

# TRANSISTORI

Wednesday, March 8, 2017 3:20 PM

dispositivi a 3 terminali

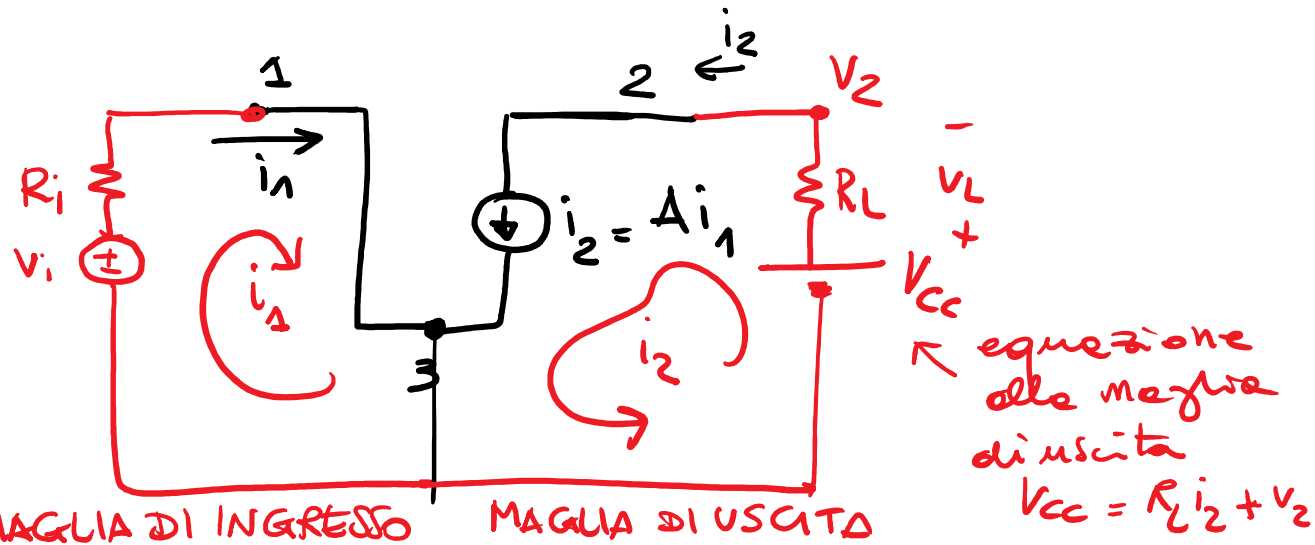
→ funzionano da generatori controllati di corrente

1. La CORRENTE tra due terminali viene controllata  
dalla TENSIONE applicata al terzo terminale  
(di controllo)  
[TRANSISTORE A EFFETTO DI CAMPO]

2. La corrente tra due terminali viene controllata  
dalla CORRENTE iniettata nel terzo terminale  
(di controllo)  
[TRANSISTORE BIPOLORE A GIUNZIONE]

# generatore di corrente controllato da corrente

Wednesday, March 8, 2017 3:25 PM



$$\underline{v_i} = R_i \underline{i_1} \rightarrow \underline{i_2} = A \underline{i_1} \rightarrow \underline{v_L} = R_L \underline{i_2} \rightarrow \underline{i_2} = \left( \frac{R_L A}{R_i} \right) \underline{v_i}$$

Potenza erogata dal generatore di ingresso

$$P_i = v_i i_i = \frac{v_i^2}{R_i}$$

Potenza assorbita dal carico ( $R_L$ )

$$P_u = \frac{v_L^2}{R_L} = \left( \frac{R_L A}{R_i} \right)^2 \frac{v_i^2}{R_L}$$

Amplificazione di potenza

$$\frac{P_u}{P_i} = \frac{R_L A^2}{R_i}$$

$$\text{se } \frac{P_u}{P_i} > 1$$

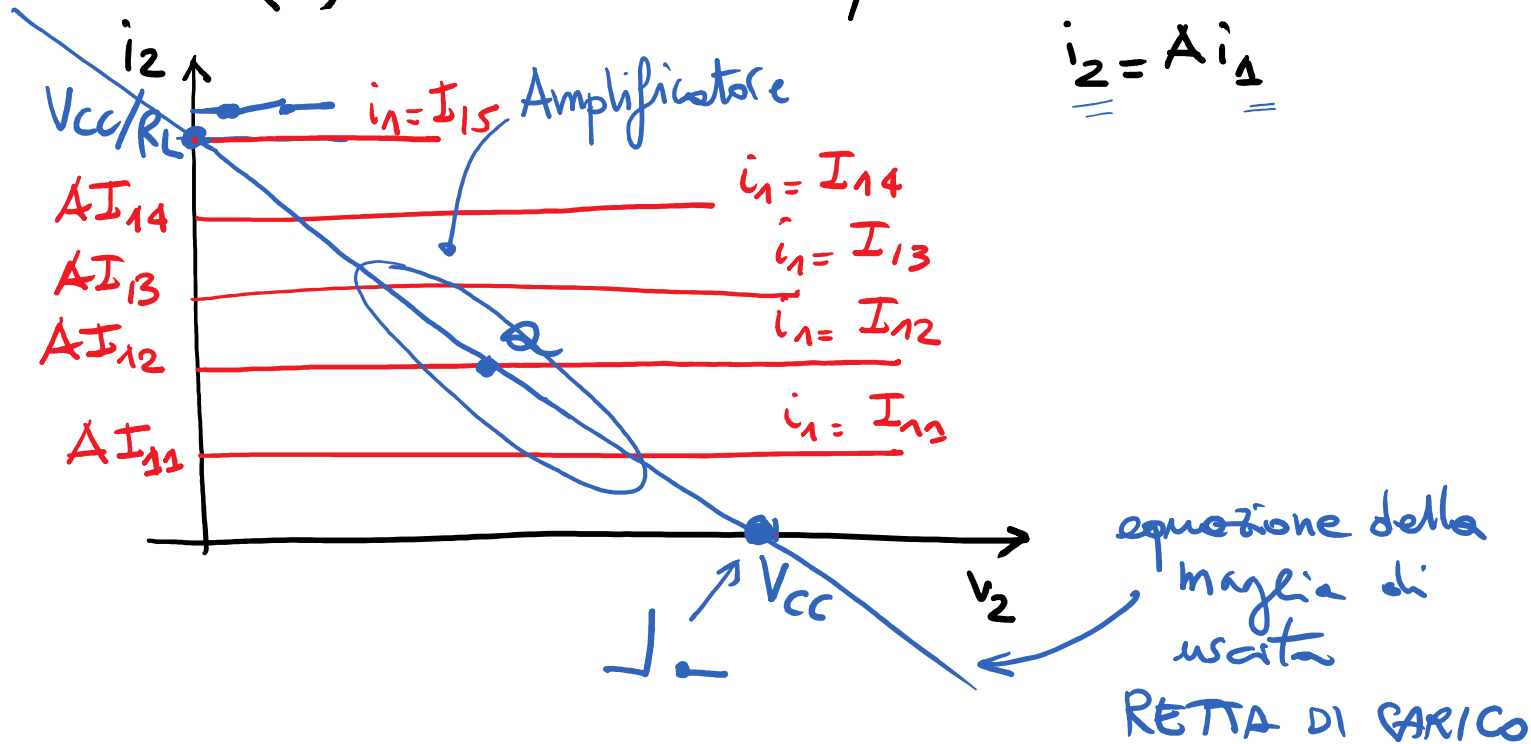
ho un  
amplificatore

# Caratteristiche di uscita

Wednesday, March 8, 2017 3:35 PM

$i_2(v_2)$  usando  $i_1$  come parametro.

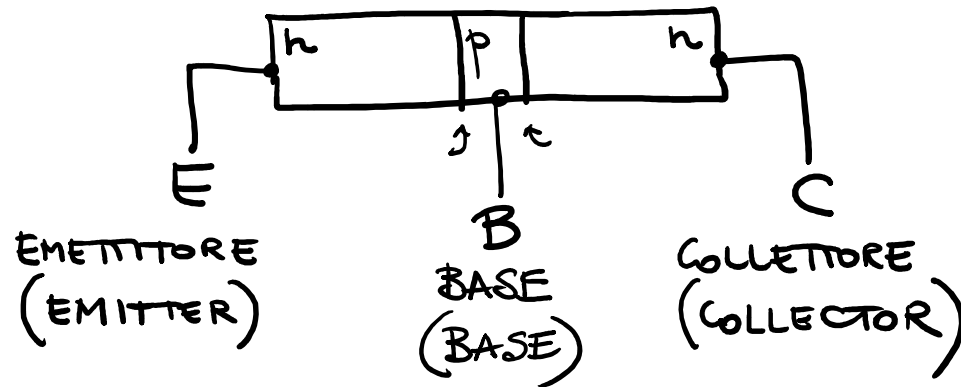
$$\underline{i_2 = A i_1}$$



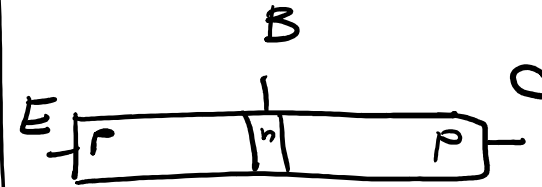
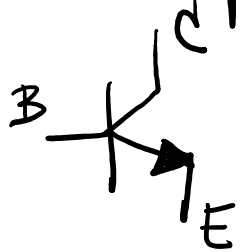
# TRANSISTORE BIPOLARE A GIUNZIONE

Wednesday, March 8, 2017 3:45 PM

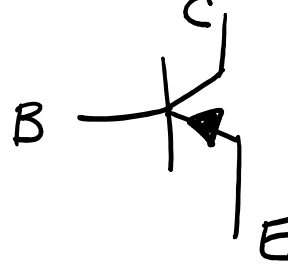
[Bipolar Junction Transistor - BJT]



BJT npn



BJT pnp

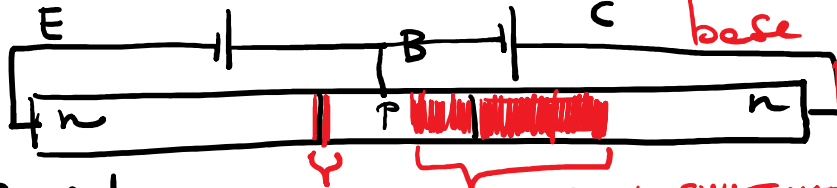


# Funzionamento BJT

Wednesday, March 8, 2017 3:50 PM

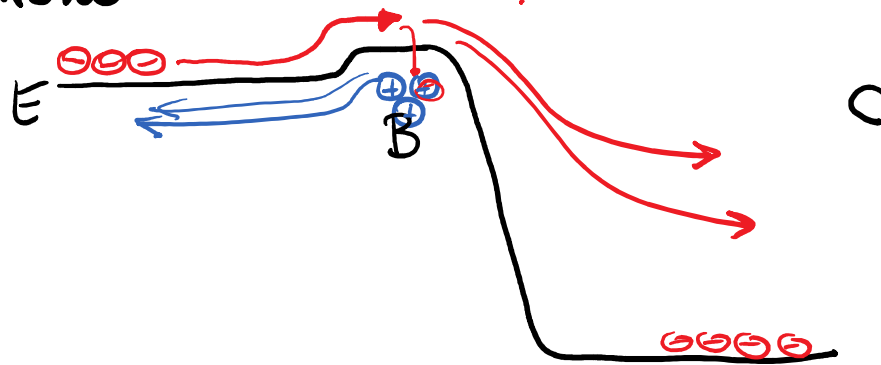


NO, perché la base è corta



REGIONE DI SVUOTAMENTO

ENERGIA potenziale per gli elettroni

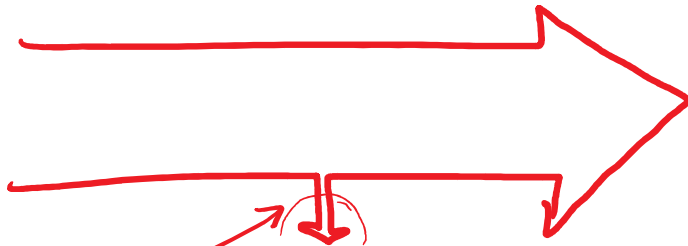


componente molto piccola

# FLUSSI DI CARICA IN UN BJT

Wednesday, March 8, 2017 3:58 PM

in ZONA ATTIVA DIRETTA  $[V_{BE} > 0 \quad V_{BC} < 0]$



Componente  
che ricomincia  
in base

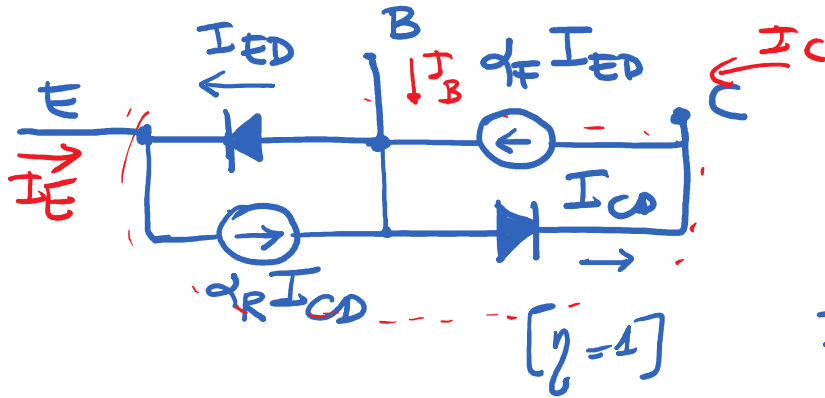


← PIÙ PICCOLA PERCHÈ LA BASE È MENO  
DROGATA DELL'EMETTITORE

$\ominus \rightarrow$  } CORRENTE DI SATURAZIONE  
 $\leftarrow \oplus$  } INVERSA DELLA GIUNZIONE BC

# Modello di EBERS e MOLL

Wednesday, March 8, 2017 4:05 PM



$$0 < \underline{\alpha_F} < 1$$

$$0 < \underline{\alpha_R} < 1$$

$$I_{ED} = \underline{I_{ES}} \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)$$

$$I_{CD} = \underline{I_{CS}} \left( e^{\frac{V_{BC}}{V_T}} - 1 \right)$$

$$\begin{cases} I_E = -I_{ED} + \alpha_R I_{CD} \\ I_C = -I_{CD} + \alpha_F I_{ED} \\ I_E + I_B + I_C = 0 \end{cases}$$

Modello a 4 PARAMETRI  
( $\alpha_F, \alpha_R, I_{ES}, I_{CS}$ )

DI CUI SOLO 3 SONO INDIPENDENTI

# Condizione di reciprocità

Wednesday, March 8, 2017 4:13 PM

$$\text{se } \underline{V_{CE} = 0} \quad \underline{V_{BE} = V_{BC}} \rightarrow \underline{\alpha_R I_{CS} = \alpha_F I_{ES}}$$

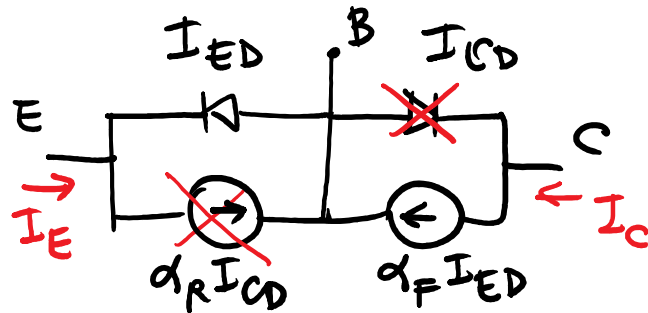
$$\cancel{\alpha_R I_{CS} \left( e^{\frac{V_{BC}}{V_T}} - 1 \right)} = \cancel{\alpha_F I_{ES} \left( e^{\frac{V_{BE}}{V_T}} - 1 \right)}$$

$$\boxed{\alpha_R I_{CS} = \alpha_F I_{ES}}$$

Poniamo  $V_{BC} = 0$

Thursday, March 9, 2017 8:14 AM

$$I_{CD} = I_{CS} \left[ e^{\frac{V_{BC}}{V_T}} - 1 \right] = 0$$



$$I_E = -I_{ED}$$

$$I_C = \alpha_F I_{ED}$$

$$\alpha_F \triangleq \left| \frac{I_C}{I_E} \right|$$

diretto  
guadagno di corrente di corto circuito  $V_{BC}=0$   
forward short-circuit current gain  $V_{BC}=0$

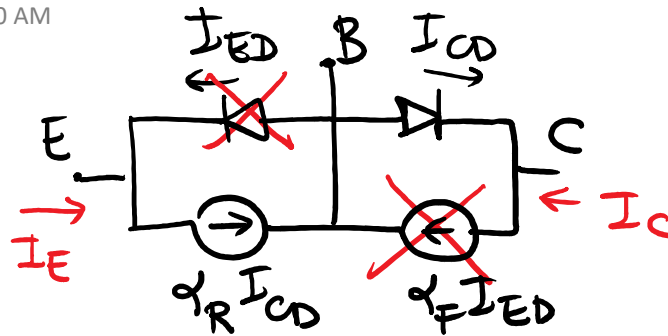
F

$$\alpha_F \approx 0.9 \div 0.995$$

Poniamo  $V_{BE} = 0$

Thursday, March 9, 2017 9:00 AM

$$\underline{I_{ED} = 0}$$



$$I_E = \alpha_R I_{CD}$$

$$I_C = -I_{CD}$$

$$\alpha_R = \left| \frac{I_E}{I_C} \right|_{V_{BE}=0}$$

INVERSO  
GUADAGNO DI CORRENTE  
DI CIRCUITO

$$V_{BE} = 0$$

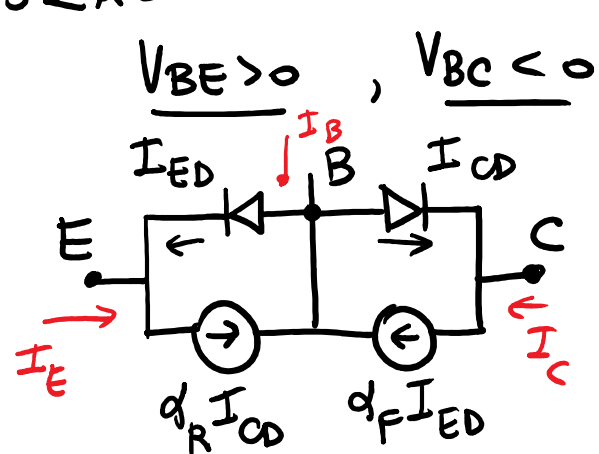
Reverse short-circuit  
current gain

$$\alpha_R = 0.4 \div 0.6$$

# Regioni di funzionamento del BJT

Thursday, March 9, 2017 9:06 AM

2 AD Zona Attiva Diretta



$$I_{CO} = I_{CS} \left[ e^{\frac{V_{BC}}{V_T}} - 1 \right] \sim -I_{CS}$$

$$I_E = -I_{ED} - q_R I_{CS}$$

$$I_C = I_{CS} + q_F I_{ED} =$$

$$I_C = I_{CS} - q_F I_E - q_F q_R I_{CS} \quad \leftarrow$$

$$I_C = q_F I_C + q_F I_B + I_{CS} (1 - q_F q_R)$$

$$I_B + I_C + I_E = 0$$

$$I_E = -I_C - I_B$$

$$I_C = \left( \frac{q_F}{1 - q_F} \right) I_B + \frac{I_{CO}}{1 - q_F}$$

$$\beta_F \cong \left( \frac{\alpha_F}{1 - \alpha_F} \right)$$

notare che

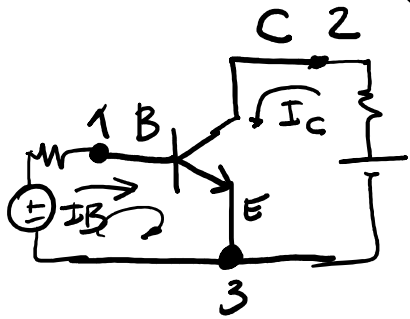
$$1 + \beta_F = \frac{1}{1 - \alpha_F}$$

$$I_C = \beta_F I_B + (\beta_F + 1) I_{C0}$$

Z.A.D.

← configurazione  
a emettitore comune

GUADAGNO DI  
CORRENTE DIRETTO  
IN CONFIGURAZIONE  
A EMETTITORE COMUNE



$$I_C \sim \beta_F I_B$$

$$\alpha_F = 0.9 \rightarrow \beta_F = 9$$

$$\alpha_F = 0.99 \rightarrow \beta_F = 99$$

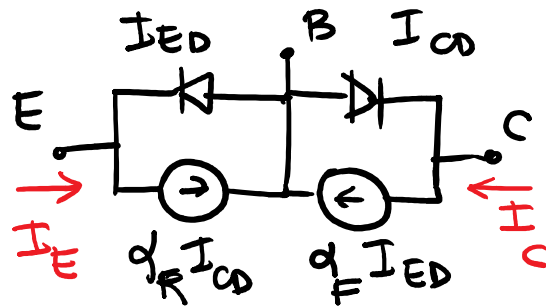
$$\alpha_F = 0.995 \rightarrow \beta_F = 199$$



# Zona Attiva Inversa

Thursday, March 9, 2017 9:21 AM

$$V_{BC} > 0, \quad \underline{V_{BE} < 0}$$



$$I_{ED} = -I_{ES}$$

$$I_E = I_{ES} + \alpha_R I_{CB}$$

$$I_C = -I_{CB} - \alpha_F I_{ES}$$

$$I_E = I_{ES} - \alpha_R I_C - \alpha_F \alpha_R I_{ES}$$

$$I_E = -\alpha_R I_C + \underbrace{I_{ES} (1 - \alpha_F \alpha_R)}_{I_{EO}}$$

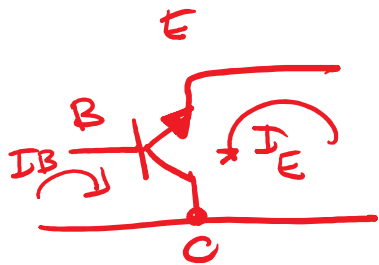
$$I_C = I_E - I_B$$

$$I_E = +\alpha_R I_E + \alpha_R I_B + I_{EO}$$

$$I_E = \left( \frac{\alpha_R}{1 - \alpha_R} \right) I_B + \frac{I_{EO}}{1 - \alpha_R}$$

$$\beta_R = \frac{\alpha_R}{1 - \alpha_R}$$

$$1 + \beta_R = \frac{1}{1 - \alpha_R}$$



$$\rightarrow I_E = \beta_R I_B + (\beta_R + 1) I_{E0}$$

$$I_E \sim \beta_R I_B$$

$\beta_R$  GUADAGNO INVERSO DI CORRENTE  
IN CONFIGURAZIONE A COLLETTORE  
COMUNE

$$\alpha_R = 0.6 \rightarrow \beta_R = 1.5$$

$$\alpha_R = 0.4 \rightarrow \beta_R = 0.67$$

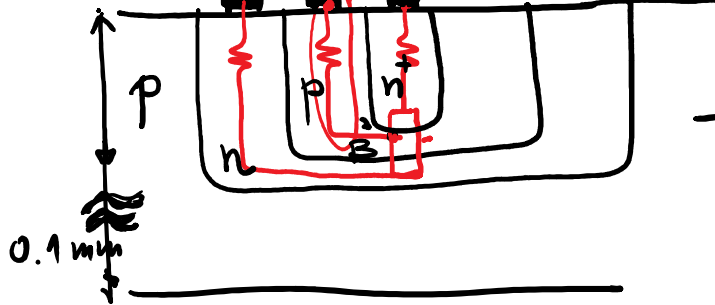


$r_b$  RESISTENZA SERIE DELLA BASE

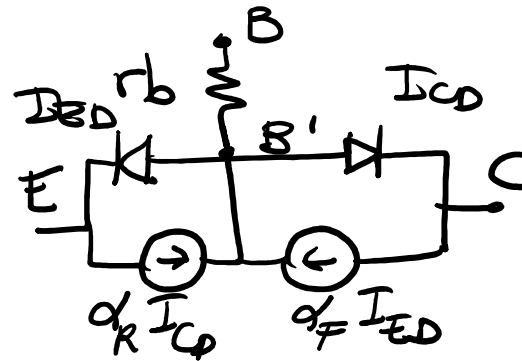
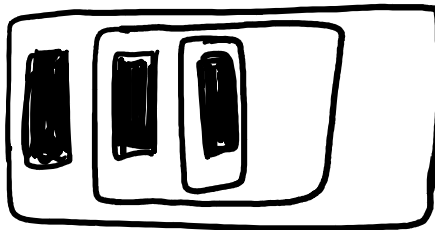
EMETTITTORE È MOLTO PIÙ DROGATO DEL COLLETORE

$$\beta_F \gg \beta_R$$

TAGLIO


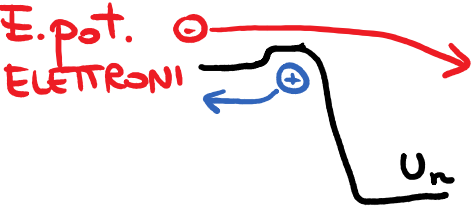
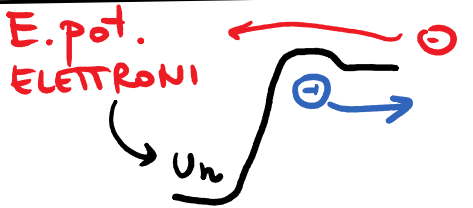


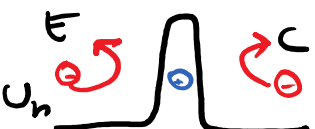



DALL'ATO



# REGIONI DI FUNZIONAMENTO DEL BJT

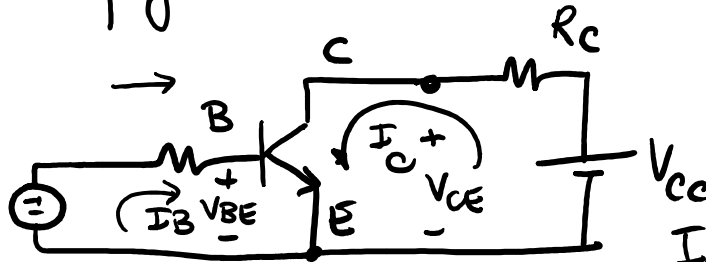
Thursday, March 9, 2017 9:41 AM

	$V_{BE}$	$V_{BC}$	E -  - C
ZONA ATTIVA DIRETTA	$> 0$	$< 0$	 $I_C = \beta_F I_B + (\beta_F + 1) I_{C0}$ <p>AMPLIFICATORE</p>
ZONA ATTIVA INVERSA	$< 0$	$> 0$	 $I_E = \beta_R I_B + (\beta_R + 1) I_{E0}$
SATURAZIONE (SATURATION)	$> 0$	$> 0$	 
INTERDIZIONE (CUT OFF)	$< 0$	$< 0$	 

# Caratteristiche di uscita del BJT

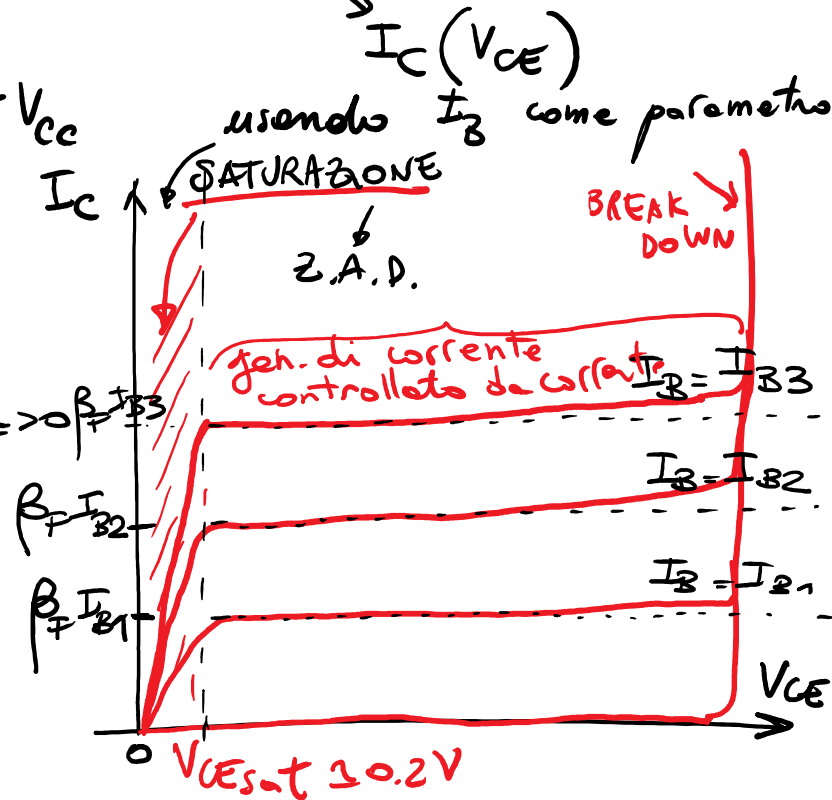
Thursday, March 9, 2017 10:01 AM

(in configurazione a emettitore comune)



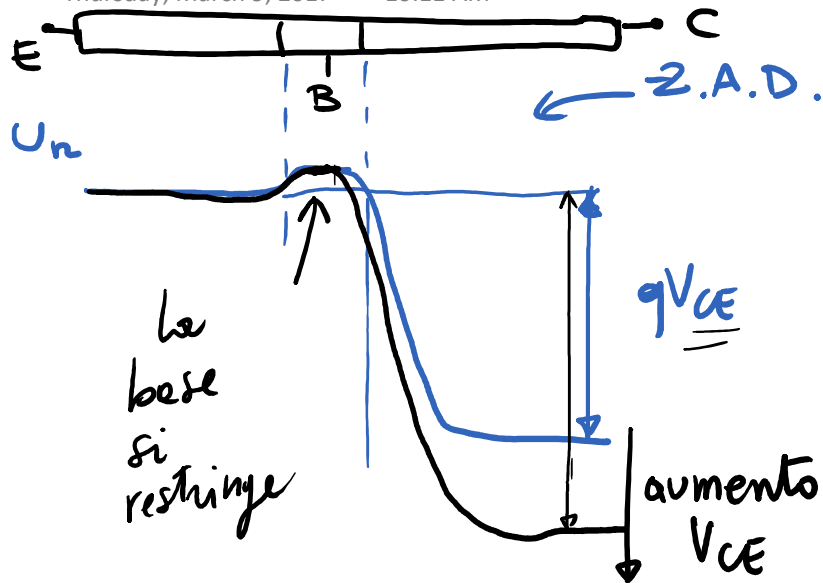
in z.a.d.  $I_C \approx \beta_F I_B$

$$\left[ V_{BE} > 0, V_{BC} < 0 \right] \rightarrow V_{CE} = V_{CB} + V_{BE} \\ = -V_{BC} + V_{BE} \Rightarrow \beta_F I_B$$



# EFFETTO EARLY

Thursday, March 9, 2017 10:11 AM

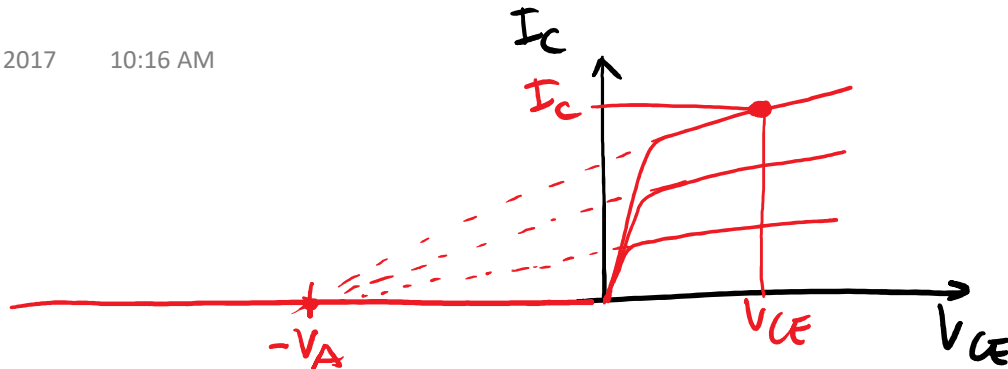


se aumento  $V_{CE}$   
 ↓  
 aumenta la  
 zona di svuotamento  
 tra B e C

↓  
 si restringe la  
 zona neutra nella  
 base

↓  
 si riduce la ricombinazione  
 in base

↓  $\beta_F$  aumenta  
 $I_C = \beta_F I_B$  aumenta in funzione di  $V_{CE}$



PENDENZA DELLE CARATTERISTICHE IN ZONA A.D.

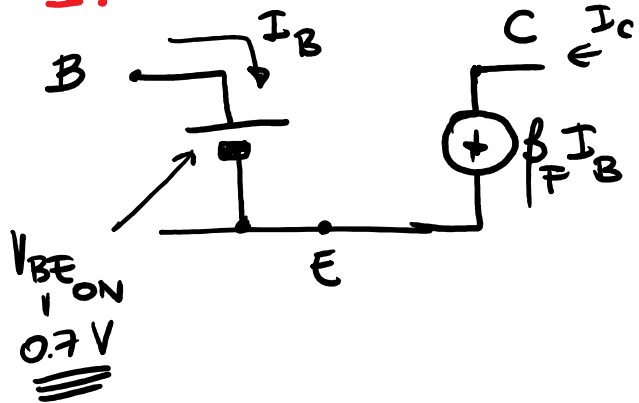
$$\frac{I_C}{V_{CE} + V_A} \sim \left( \frac{I_C}{V_A} \right) \quad \text{Tensione di Early}$$

$V_A \gg V_{CE}$

# Modello del BJT di grande segnale

Thursday, March 9, 2017 10:19 AM

## 1. Zona Attiva DIRETTA — $[V_{BE} > 0, V_{BC} < 0]$

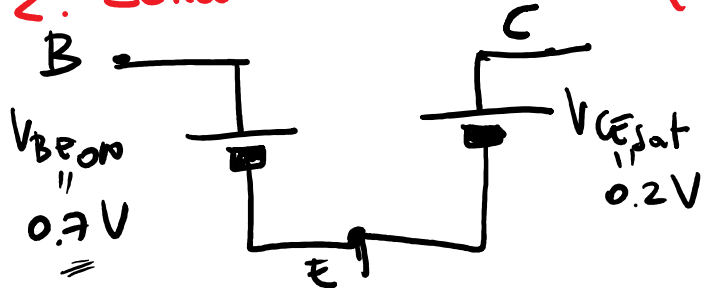


$$I_C = \beta_F I_B$$

CONDIZIONI DA VERIFICARE

$$\begin{cases} V_{CE} = -V_{BC} + V_{BE} > V_{CE(sat)} (\underline{0.2V}) \\ I_C > 0 \quad (I_B > 0) \end{cases}$$

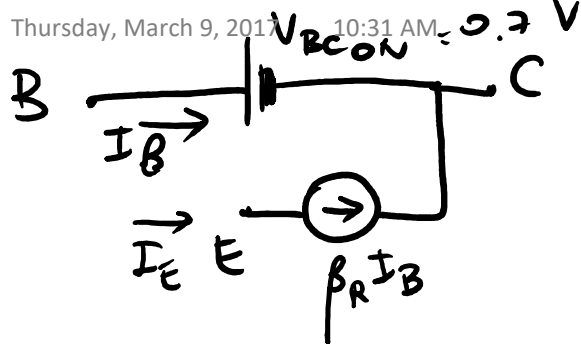
## 2. Zona di Saturazione (DIRETTA) $[V_{BE} > 0, V_{BC} > 0, V_{CE} > 0]$



CONDIZIONI DA VERIFICARE

$$\begin{cases} I_C > 0 \quad I_B > 0 \\ I_C < \beta_F I_B \end{cases}$$

### 3. Zona Attiva INVERSA $[V_{BC} > 0, V_{BE} < 0]$

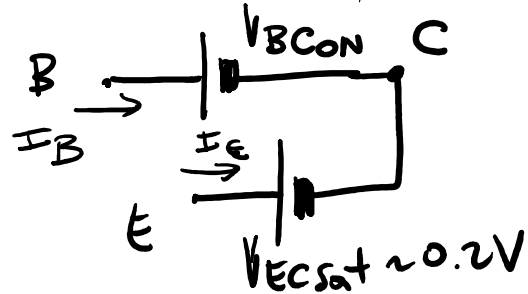


$$I_E = \beta_R I_B$$

CONDIZIONI DA VERIFICARE

- $I_E > 0$
- $V_{EC} > V_{ECsat} = \underline{0.2V}$

### 4. Zona di sat inversa $[V_{BC} > 0, V_{BE} > 0, V_{EC} > 0]$



CONDIZIONI DA VERIFICARE

$$I_E > 0, I_B > 0$$

$$I_E < \beta_R I_B$$

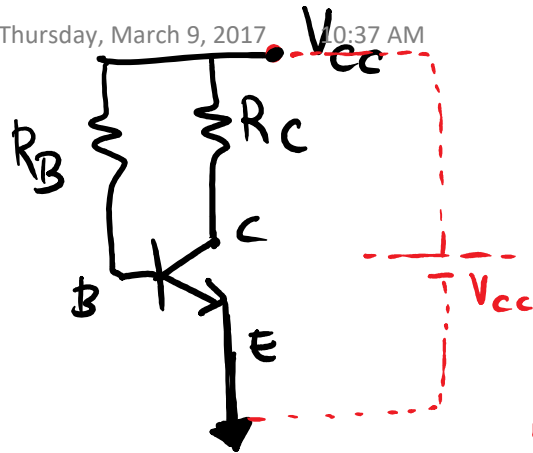
### 5. Zona di interdizione $B, C$

CONDIZIONI DA VERIFICARE

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

Es.

Thursday, March 9, 2017 10:37 AM



$$R_B = 300 \text{ k}\Omega$$

$$R_C = 2 \text{ k}\Omega$$

$$V_{CC} = 10 \text{ V}$$

$$\beta_F = 100$$

Hp. 2 A.D.  $\nearrow 0.7 \text{ V}$

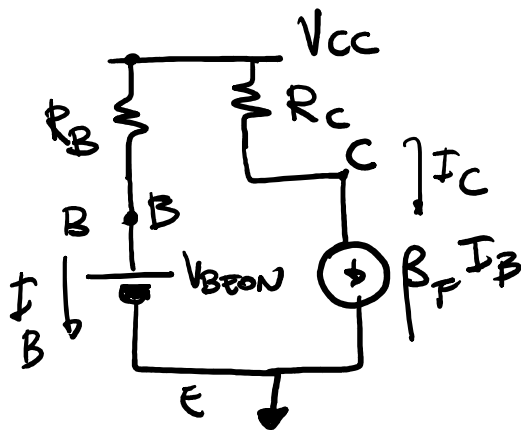
$$I_B = \frac{V_{CC} - V_{BE_{ON}}}{R_B} = \frac{10 - 0.7}{300 \cdot 10^3} = \underline{3.1 \mu\text{A}}$$

$$I_C = \beta_F I_B = \underline{3.1 \text{ mA}}$$

$$V_{CE} = V_{CC} - R_C I_C = 10 - 2 \cdot 3.1 = \underline{3.8 \text{ V}}$$

$$> V_{CE_{sat}}$$

ok



Es Come prima, ma  $R_B = 150 \text{ k}\Omega$

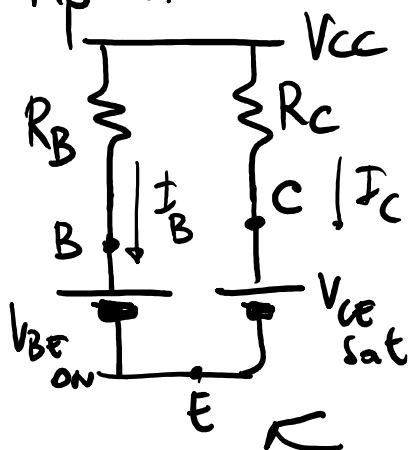
Thursday, March 9, 2017 10:46 AM

$$I_B = 62 \mu\text{A}$$

$$I_C = \beta_F I_B = 6.2 \text{ mA}$$

$$V_{CE} = V_{CC} - R_C I_C = 10 - 2 \cdot 6.2 = \underline{-2.4 \text{ V}} \quad (\text{No})$$

Hp SATURAZIONE DIRETTA



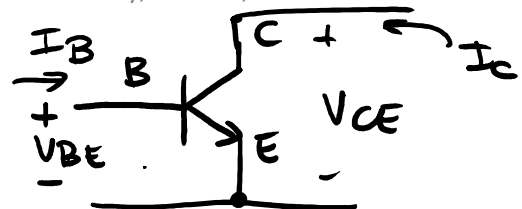
$$I_B = \underline{62 \mu\text{A}}$$

$$I_C = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10 - 0.2}{2 \cdot 10^3} = \underline{4.9 \text{ mA}}$$

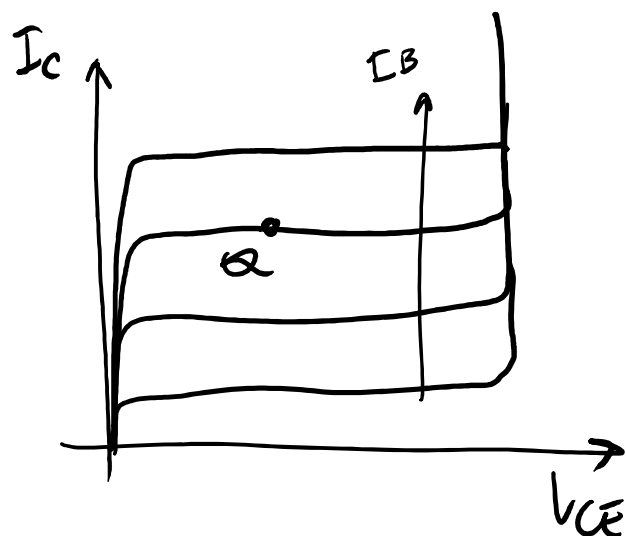
$$\text{VERIFICO: } I_C < \beta_F I_B \quad (\text{ok})$$

# Ciruito equivalente per il piccolo segnale

Thursday, March 9, 2017 10:59 AM



CONF. EMETTITORE COMUNE  
(Common Emitter CE)

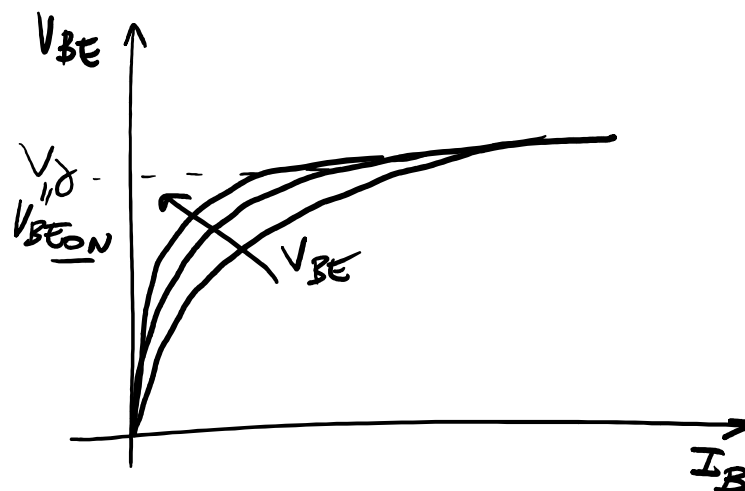


Caratteristiche di uscita

$$I_C(V_{CE}, I_B)$$

Caratteristiche di ingresso

$$V_{BE}(I_B, V_{CE})$$



Espansione al 1° ordine

Thursday, March 9, 2017 11:06 AM

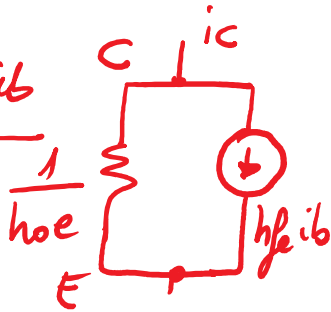
delle caratteristiche di uscita

$$i_c = i_c(v_{CE}, i_B)$$

$$I_C + i_c = i_c(\underline{V_{CE}} + \underline{v_{CE}}, \underline{I_B} + \underline{i_B}) =$$

$$\cancel{I_C + i_c} = \underbrace{i_c(\underline{V_{CE}}, \underline{I_B})}_Q + \underbrace{\frac{\partial i_c}{\partial v_{CE}}}_{hoe} v_{CE} + \underbrace{\frac{\partial i_c}{\partial i_B}}_{hfe} i_B$$

$$i_c = hoe v_{CE} + hfe i_B$$



hoe  
↑  
CE

hfe

# ESPANSIONE AL 1° ORDINE

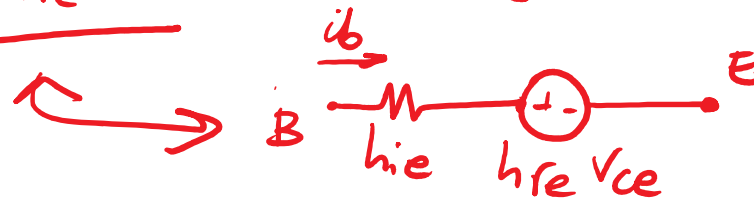
DELLE CARATTERISTICHE DI INGRESSO

$$V_{BE} = V_{BE}(I_B, V_{CE})$$

$$V_{BE} + v_{be} = V_{BE}(I_B + i_b, V_{CE} + v_{ce})$$

$$\cancel{V_{BE}} + v_{be} = \underbrace{V_{BE}(I_B, V_{CE})}_{V_{BE}} + \underbrace{\frac{\partial V_{BE}}{\partial i_b}}_{h_{ie}} i_b - \underbrace{\frac{\partial V_{BE}}{\partial V_{CE}}}_{h_{re}} v_{ce}$$

$$\underline{v_{be} = h_{ie} i_b + h_{re} v_{ce}}$$

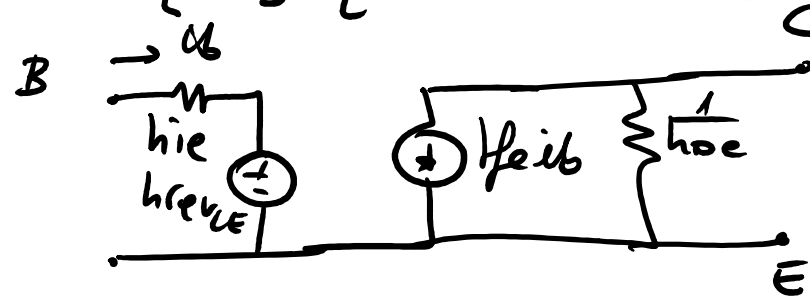
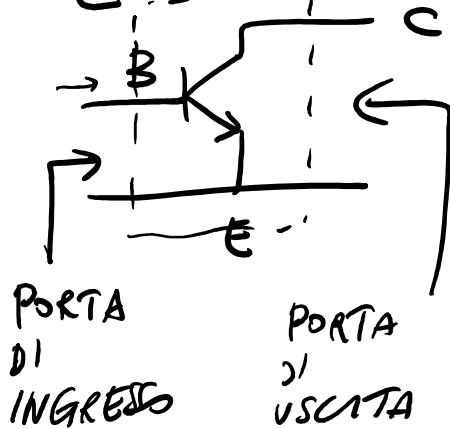


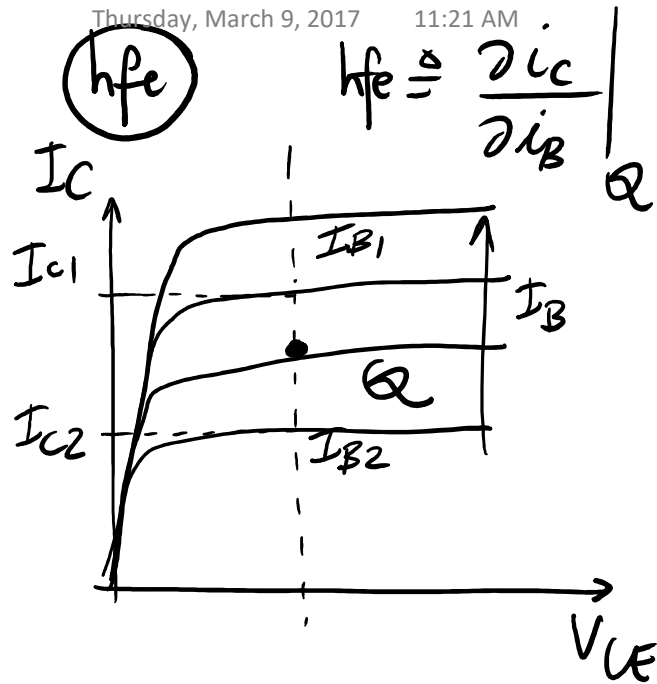
# MODELLO A PARAMETRI IBRIDI

Thursday, March 9, 2017 11:16 AM

DEL BJT in configurazione CE

$$\begin{cases} i_c = h_{fe} i_b + h_{oe} v_{ce} \\ v_{be} = h_{ie} i_b + h_{re} v_{ce} \end{cases} \rightarrow \begin{bmatrix} i_c \\ v_{be} \end{bmatrix} = \begin{bmatrix} h_{fe} & h_{oe} \\ h_{ie} & h_{re} \end{bmatrix} \begin{bmatrix} i_b \\ v_{ce} \end{bmatrix}$$





in Z.A.D.

dal modello di EBERS-MOLL

$$I_C = \beta_F I_B + (\beta_F + 1) I_{CO}$$

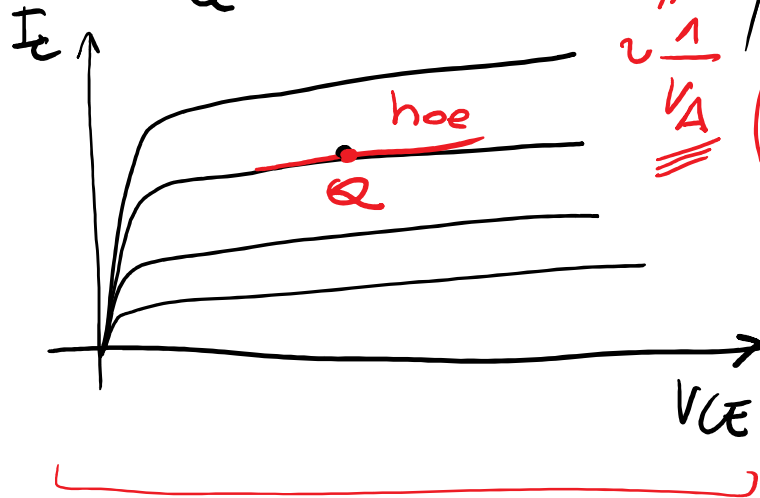
$$h_{fe} = \beta_F$$

$$h_{fe} \sim \left. \frac{\Delta I_C}{\Delta I_B} \right|_{V_{CE} = \text{cost}} \sim \frac{I_{C1} - I_{C2}}{I_{B1} - I_{B2}}$$

$h_{oe}$ .

Thursday, March 9, 2017 11:26 AM

$$h_{oe} \triangleq \left. \frac{\partial I_C}{\partial V_{CE}} \right|_Q = I_B \frac{\partial \beta_F}{\partial V_{CE}} = I_C \left[ \frac{1}{\beta_F} \frac{\partial \beta_F}{\partial V_{CE}} \right] = \beta_F I_B + \cancel{(\beta_F + 1) I_{C0}}$$



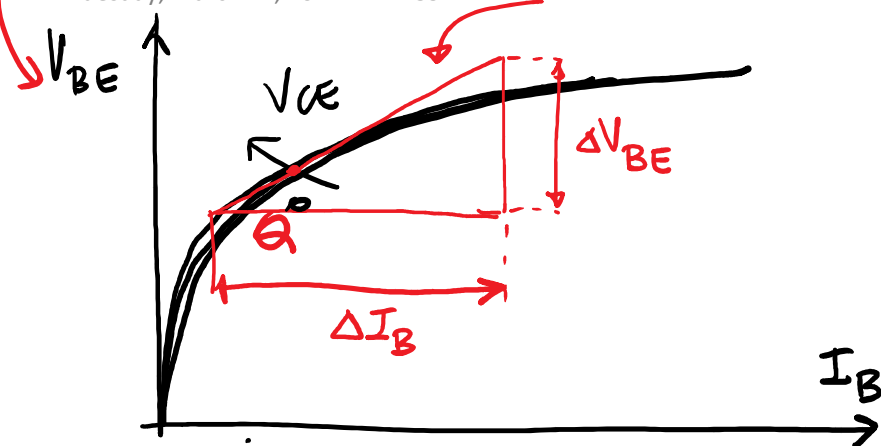
$$h_{oe} \sim \frac{I_C}{V_A}$$

# Caratteristiche di ingresso

Tuesday, March 14, 2017

1:59 PM

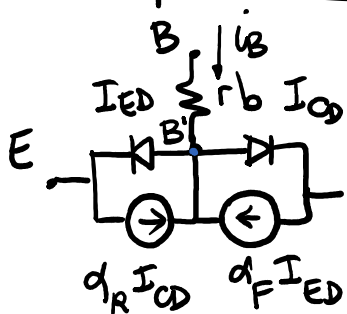
$h_{ie}$



Trascuriamo la dipendenza da  $V_{CE}$

$$\left[ h_{ie} \triangleq \frac{\partial v_{be}}{\partial i_b} \right]_Q \approx 0$$

$$h_{ie} \triangleq \frac{\partial v_{be}}{\partial i_b} \bigg|_Q \approx \frac{\Delta V_{BE}}{\Delta I_B}$$



$$i_B = I_{ED}(1-\alpha_F) + I_{CD}(1-\alpha_R)$$

in z.a.d.  $V_{BC} < 0 \Rightarrow I_{CD} = -I_{CS}$

$$i_B = I_{ES} \left[ e^{\frac{V_{BE}}{V_T}} - 1 \right] (1-\alpha_F) - I_{CS} (1-\alpha_R)$$

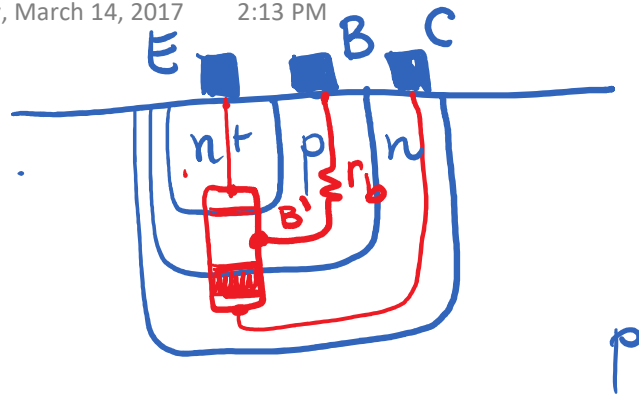
$$\frac{\partial i_B}{\partial v_{BE}} \bigg|_Q = \frac{I_{ES}}{V_T} e^{\frac{V_{BE}}{V_T}} (1-\alpha_F) \bigg|_Q \approx \frac{i_B}{V_T} = \frac{1}{r_{\pi}}$$

$$\left. \frac{\partial v_{BE}}{\partial i_B} \right|_Q = \frac{V_T}{I_B} = r_\pi$$

$$h_{ie} = \left. \frac{\partial v_{BE}}{\partial i_B} \right|_Q = \underbrace{\frac{\partial v_{BB'}}{\partial i_B}}_{r_b} + \underbrace{\frac{\partial v_{B'E}}{\partial i_B}}_{r_\pi} = r_b + r_\pi = r_b + \frac{V_T}{I_B}$$

# Capacità interne

Tuesday, March 14, 2017 2:13 PM



Giunzione p.n tra  
base ed emettitore  
[in zona attiva diretta  
pol. direttamente]

$$C_{be}' \approx C_{je}$$

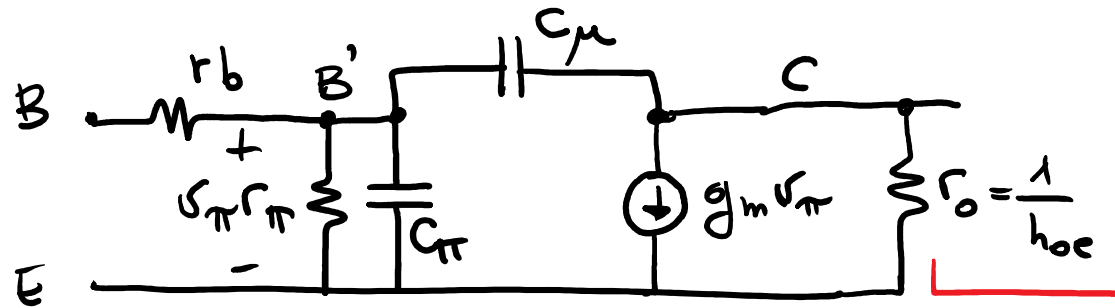
Giunzione p.n tra  
base e collettore  
[in B.A.D. pol. inversamente]

$$C_{bc}' \approx C_{jc}$$

in zona attiva diretta:  $C_{be}' > C_{bc}'$

# Circuito equivalente di GASCOLETTO del transistor

Tuesday, March 14, 2017 2:18 PM



$$\underline{h_{ie} = r_b + r_{\pi}}$$

$$h_{re} = 0$$

$$g_m v_{\pi} = h_{fe} i_b$$

in continua

$$i_b = \frac{v_{\pi}}{r_{\pi}}$$

$$\boxed{g_m = \frac{h_{fe}}{r_{\pi}}} = \frac{\beta_F I_B}{V_T} \approx \frac{I_C}{V_T}$$

# Maximum ratings

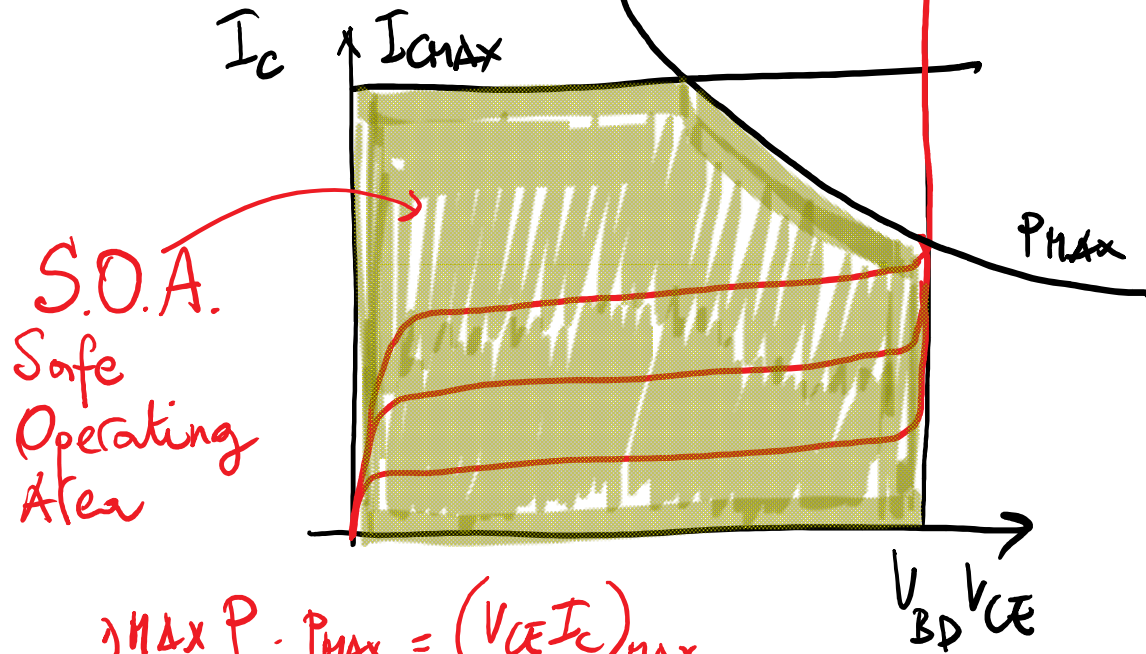
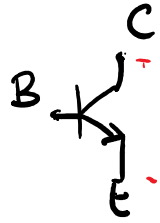
Tuesday, March 14, 2017

2:26 PM

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

MAX  $I_C$  -  $I_{C_{MAX}}$

MAX  $V_{CE}$  -  $V_{BD}$



MAX  $P \cdot \underline{P_{MAX}} = (V_{CE} I_C)_{MAX}$



Monday, June 5, 2017 10:44 PM