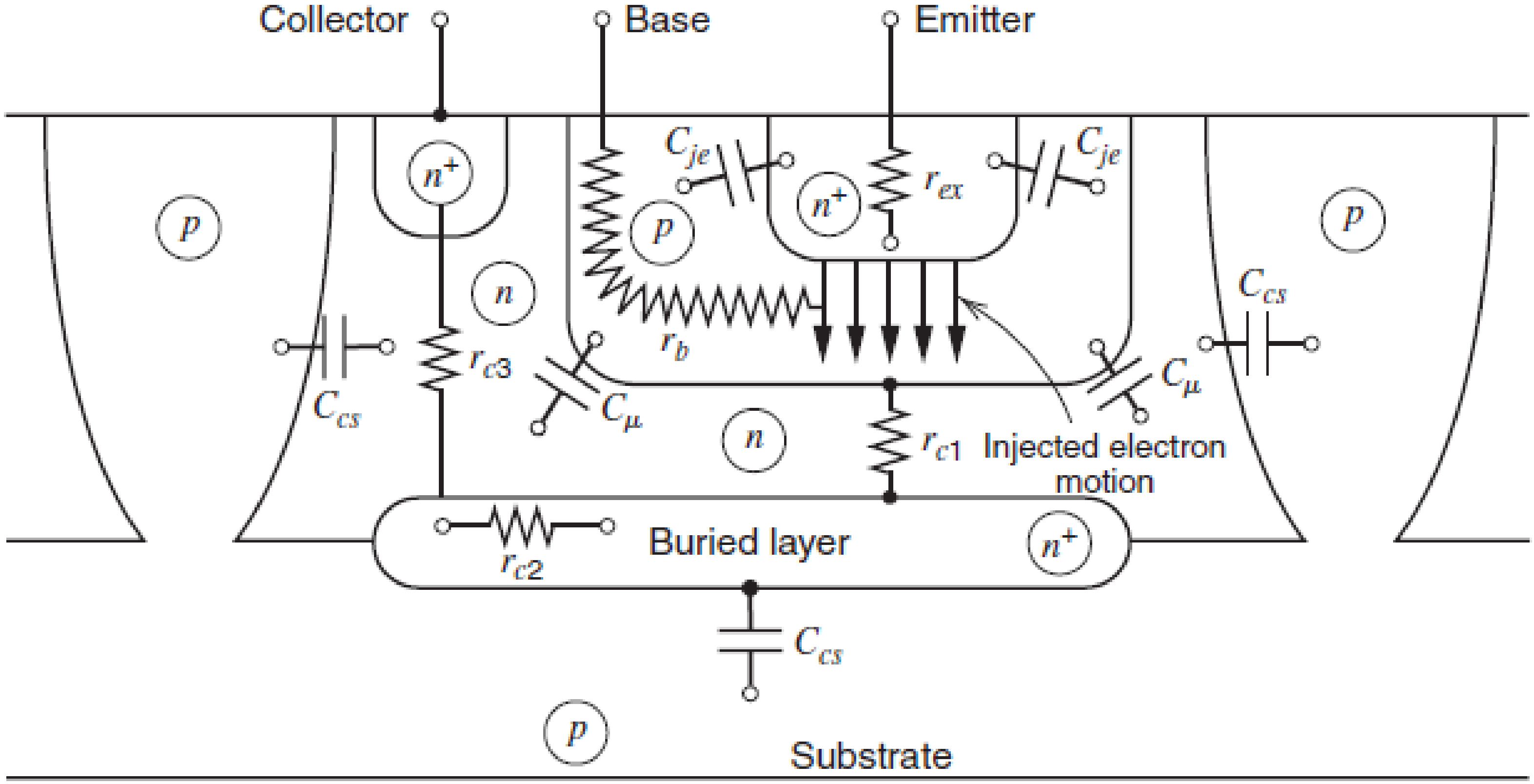
$$C_{jBC} = \frac{C_{jBC0}}{\sqrt{1 - \frac{V_{BC}}{V_{j0BC}}}}$$

Elementos parásitos

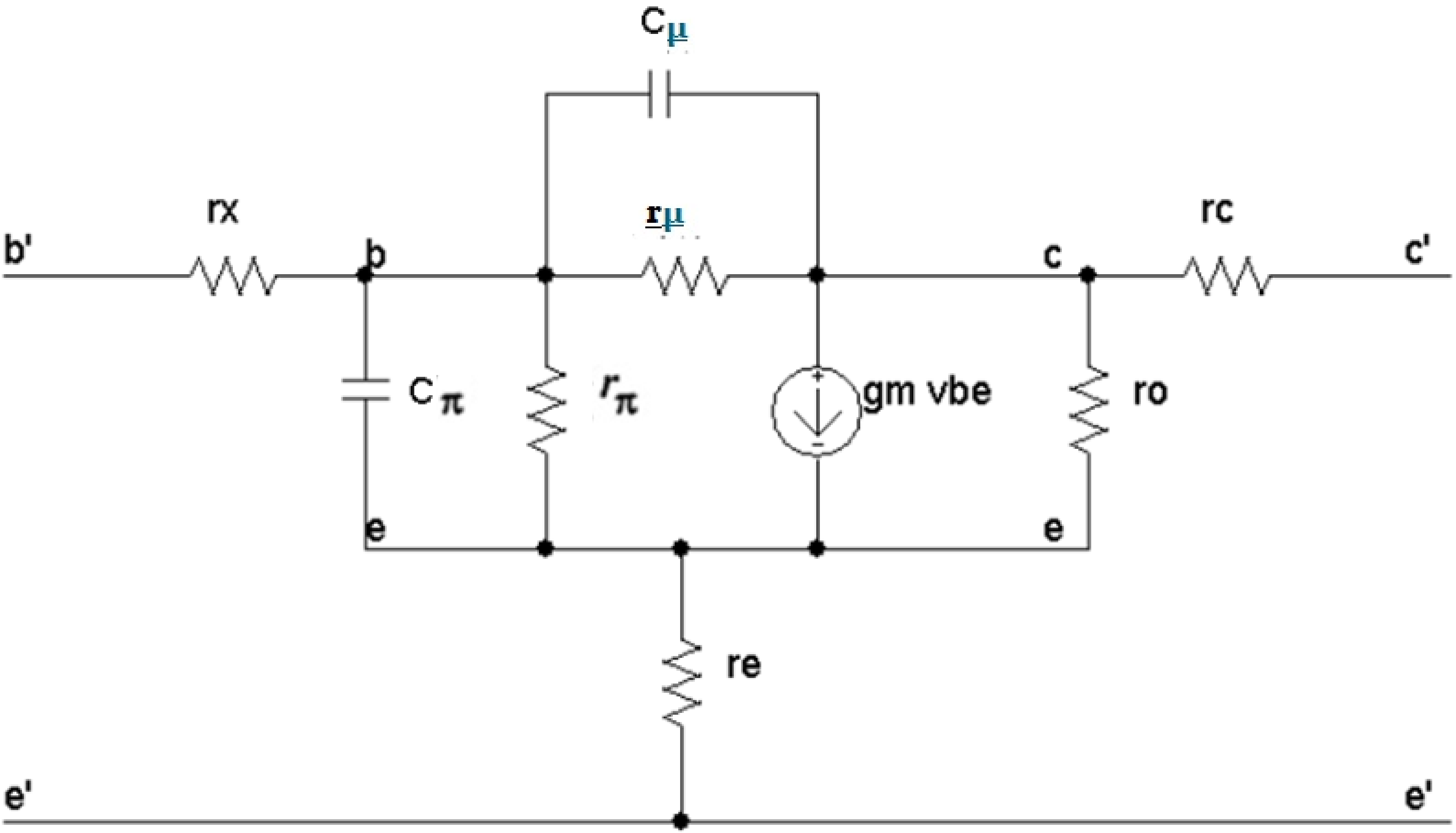




Resistencias y Capacitancias Parásitas



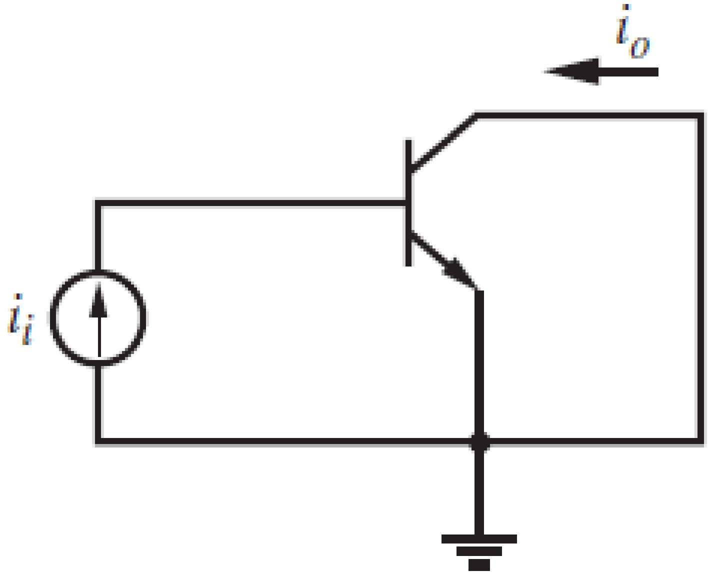
Modelo considerando efectos parasitos

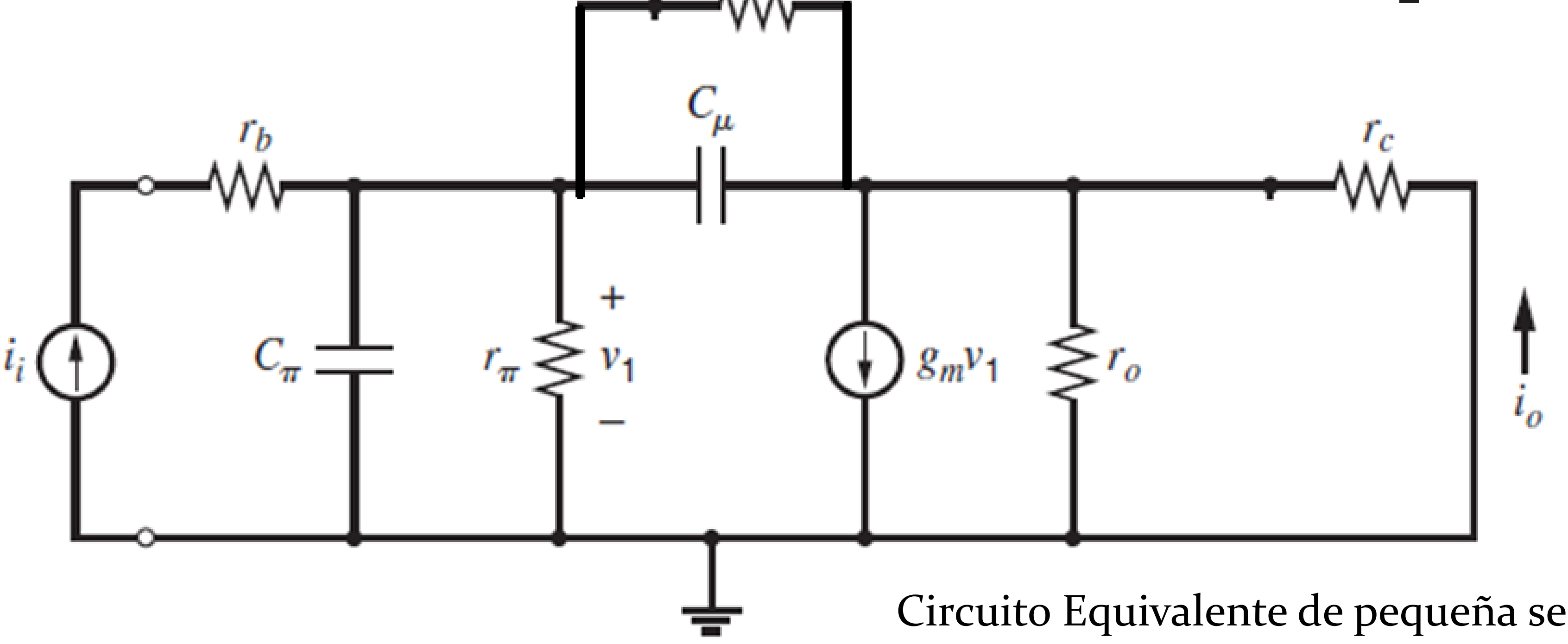


Respuesta en Frecuencia del Transistor

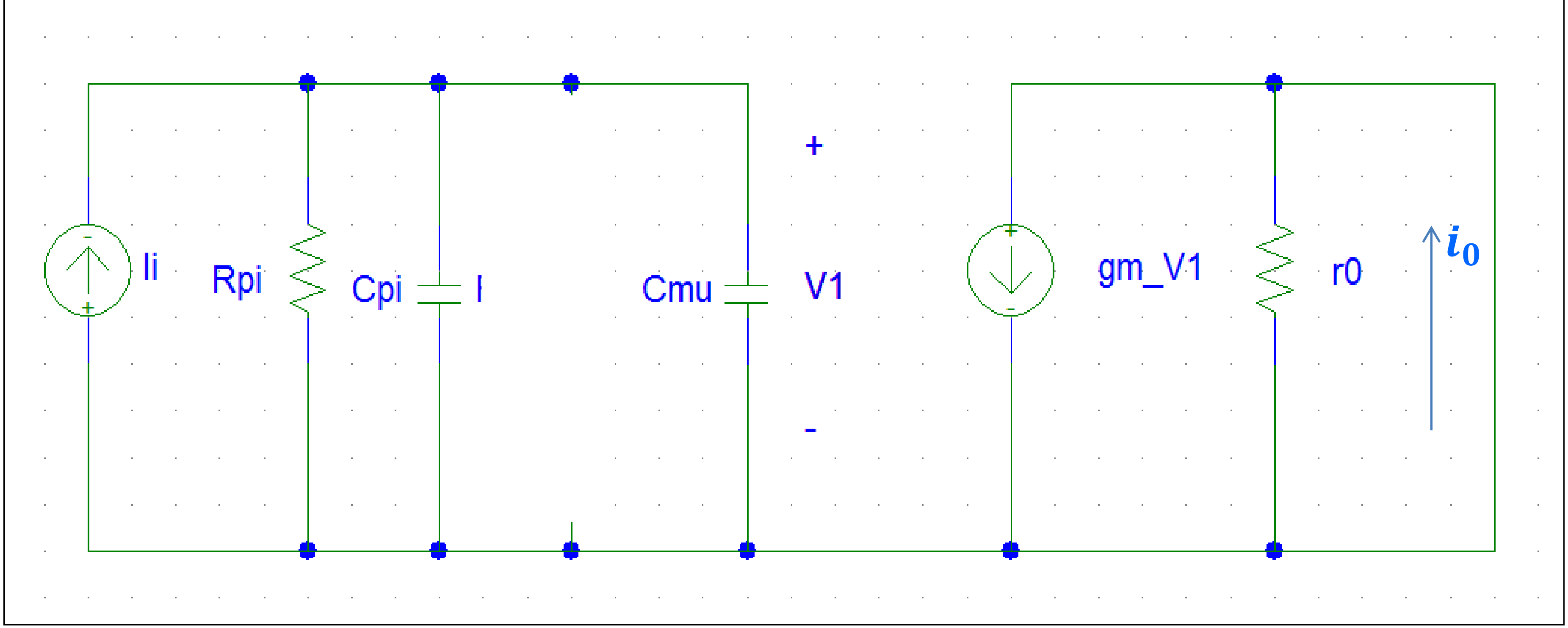
Diagrama de alterna para la medición de

f_T Frecuencia de Transición





Circuito Equivalente de pequeña señal



$$Rpi \ll Rmu \Rightarrow Puedo\ despreciar\ Rmu$$

$$i_0 = g_m \times V_1$$

$$V_1 = i_i \times \frac{r_\pi}{1 + j\omega r_\pi (C_\pi + C_\mu)}$$

$$i_0 = i_i \times \frac{g_{m\times} r_\pi}{1 + j\omega r_\pi (C_\pi + C_\mu)}$$

$$\beta(\omega) = \frac{i_0(\omega)}{i_i(\omega)}$$

$$\beta(\omega) = \frac{g_{m\times} r_\pi}{1 + j\omega r_\pi (C_\pi + C_\mu)}$$

$$\beta(\omega) = \frac{g_{m\times}r_\pi}{1 + j\omega r_\pi\left(C_\pi + C_\mu\right)}$$

Para altas frecuencias → $\omega r_\pi\left(C_\pi + C_\mu\right) \gg 1$

$$\beta(\omega) = \frac{g_m}{\omega\left(C_\pi + C_\mu\right)}$$

Definimos la frecuencia de ganancia unidad ω_T

A la frecuencia ω que $\beta = 1$

$$\boxed{\omega_T = \frac{g_m}{\left(C_\pi + C_\mu\right)}} \qquad \boxed{f_T = \frac{1}{2\pi}\frac{g_m}{\left(C_\pi + C_\mu\right)}}$$

$$\boxed{\omega_T = \frac{g_m}{\left(C_\pi + C_\mu\right)}}$$

$$\boxed{\omega_T = \frac{g_m}{\left(C_b + C_{jBE} + C_\mu\right)}}$$

$$\boxed{T_T = \frac{1}{\omega_T}}$$

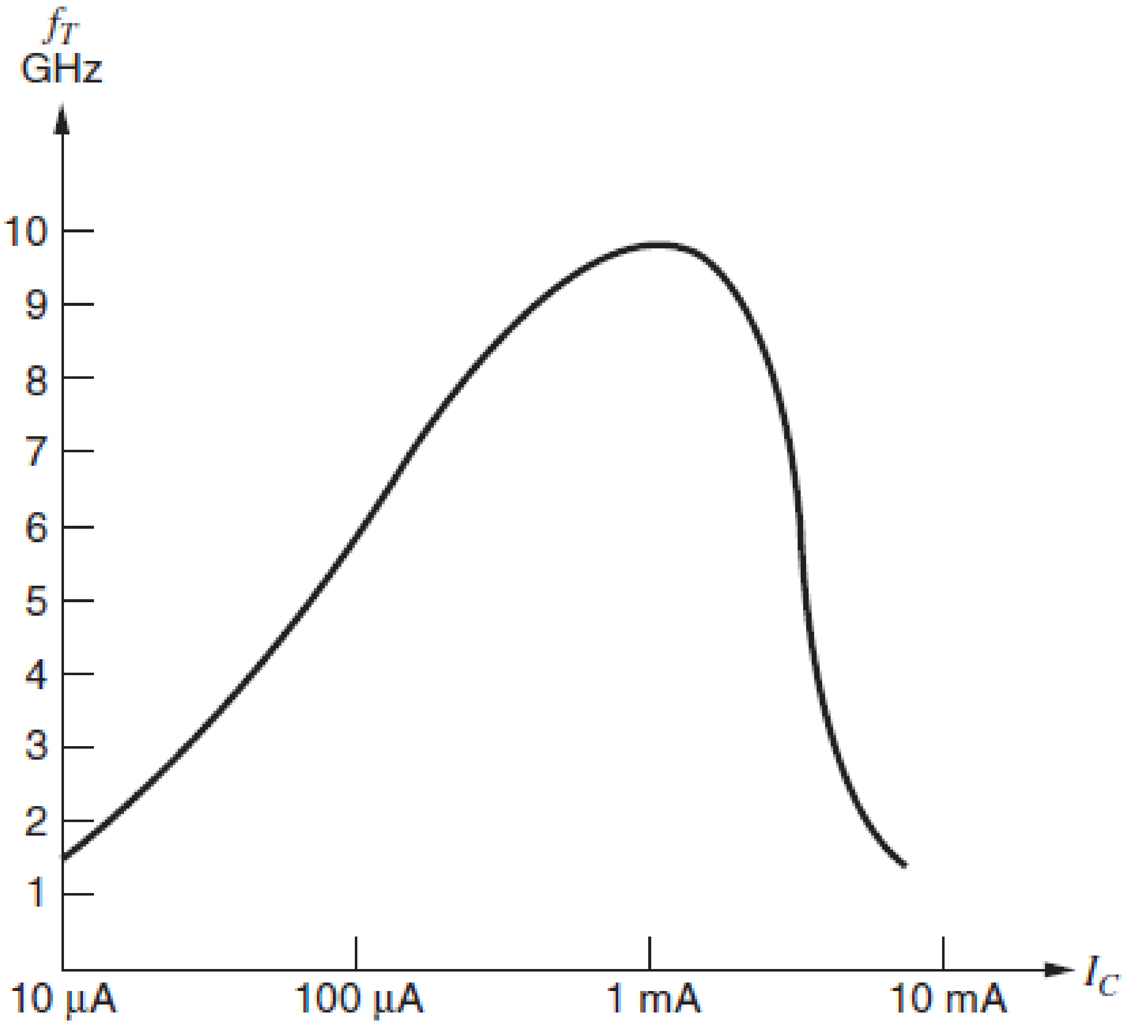
$$\boxed{T_T = \frac{C_b}{g_m} + \frac{C_{jBE}}{g_m} + \frac{C_\mu}{g_m}}$$

$$\boxed{C_b = g_m \times T_F}$$

$$\boxed{T_T = T_F + \frac{C_{jBE}}{g_m} + \frac{C_\mu}{g_m}}$$

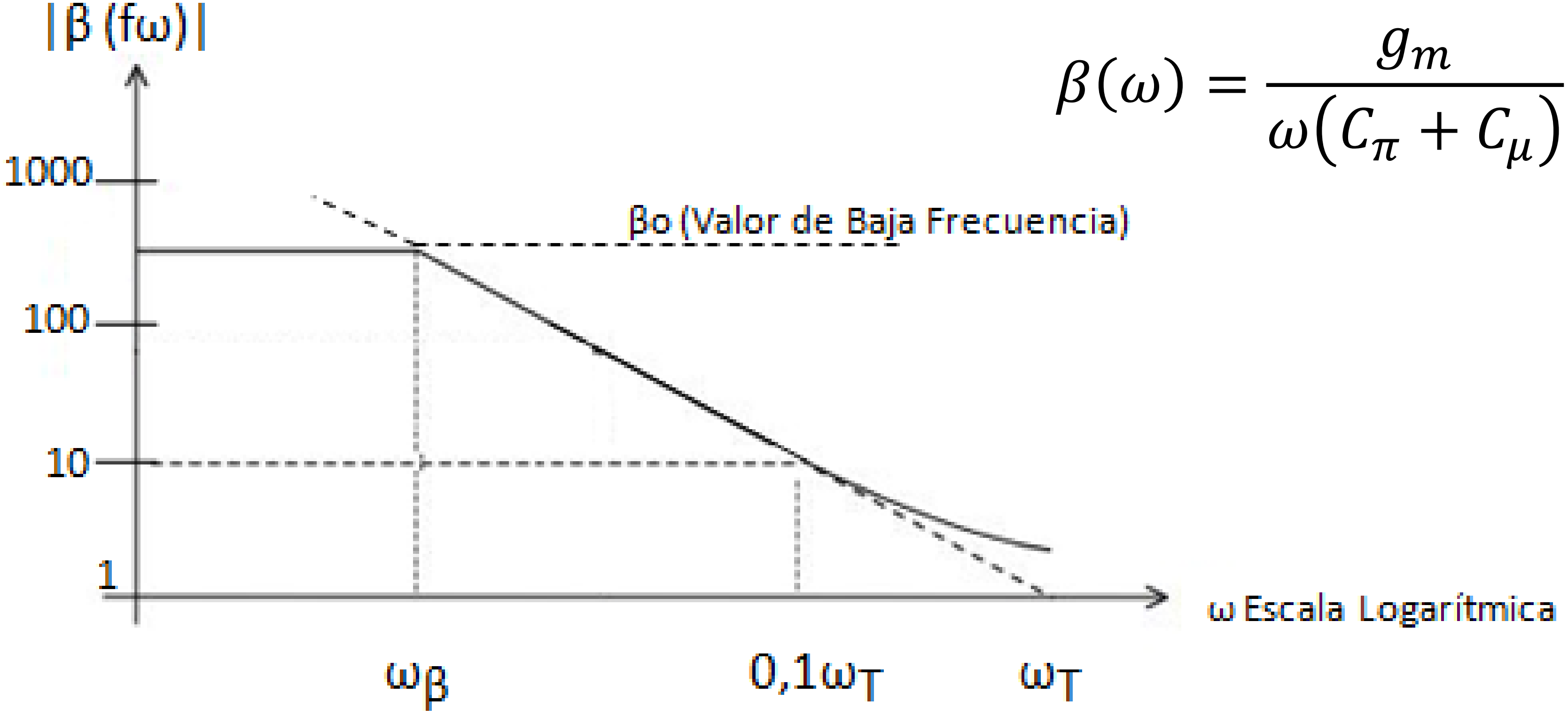
$$\boxed{T_F = \frac{{W_N}^2}{2D_n}}$$

$$\boxed{T_T = \frac{{W_N}^2}{2D_n} + \frac{C_{jBE}}{g_m} + \frac{C_\mu}{g_m}}$$



Curva Típica fT en función de Ic para un transistor npn de circuito integrado con un área de 6 μ^2 en un proceso de alta velocidad.

Frecuencia de Ganancia Unidad



$$\beta(\omega) = \frac{g_m}{\omega\left(C_\pi + C_\mu\right)}$$

$$\beta\left(\omega_\beta\right) = \frac{g_m}{\omega_\beta\left(C_\pi + C_\mu\right)} = \beta_0 \qquad \frac{g_m}{\beta_0\left(C_\pi + C_\mu\right)} = \omega_\beta \qquad \frac{\omega_T}{\beta_0} = \omega_\beta$$

$$\omega_T = \omega_x \times |\beta(j\omega_x)|$$