

# **COMPOSANTS SEMI-CONDUCTEURS**

## **VII) Principes du transistor bipolaire**

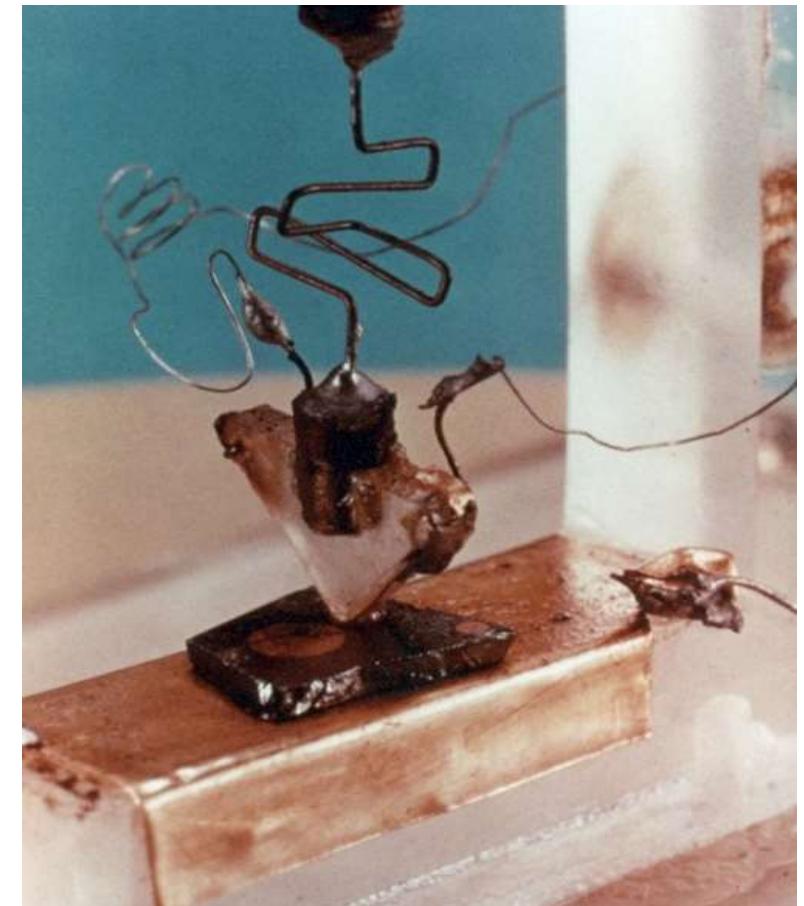
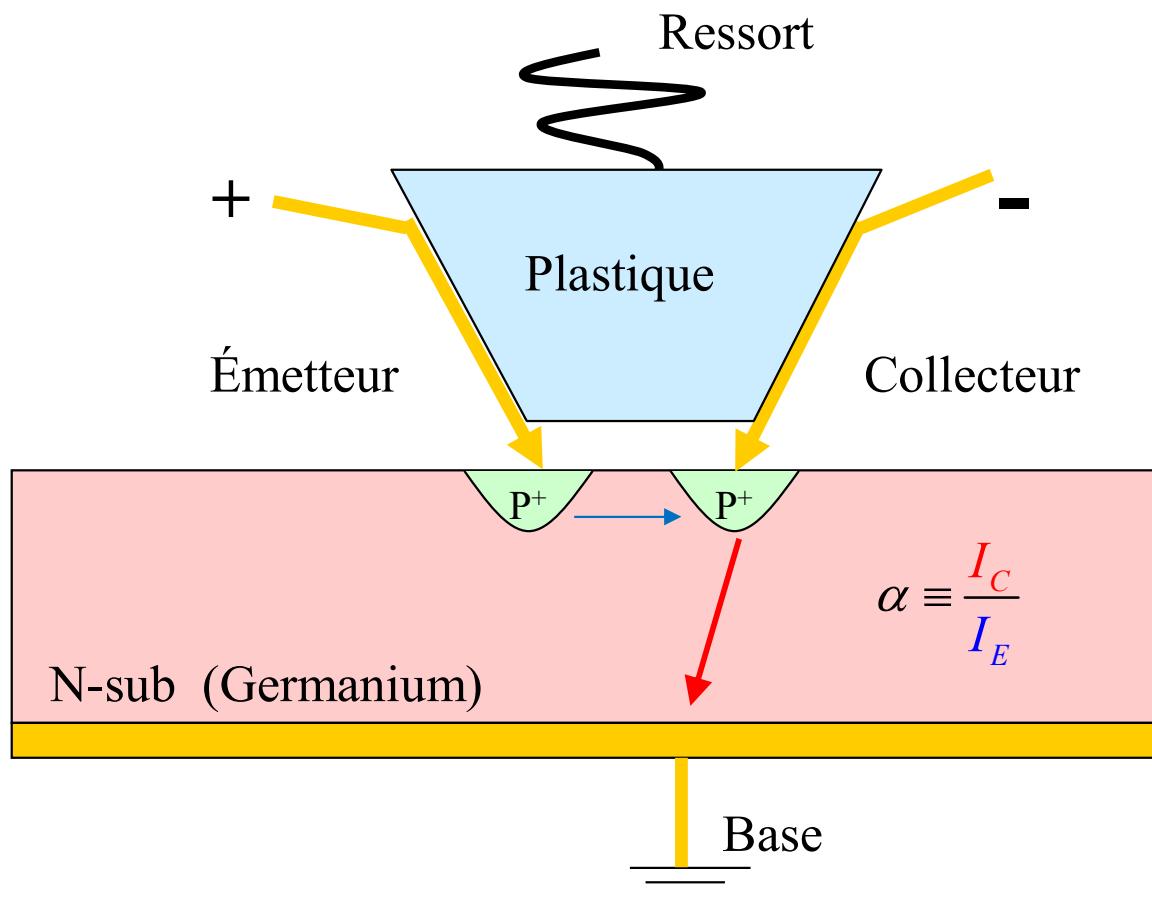
P.A. Besse

EPFL

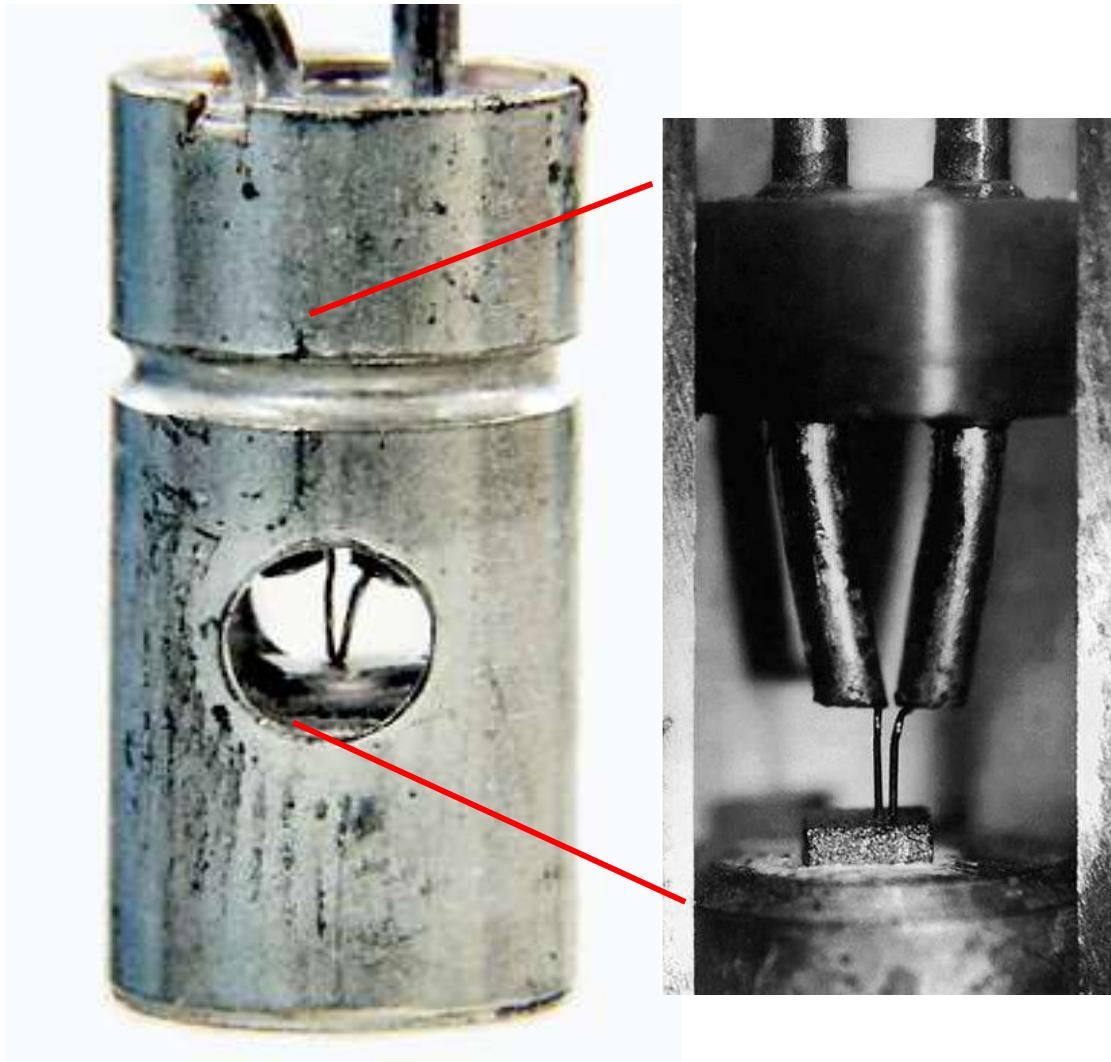
## Point contact transistor



Noel 1947 – Transistor Bipolaire à point de contact Bardeen, Brattain, Shockley (Nobel 1956)



## Point contact transistor “Type A”



Bell Labs, 1948

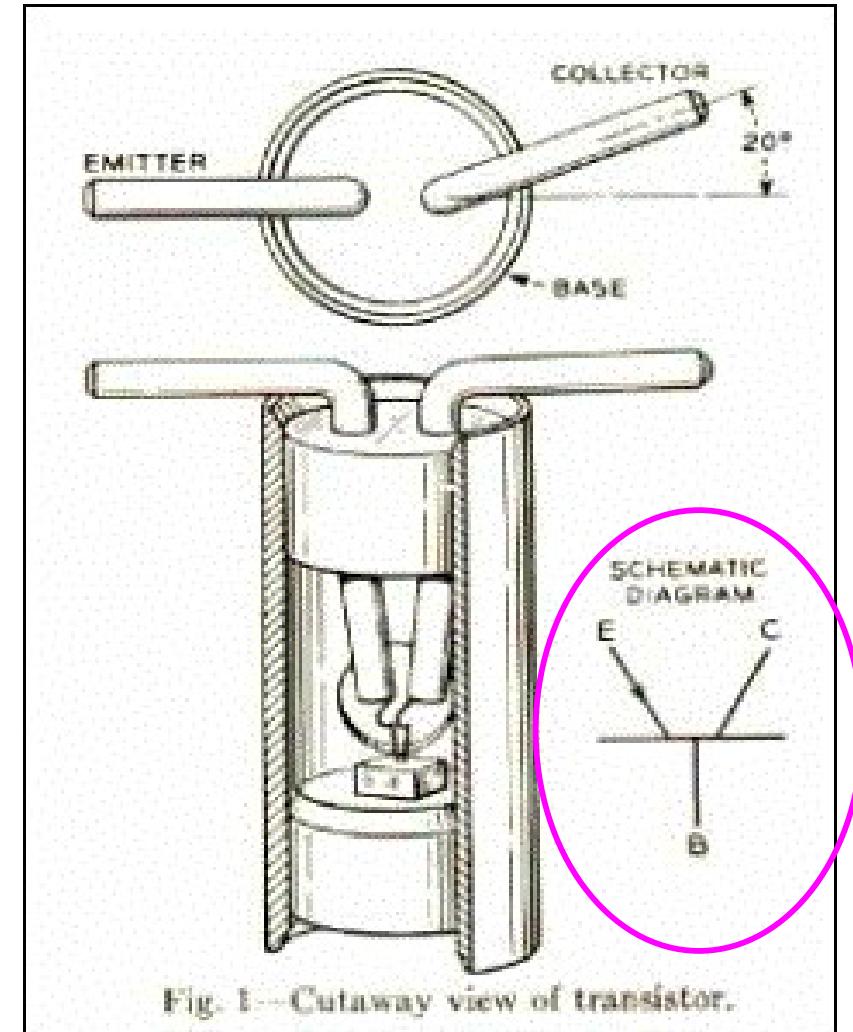
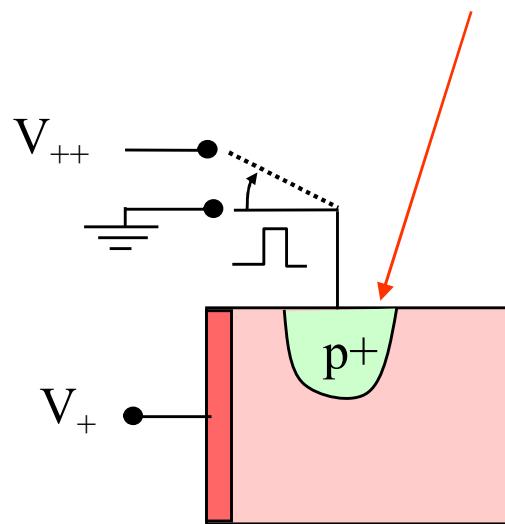


Fig. 1—Cutaway view of transistor.

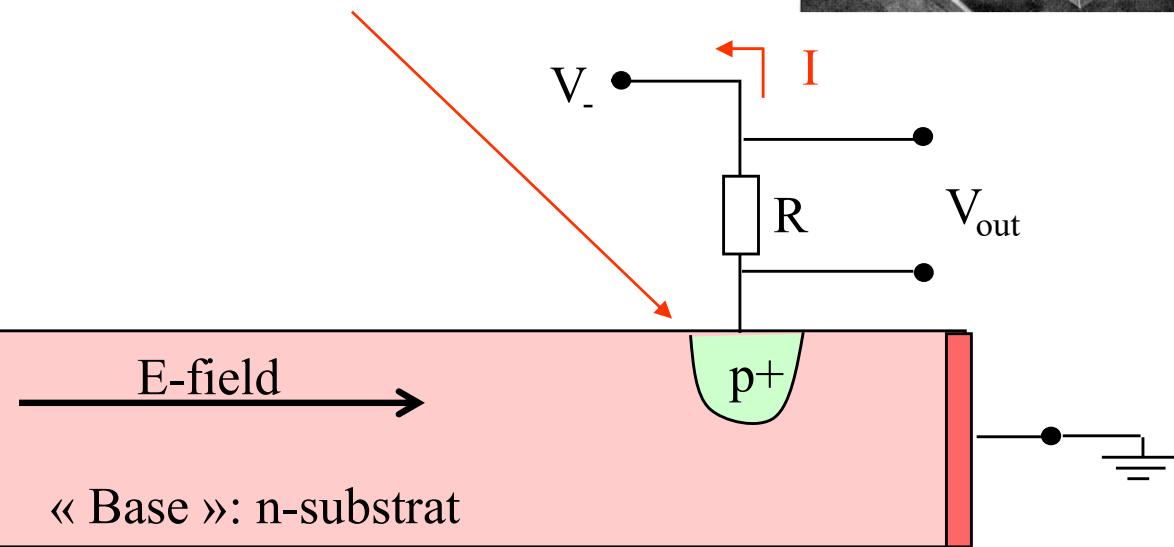
# Résumé: expérience de Haynes-Shockley (1949)

## Mesure de $\mu_n$ , $D_n$ et $\tau_n$

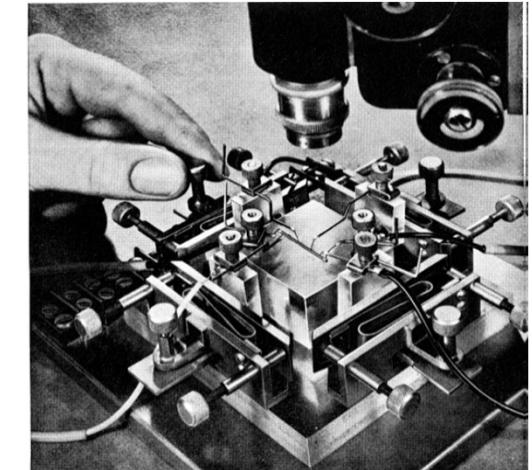
Diode direct  
« Injecteur de minoritaires »



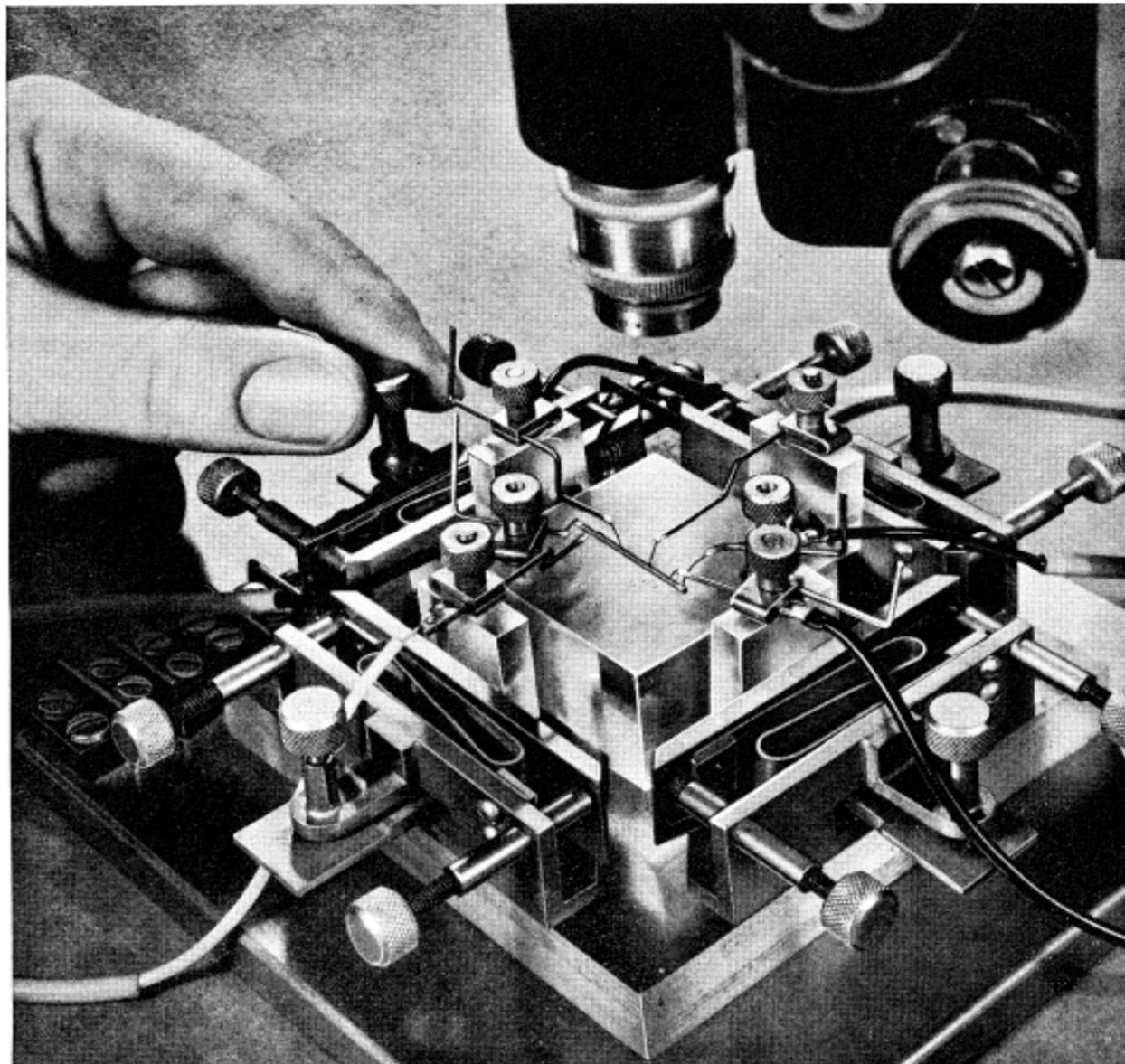
Diode inverse  
« Extracteur de minoritaires »



Haynes, Shockley  
1949

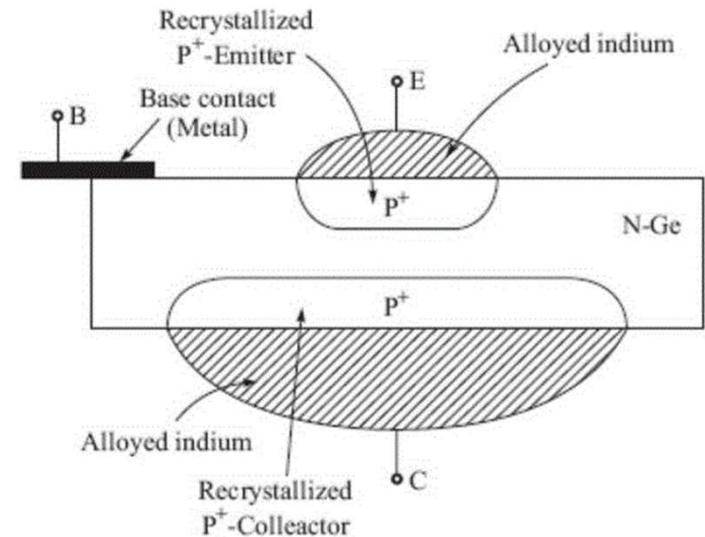


# Résumé: expérience de Haynes-Shockley (1949)



Haynes, Shockley  
1949

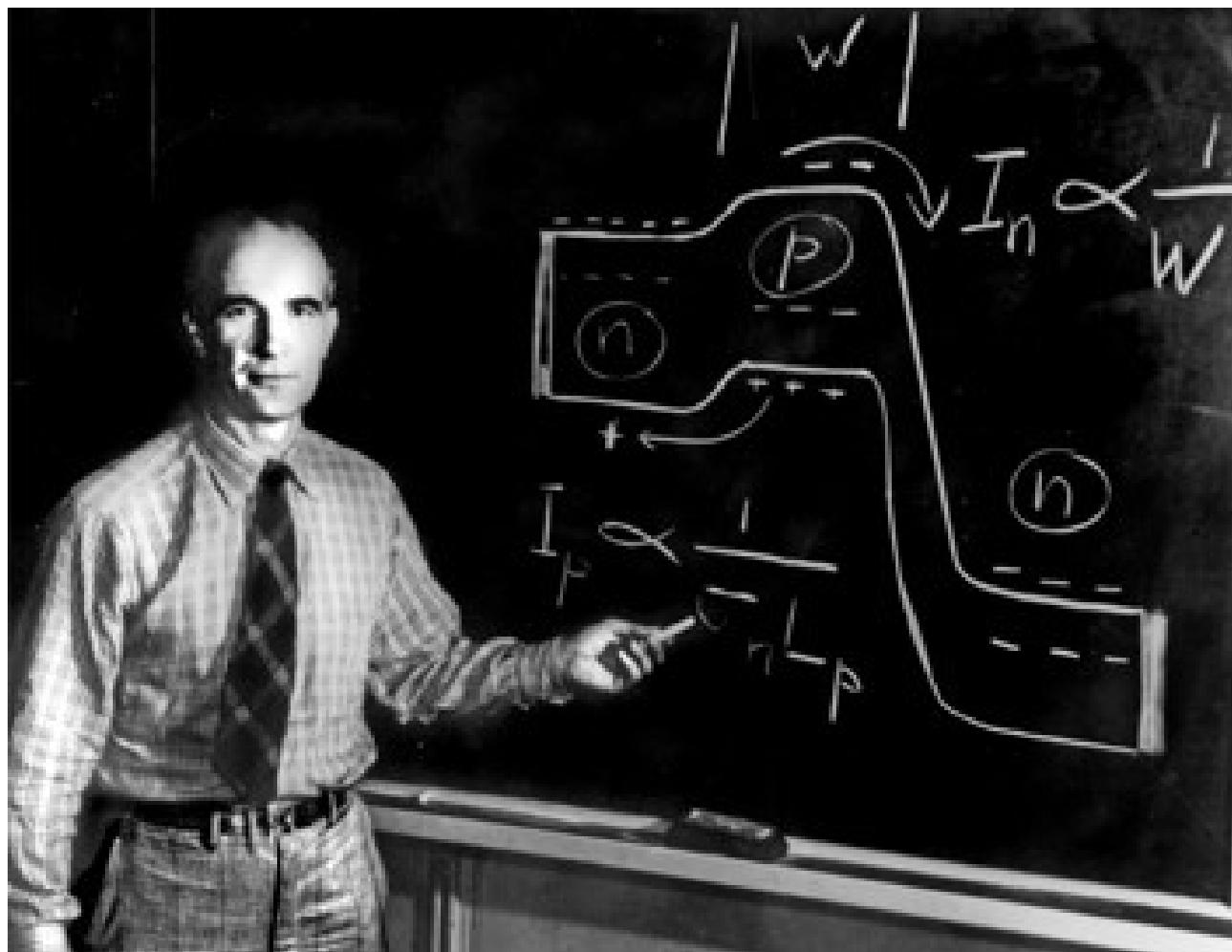
# Bipolar Junction Transistors: alloyed (1951)



<https://academic-accelerator.com/encyclopedia/alloy-junction-transistor>

# Bipolar Junction Transistor (BJT)

Shockley. Bell Labs, 1949



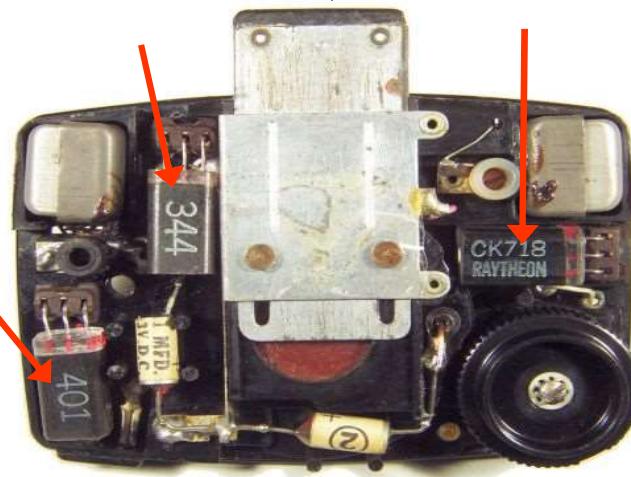
# Historique et exemples

## Market

1<sup>er</sup> appareil auditif (2 tubes, 1 transistor)  
Sonotone 1010, 1952



Appareil auditif "tout transistor"  
MAICO, 1953

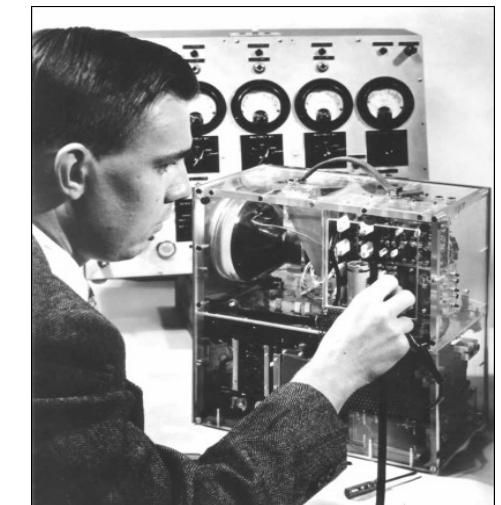


Première radio (4 transistors),  
Regency TR1, 1954

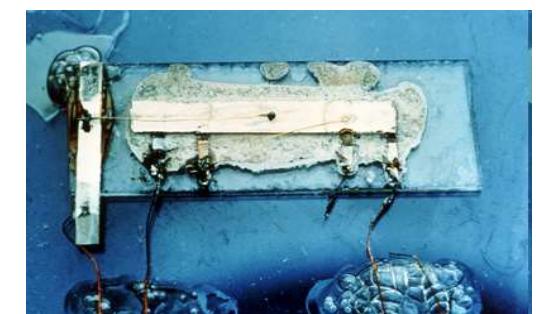


## Labo

1<sup>ère</sup> TV à transistors,  
RCA, 1952

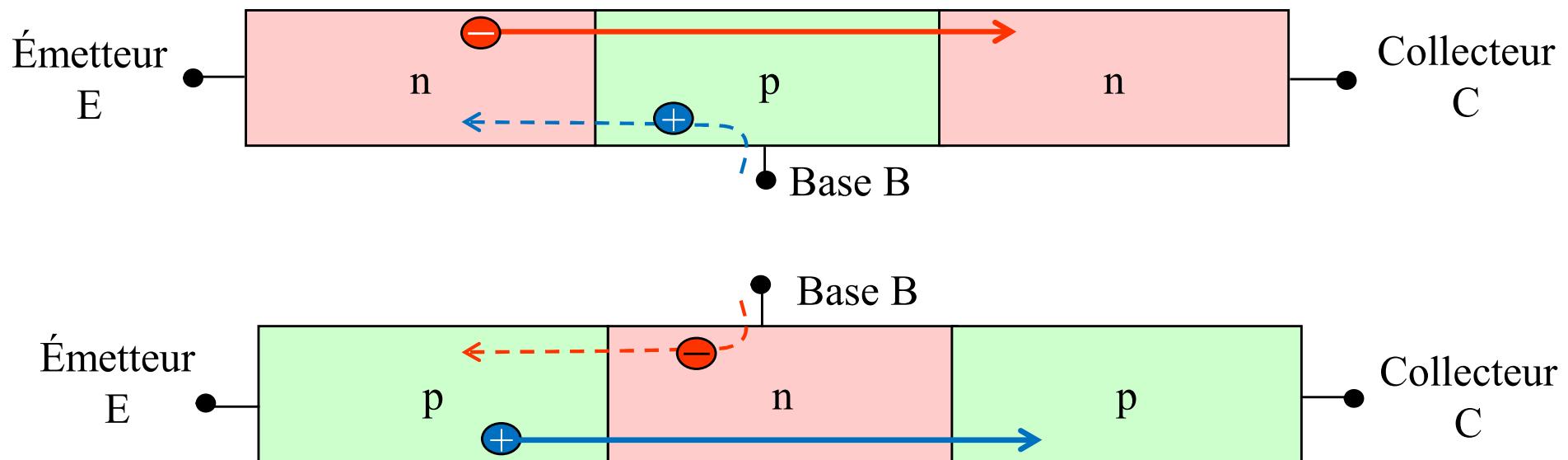


1<sup>er</sup> circuit Intégré,  
Texas Instruments, 1958  
J. Kilby (Nobel 2000)

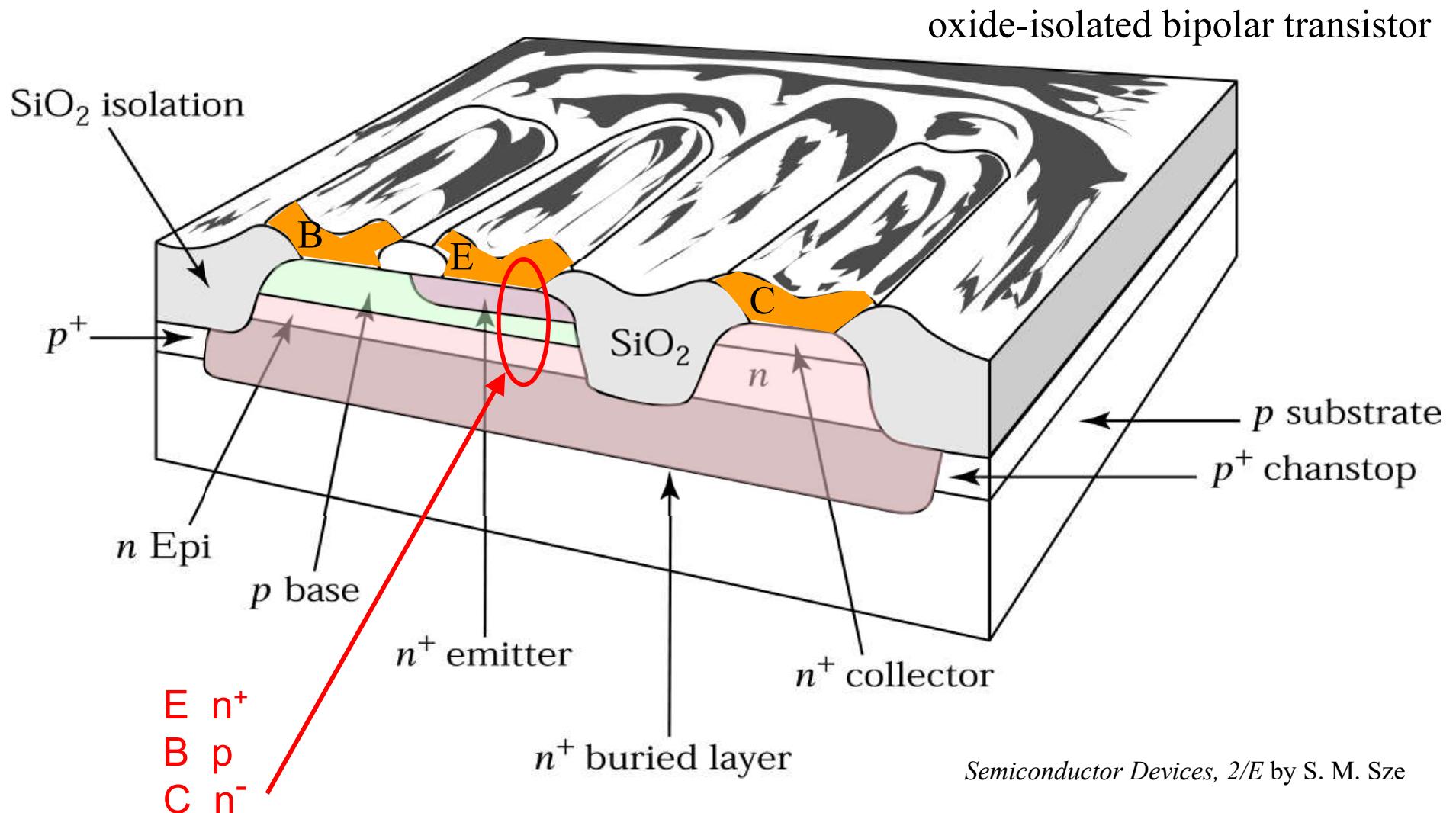


Oscillateur avec 1 pnp, 1C, 3R

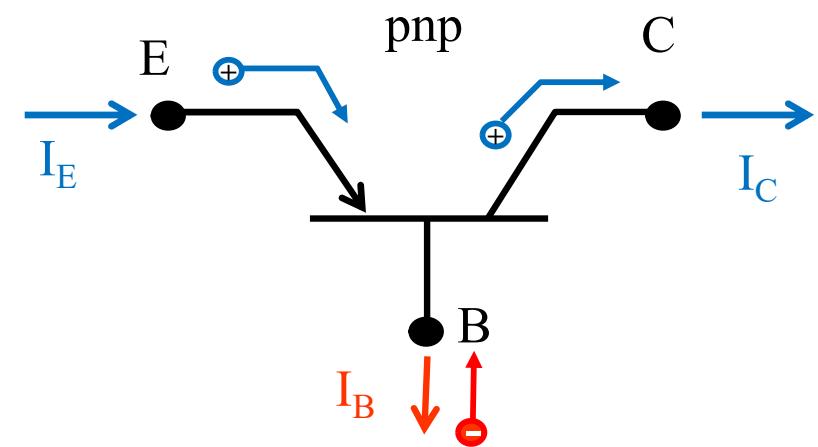
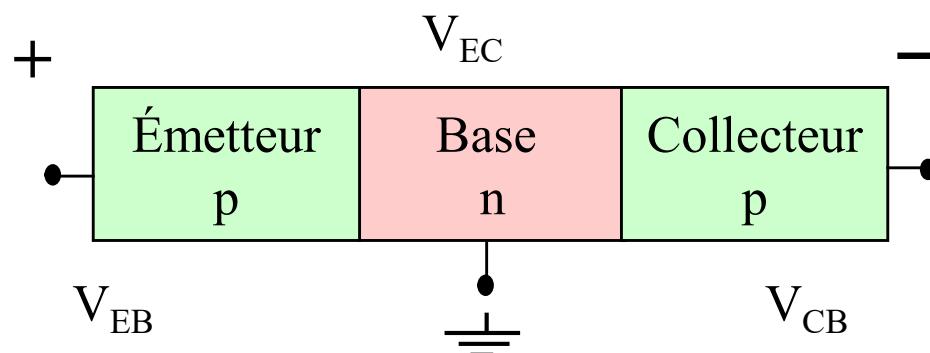
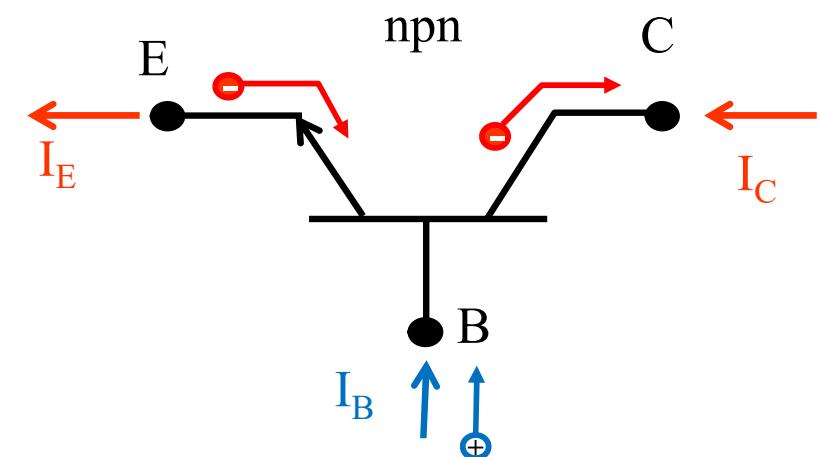
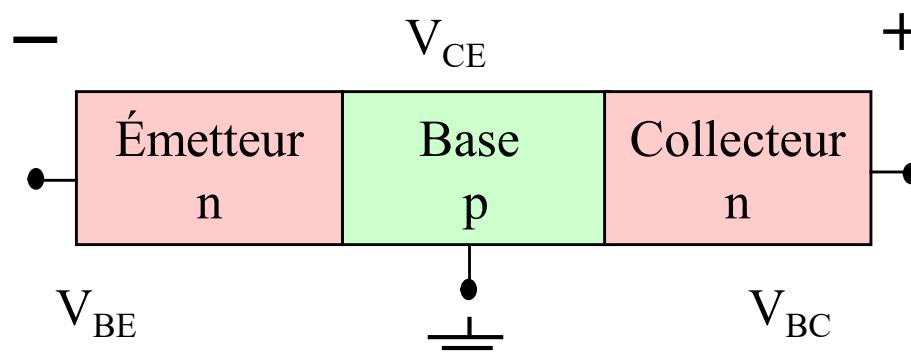
- Une diode en mode direct injecte (**émet**) des minoritaires dans la base
- Une diode en mode inverse extrait (**collecte**) ces minoritaires avant qu'ils ne recombinent dans la base. (base très courte).
- Des majoritaires de la base sont injectés comme minoritaires dans l'émetteur. Ce (faible) courant de base contrôle le courant récolté dans le collecteur.



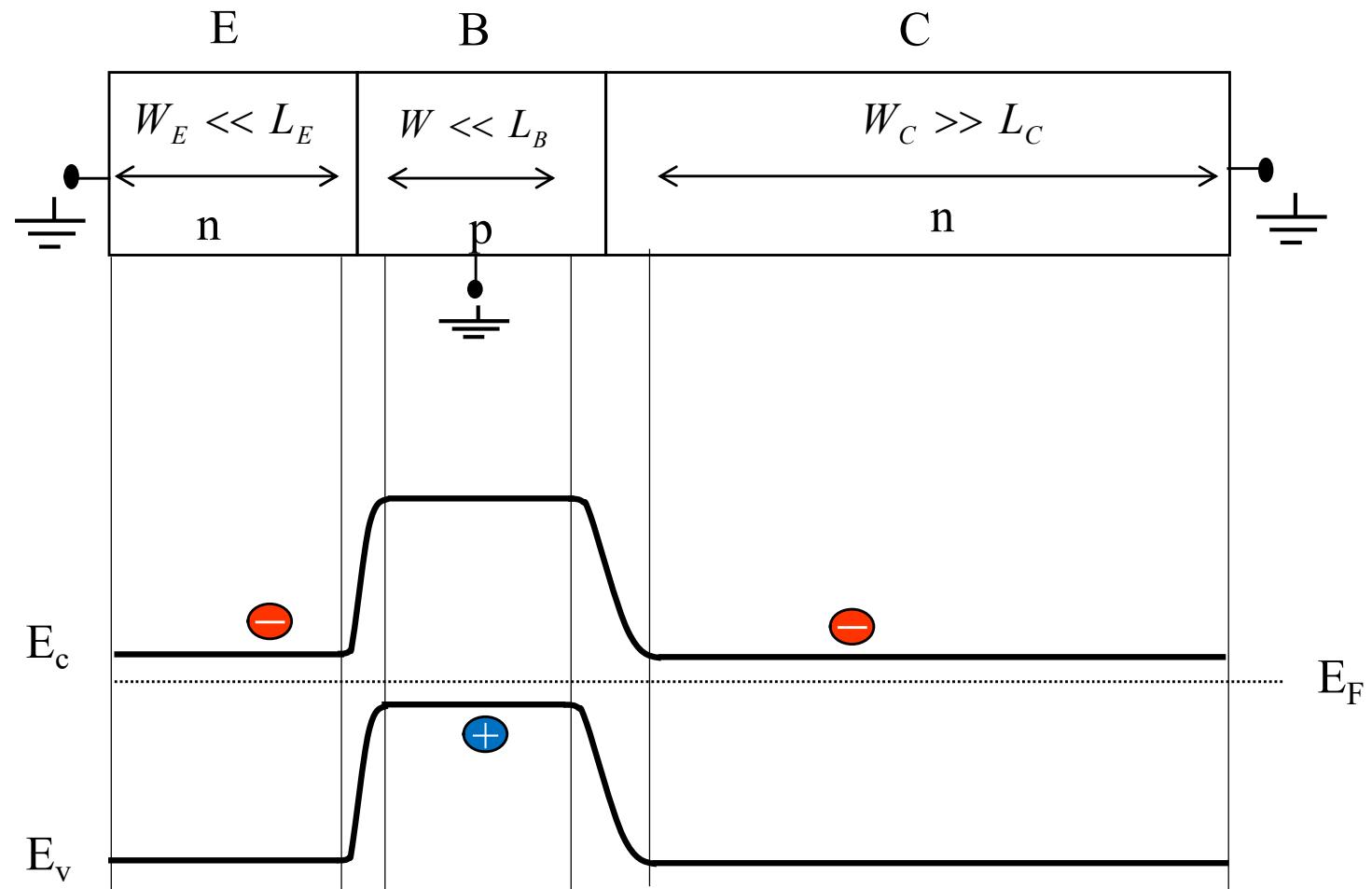
## Transistor bipolaire npn



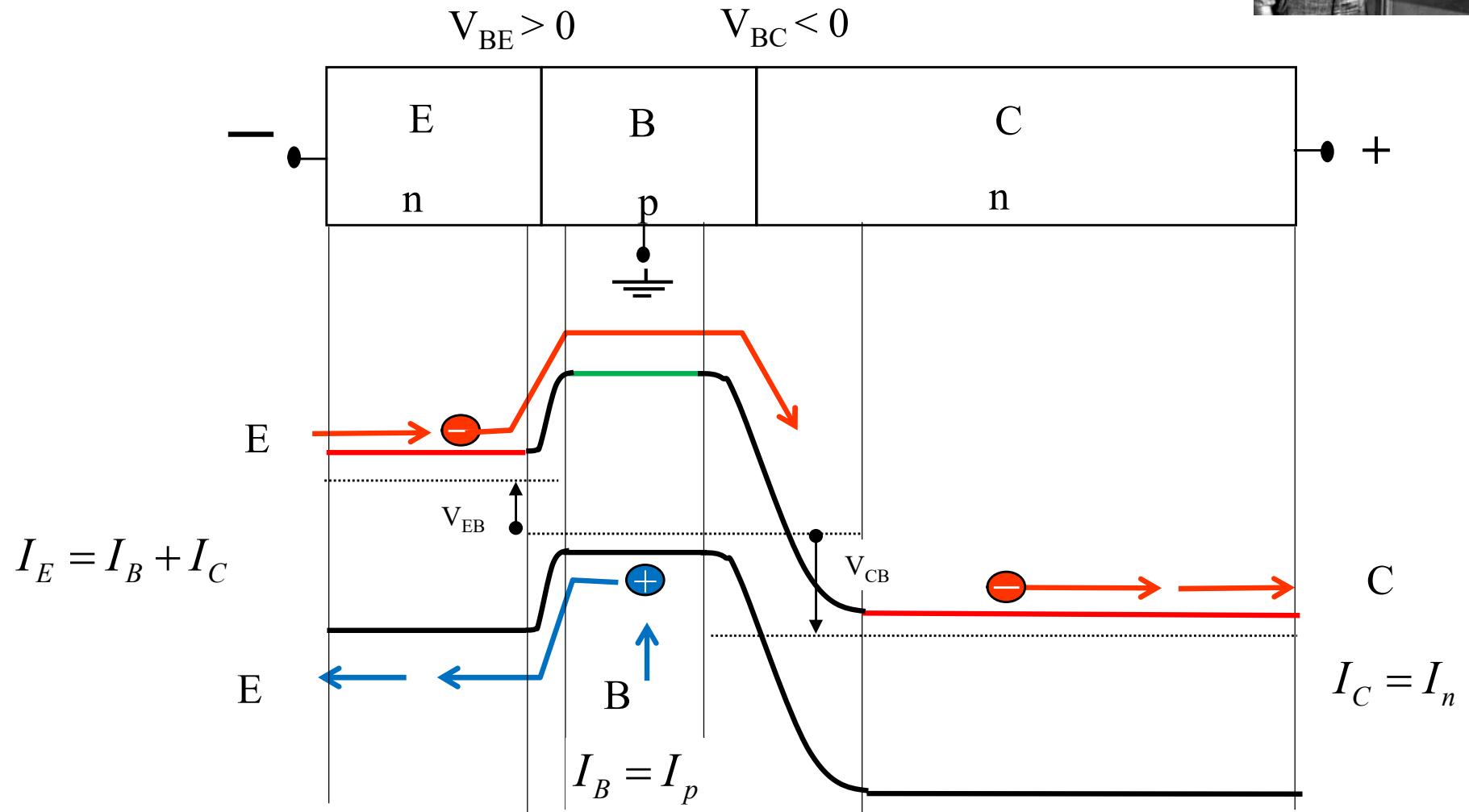
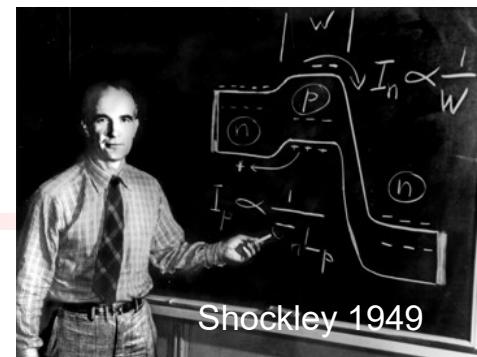
*Semiconductor Devices, 2/E by S. M. Sze*

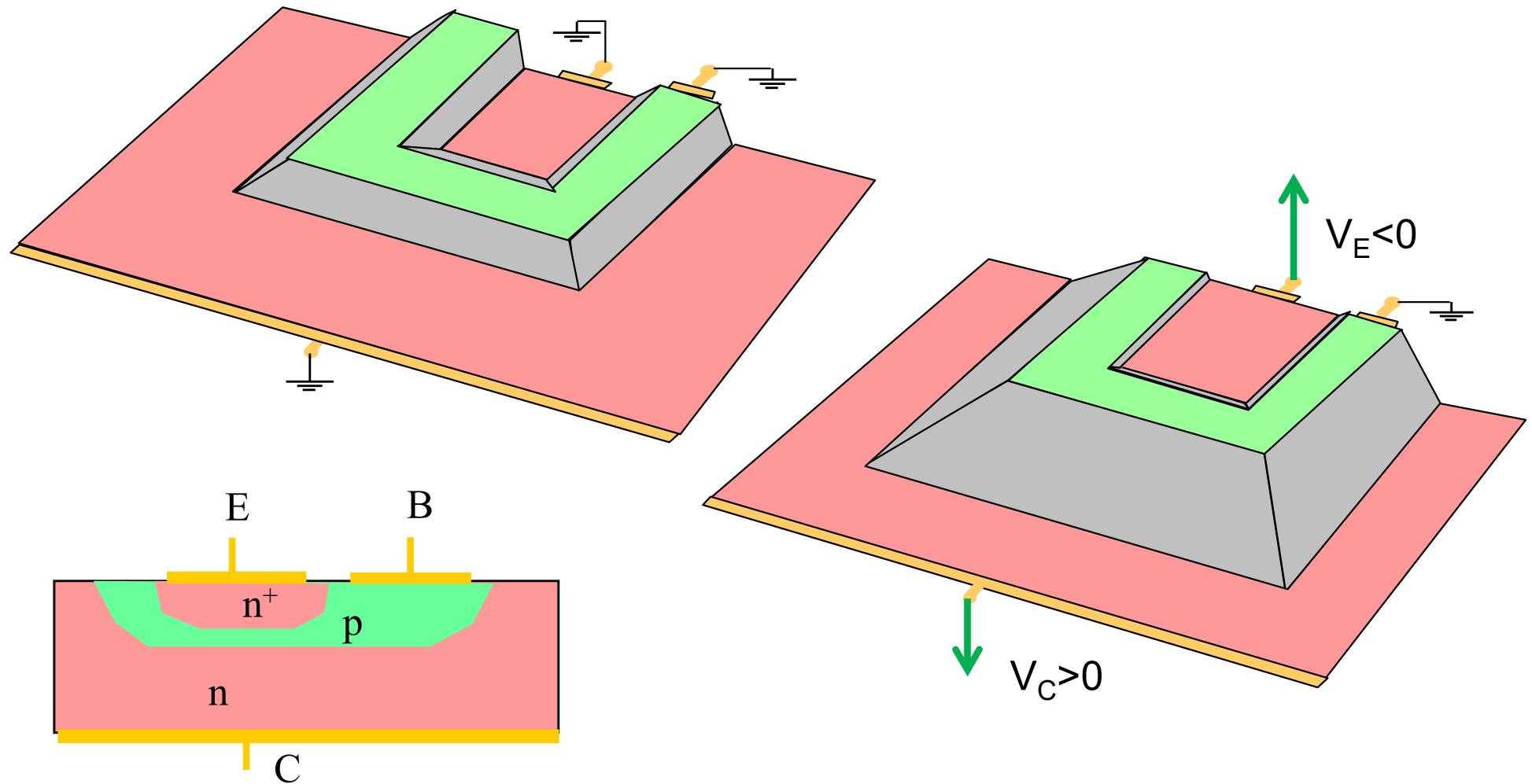


## Transistor n/p/n à l'équilibre

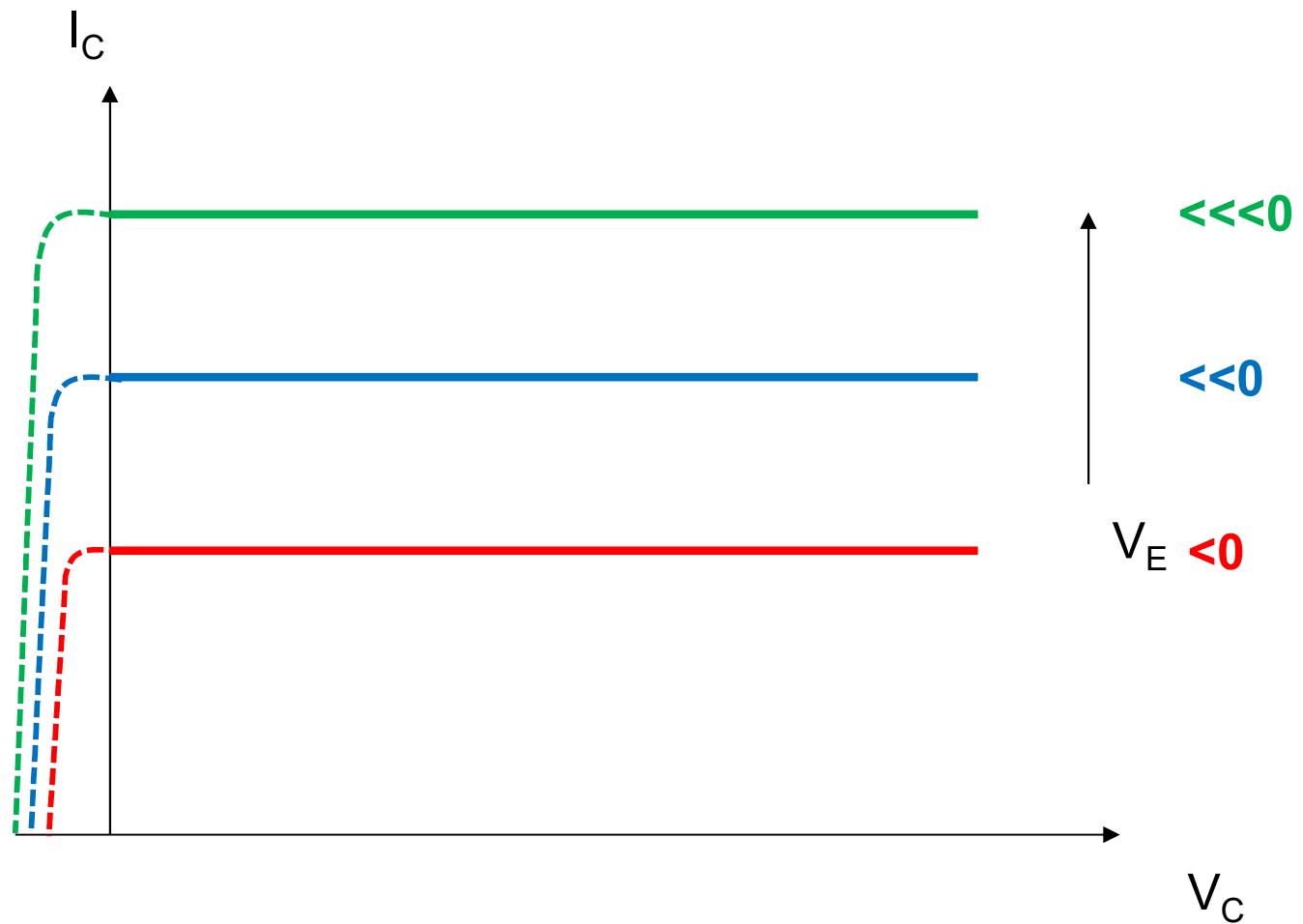
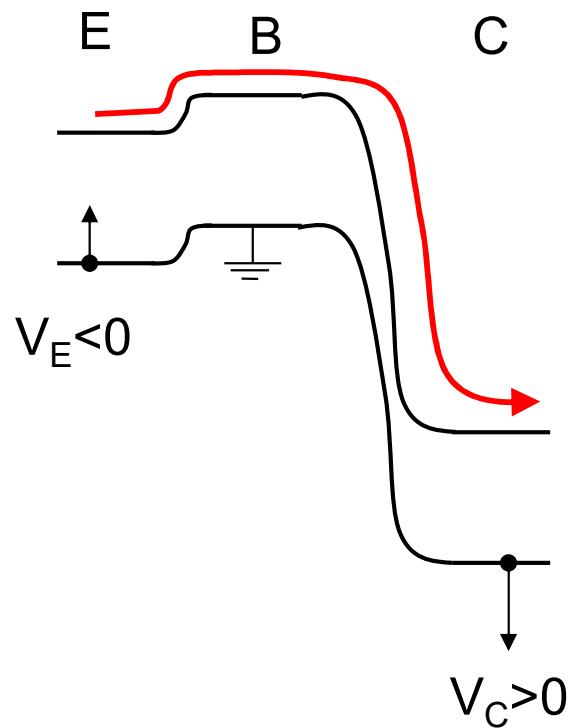


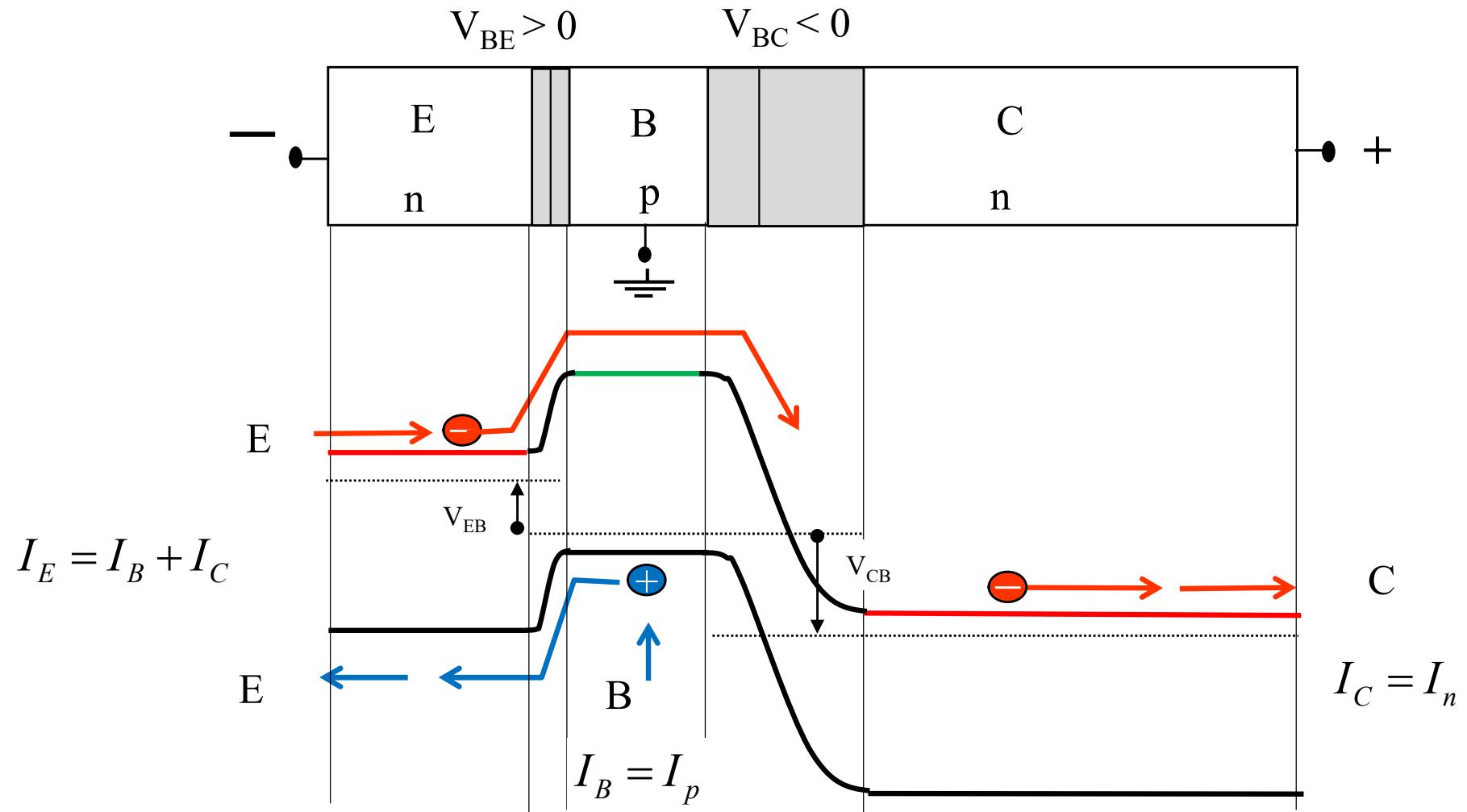
## Transistor npn en mode actif



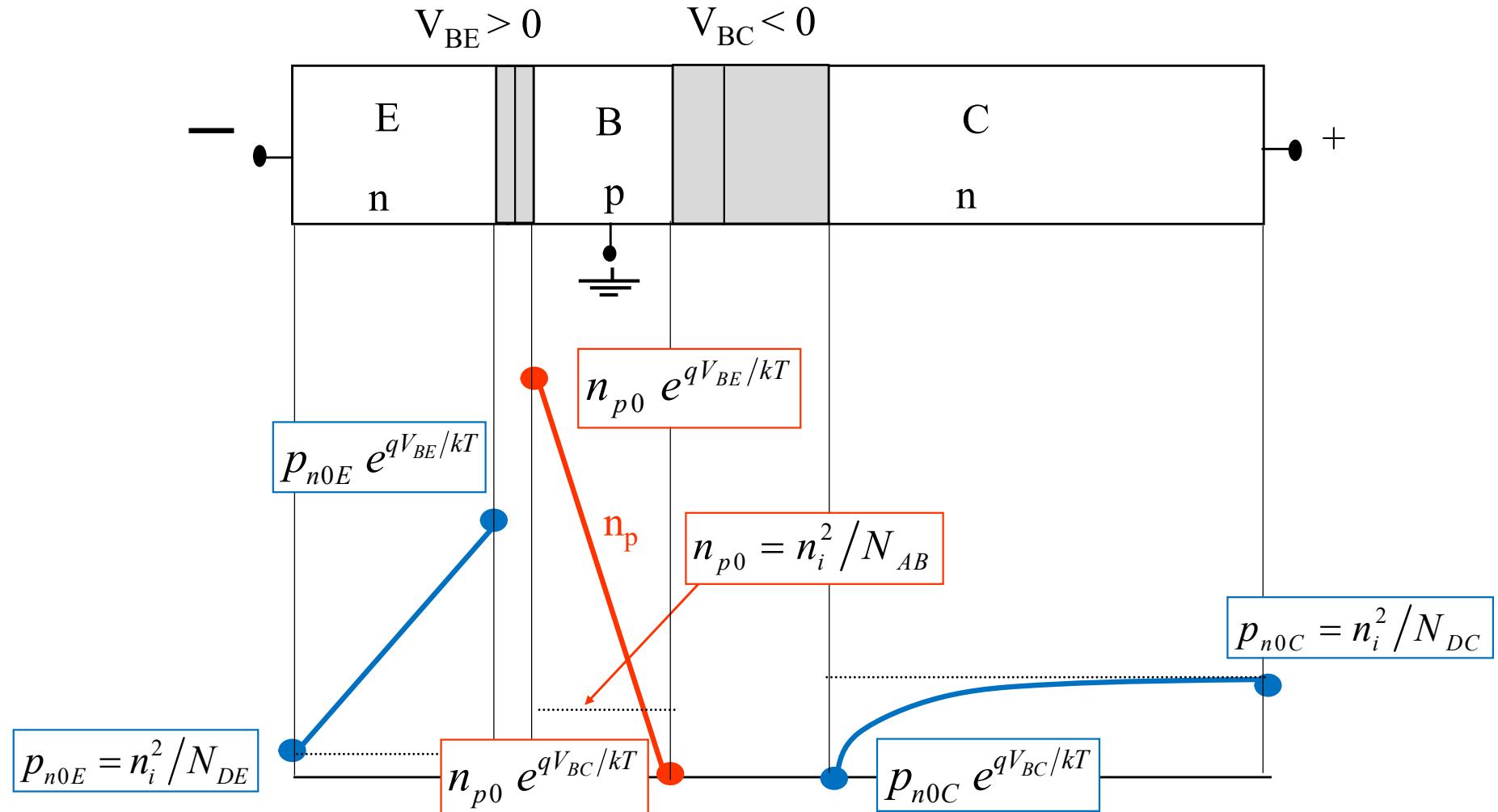


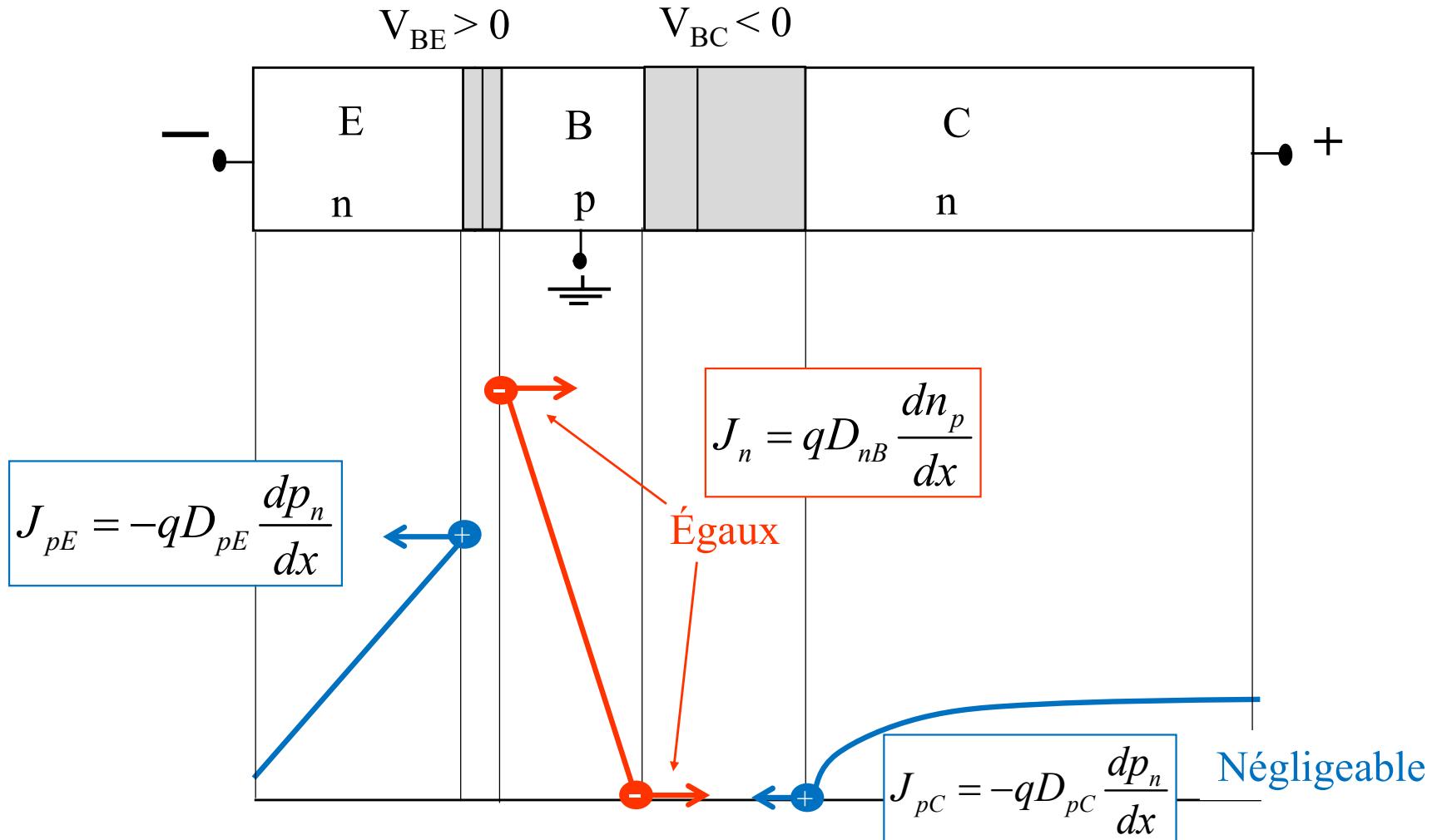
# Esquisse des courants principaux (en base commune)





# Mode actif: densité des minoritaires (npn)





# Courants principaux: solutions en mode actif (npn)

En résolvant les équations pour les courants de diffusion,  
avec les conditions aux bords données,  
nous obtenons pour le mode actif, pour un transistor de surface A:

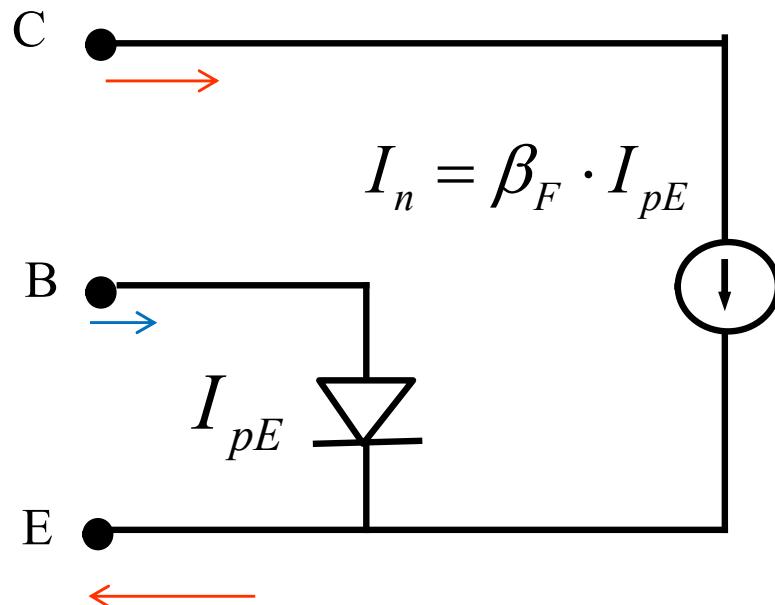
$$I_B = I_{pE} = I_{pE0} \cdot (e^{qV_{BE}/kT} - 1) \quad \text{avec} \quad I_{pE0} = A \frac{qD_{pE}}{W_E} \frac{n_i^2}{N_{DE}}$$

$$I_C = I_n = \beta_F \cdot I_{pE} \quad \text{avec} \quad \beta_F = \frac{D_{nB}}{D_{pE}} \cdot \frac{W_E}{W} \cdot \frac{N_{DE}}{N_{AB}}$$

$$I_E = I_B + I_C = (1 + \beta_F) \cdot I_{pE}$$

Remarque: Le courant  $I_{pC}$  est négligeable en mode actif

# Modèle de Ebers-Moll en mode actif (npn)

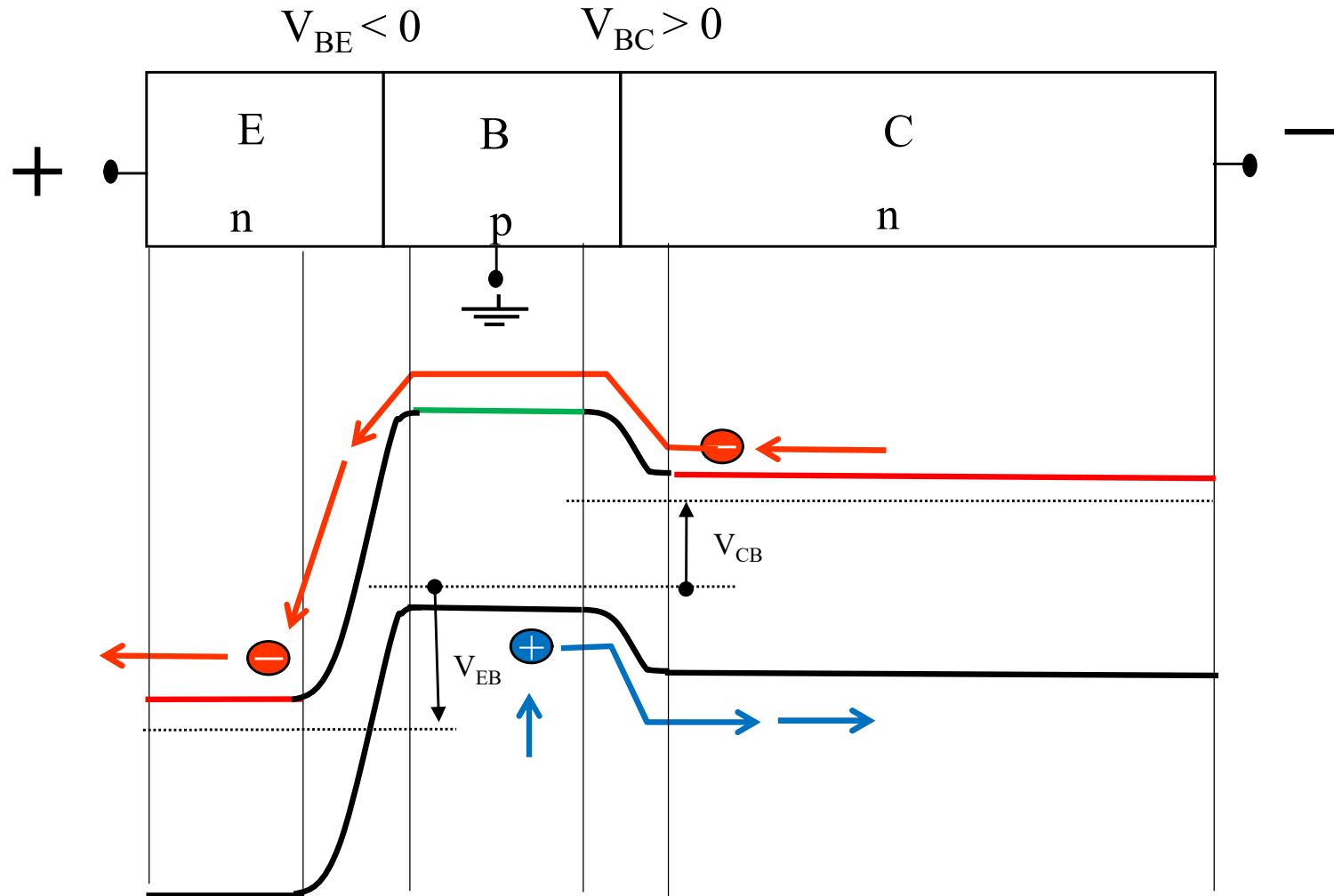


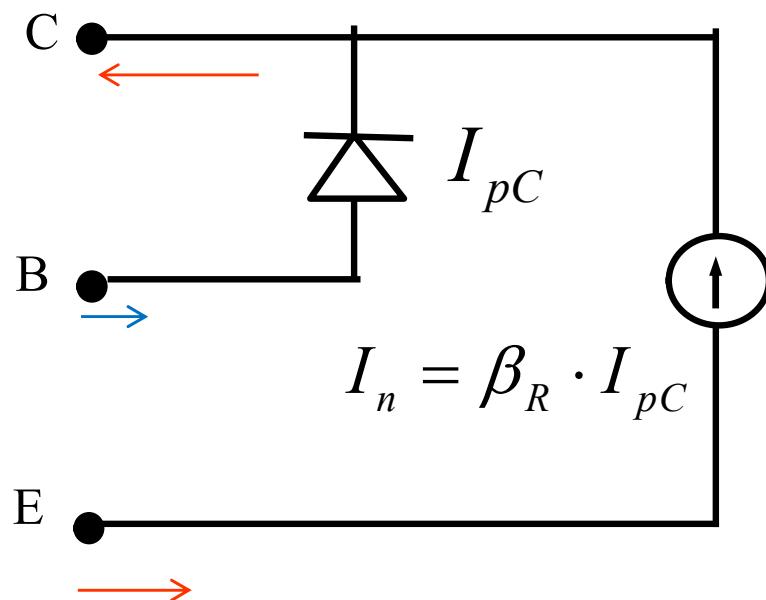
$$I_{pE} = I_{pE0} \cdot (e^{qV_{BE}/kT} - 1)$$

$$I_{pE0} = A \frac{qD_{pE}}{W_E} \frac{n_i^2}{N_{DE}}$$

$$\beta_F = \frac{D_{nB}}{D_{pE}} \cdot \frac{W_E}{W} \cdot \frac{N_{DE}}{N_{AB}}$$

## Transistor npn en mode reverse

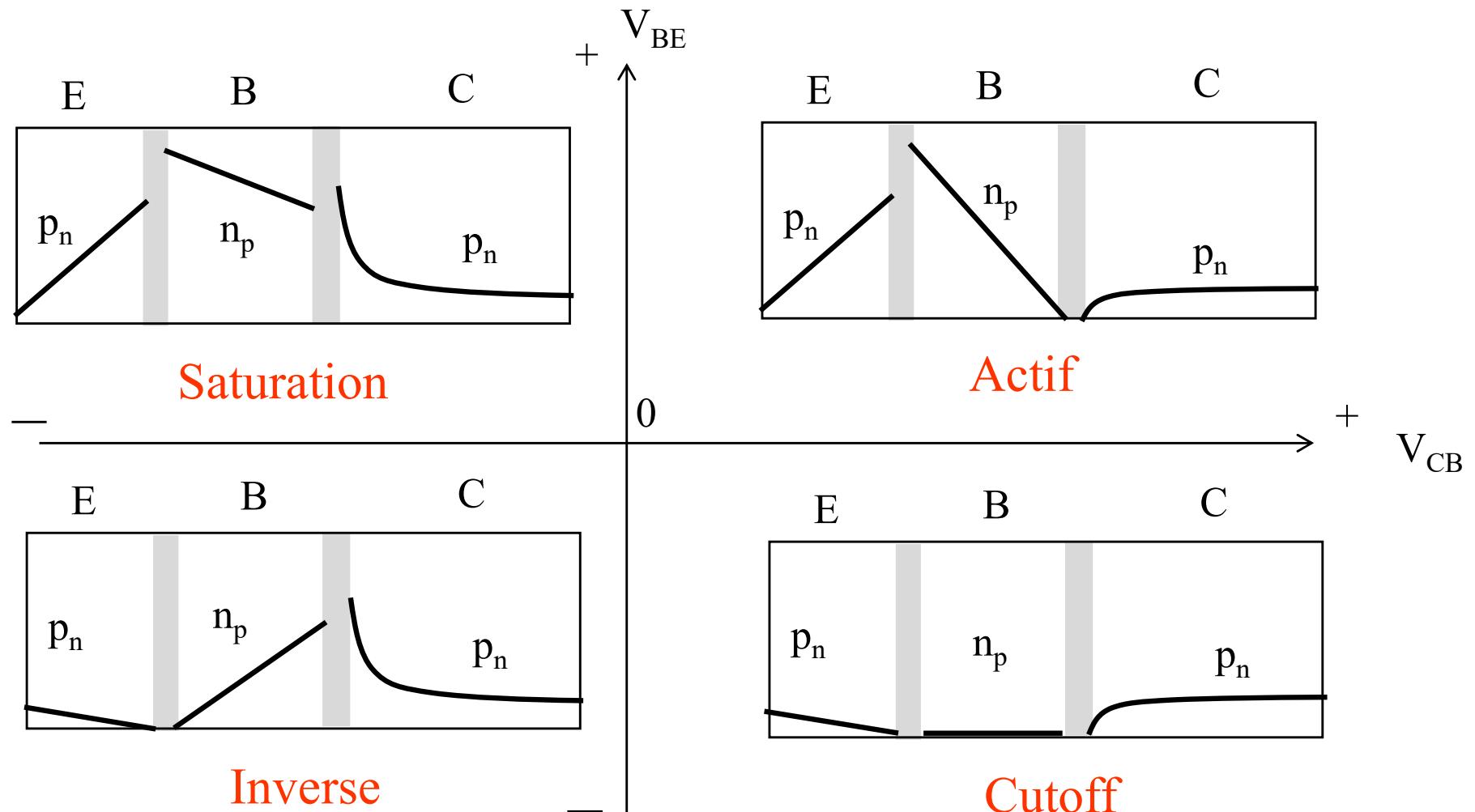




$$I_{pC} = I_{pC0} \cdot (e^{qV_{BC}/kT} - 1)$$

$$I_{pC0} = A \frac{qD_{pC}}{L_C} \frac{n_i^2}{N_{DC}}$$

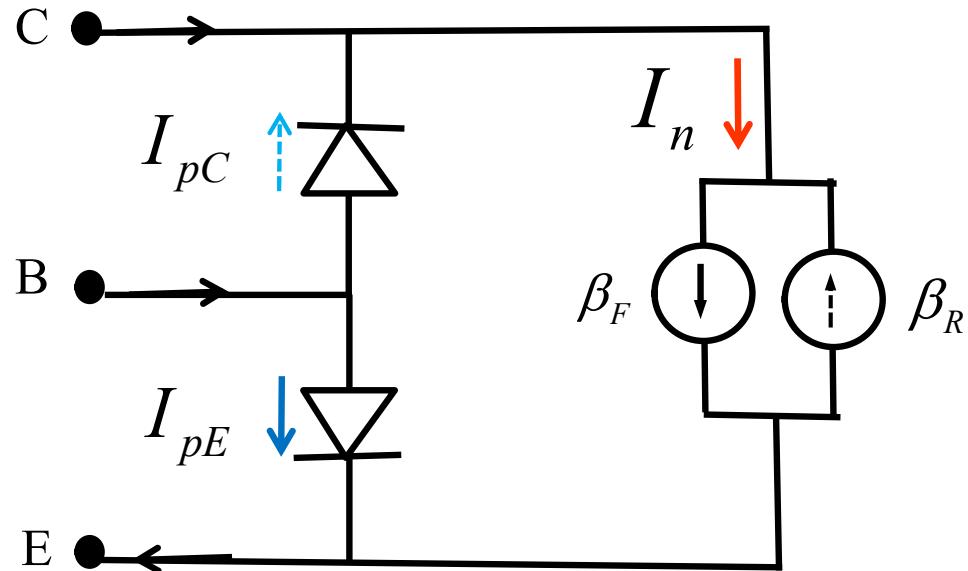
$$\beta_R = \frac{D_{nB}}{D_{pC}} \cdot \frac{L_C}{W} \cdot \frac{N_{DC}}{N_{AB}}$$



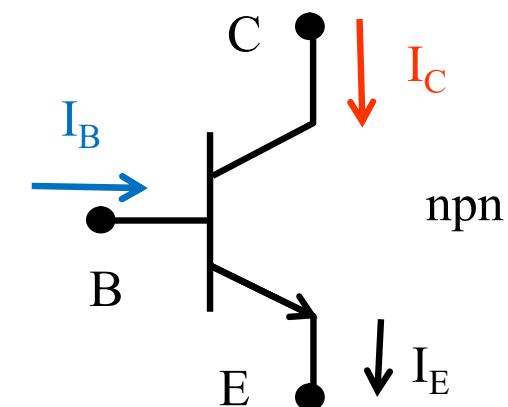
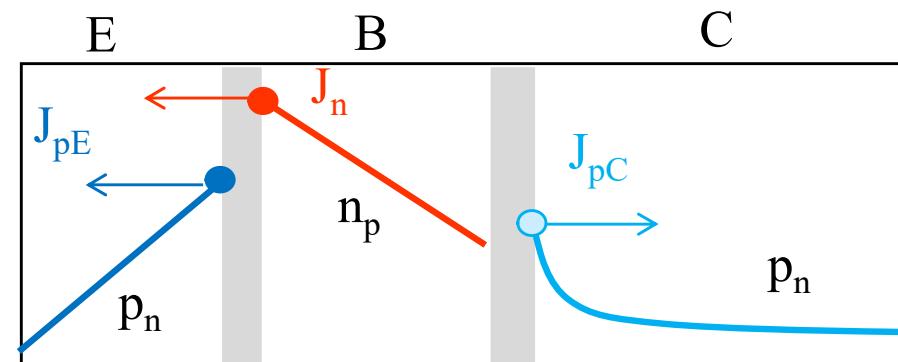


# Modèle de Ebers-Moll: cas général (npn)

Schéma électrique



Densité de minoritaires





# Courants principaux: solution générale (npn)

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

$$I_C = I_n - I_{pC}$$

$$I_n = \beta_F I_{pE} - \beta_R I_{pC}$$

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

Avec:

$$I_{pE} = I_{pE0} \cdot (e^{qV_{BE}/kT} - 1)$$

$$I_{pE0} = A \frac{qD_{pE}}{W_E} \frac{n_i^2}{N_{DE}}$$

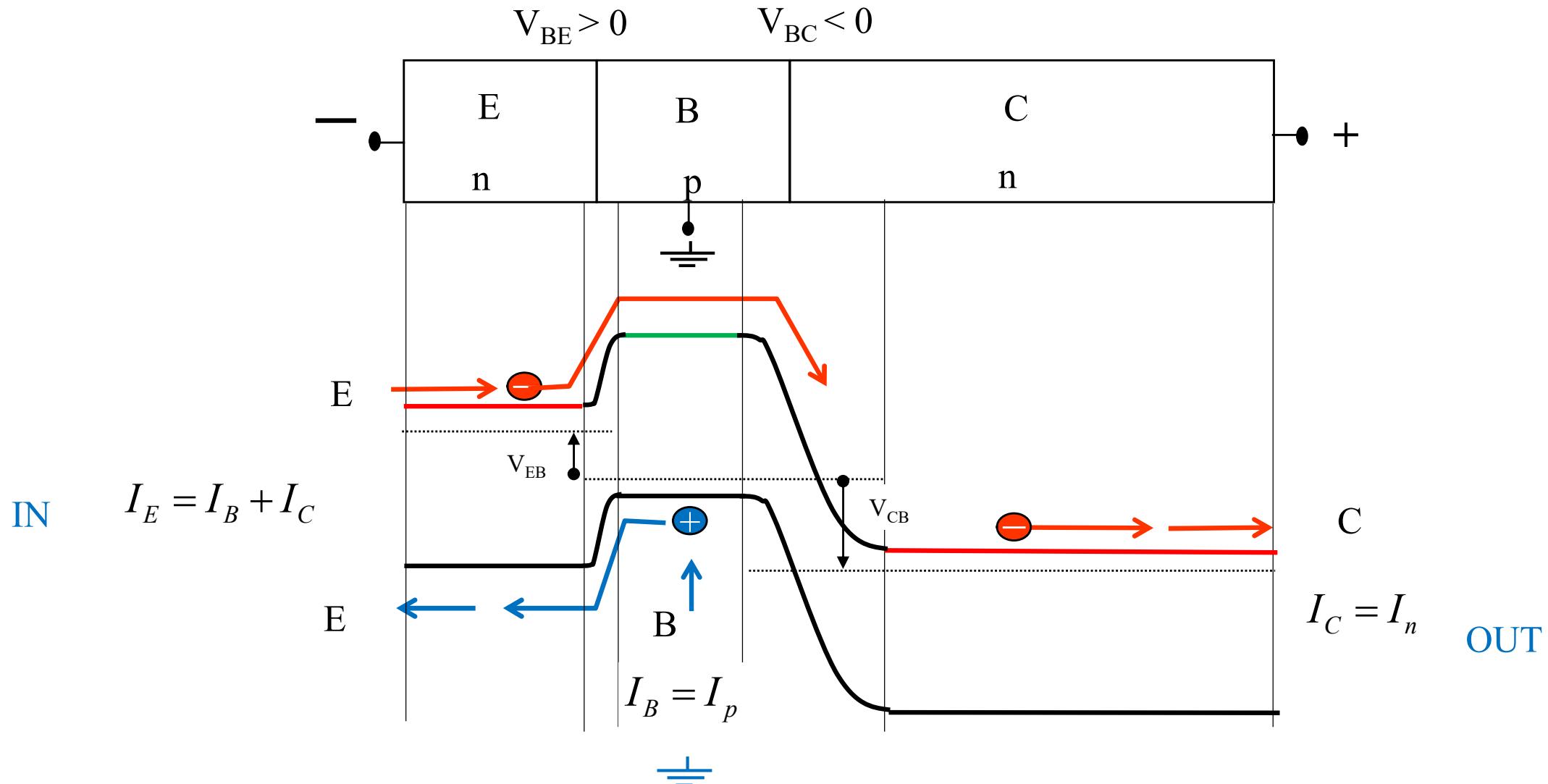
$$\beta_F = \frac{D_{nB}}{D_{pE}} \cdot \frac{W_E}{W} \cdot \frac{N_{DE}}{N_{AB}}$$

$$I_{pC} = I_{pC0} \cdot (e^{qV_{BC}/kT} - 1)$$

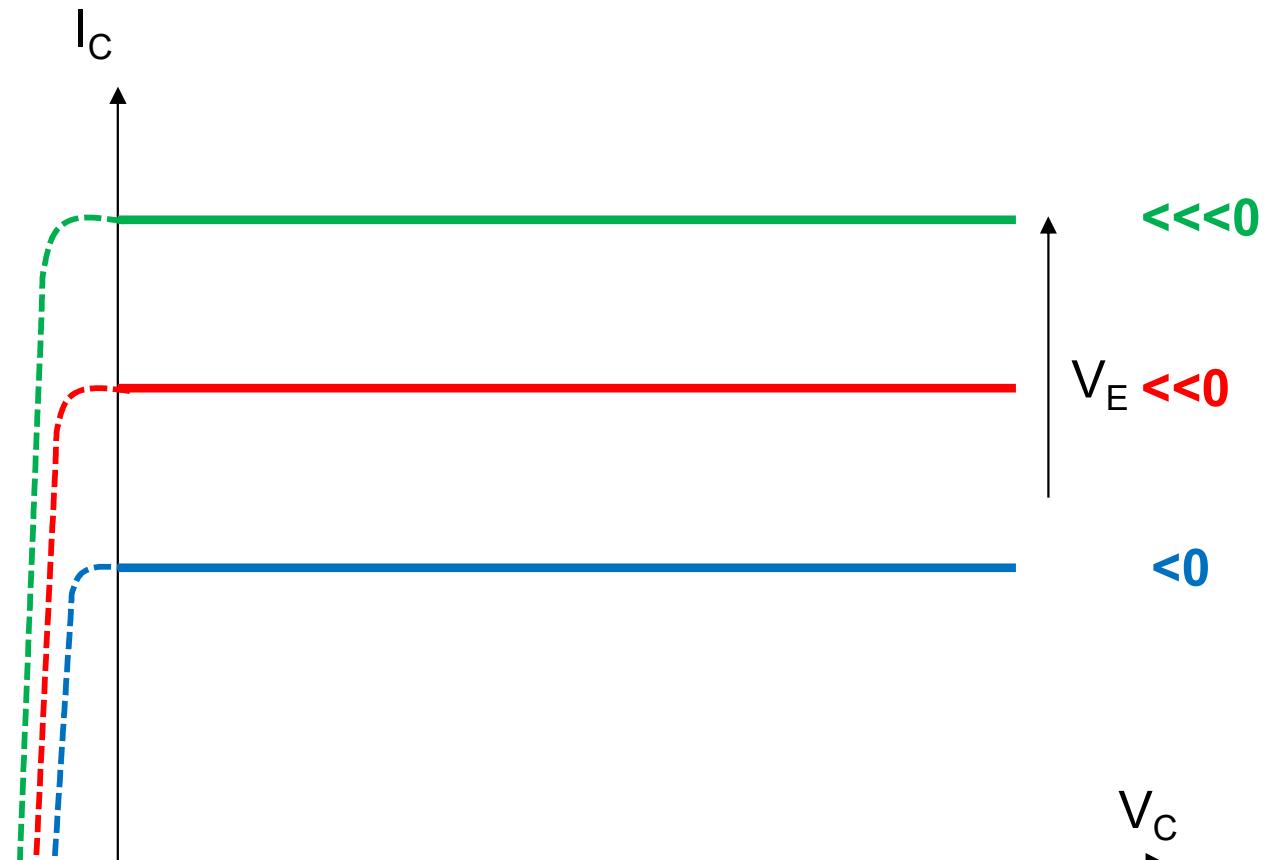
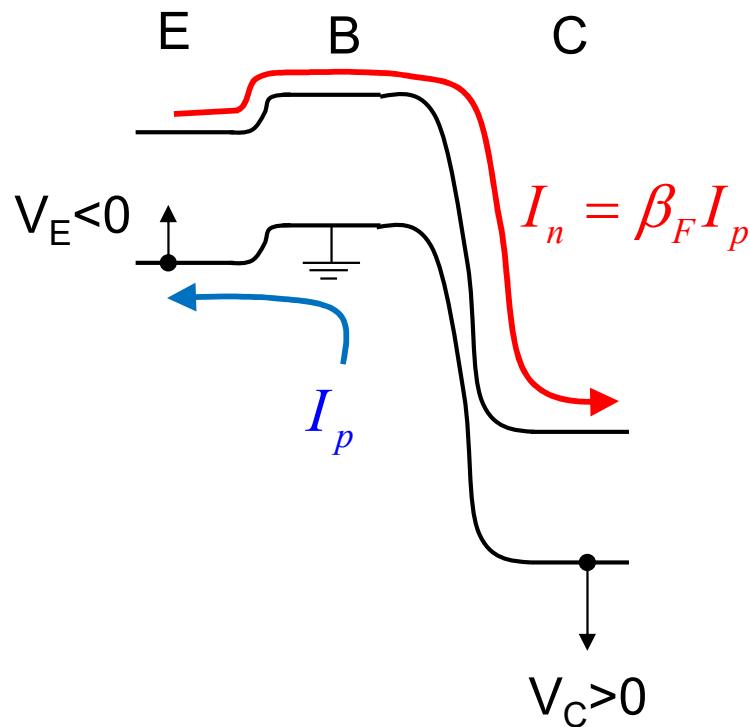
$$I_{pC0} = A \frac{qD_{pC}}{L_C} \frac{n_i^2}{N_{DC}}$$

$$\beta_R = \frac{D_{nB}}{D_{pC}} \cdot \frac{L_C}{W} \cdot \frac{N_{DC}}{N_{AB}}$$

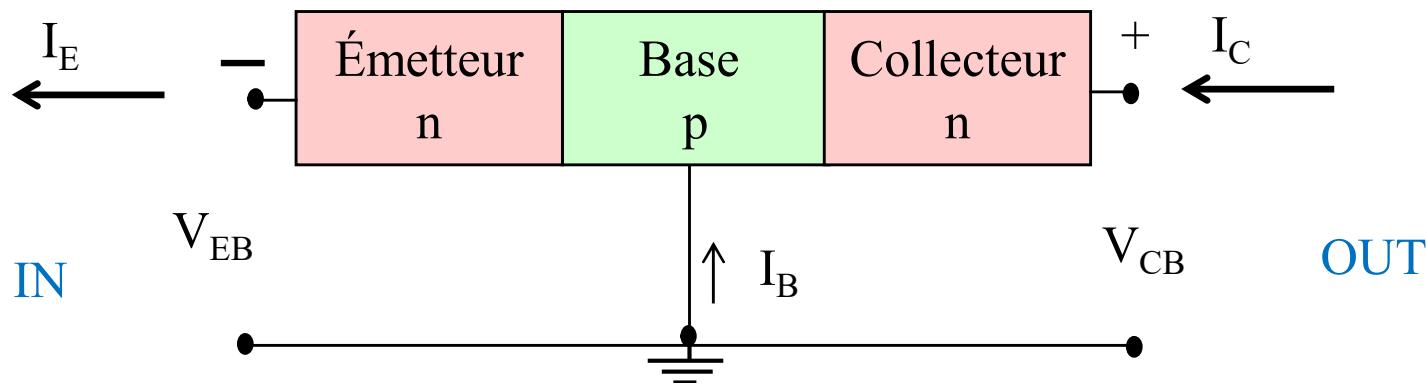
**BJT****Base commune**

Transistor npn **base commune**

# Esquisse des courants principaux (en base commune)



## Configuration en base commune



Gain en courant en mode base commune « Common base current gain »:

$$\alpha_F = \frac{I_C}{I_E} \cong \frac{\beta_F}{\beta_F + 1}$$

Typique:  $\alpha_F = 0.99$

Caractéristique:  $I_{out}(V_{out}) = I_C(V_{CB})$  contrôlé par le courant  $I_{in} = I_E$

# Caractéristiques en base commune: théorie

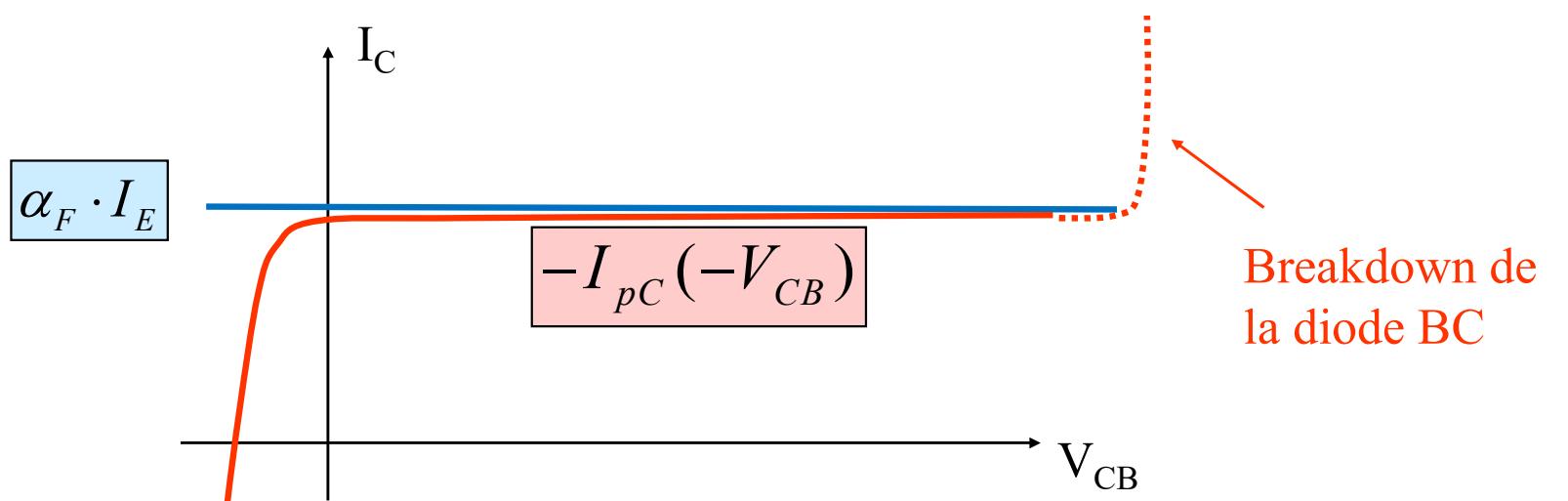
À partir des équations du modèle Ebers-Moll (npn):

$$I_C(V_{CB}, I_E) = \alpha_F \cdot I_E - \left( \frac{1 + \beta_F + \beta_R}{1 + \beta_F} \right) \cdot I_{pC}(-V_{CB})$$

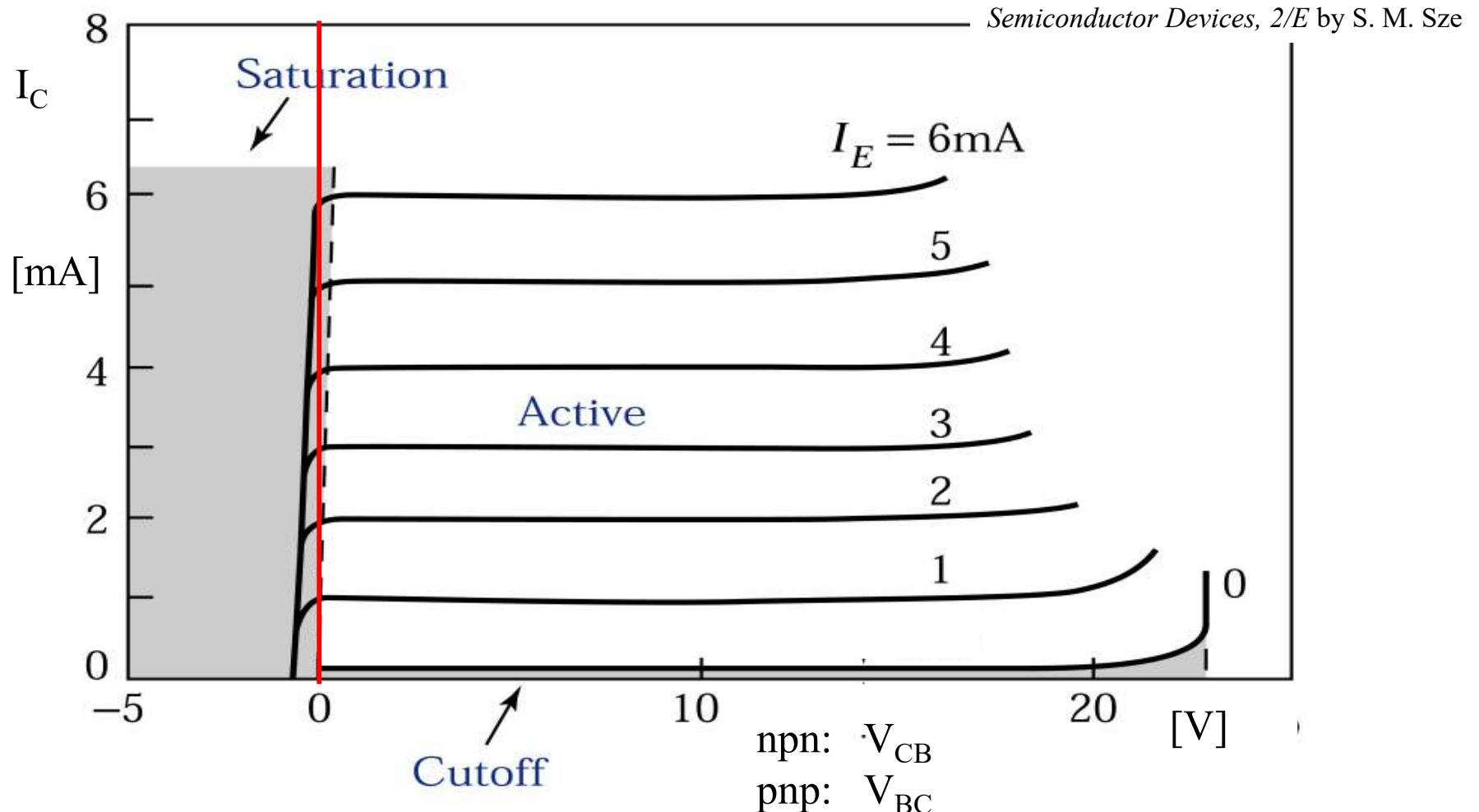
$\sim 1$

$\sim 1$

Courant de trous dans la diode BC  
→ Caractéristique de diode !!



# Caractéristiques en base commune: exemple

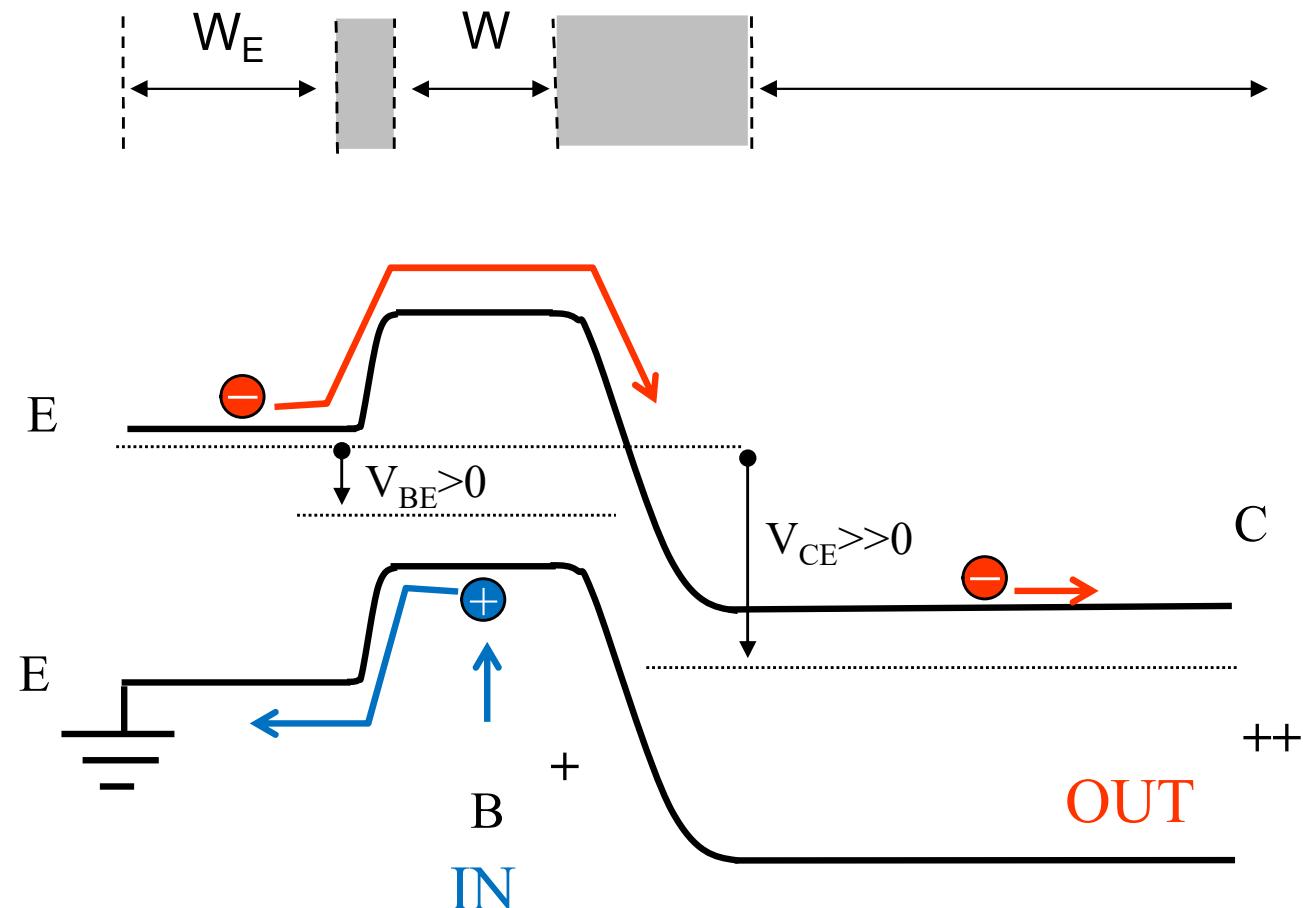


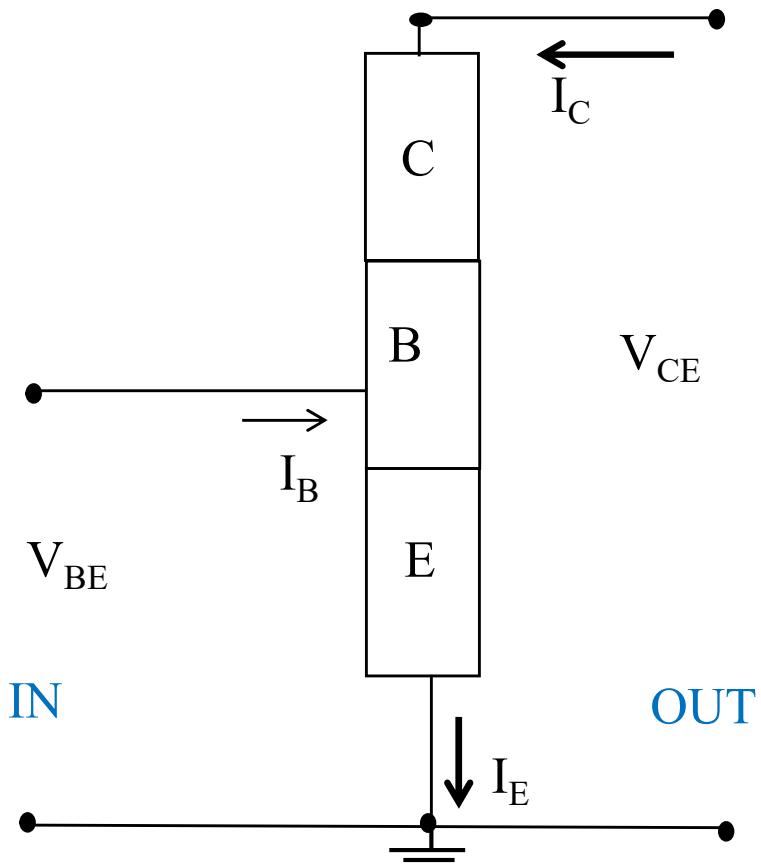
**BJT**

# Emetteur commun

# Émetteur commun: schéma de bandes

Transistor npn

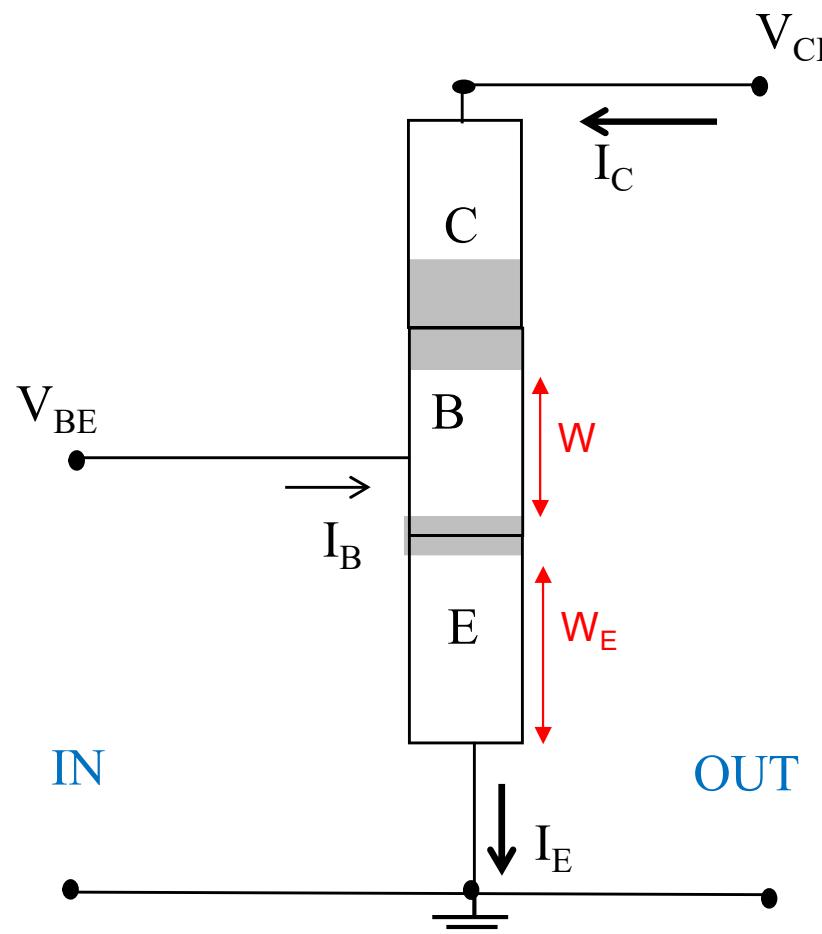




Gain en courant en  
mode émetteur commun  
« Common-emitter current gain »:

$$\frac{I_C}{I_B} \equiv \beta_F$$

## Configuration en émetteur commun



Gain en courant en mode émetteur commun  
« Common-emitter current gain »:

$$\frac{I_C}{I_B} = \beta_F = \frac{D_{nB}}{D_{pE}} \cdot \frac{W_E}{W} \cdot \frac{N_{DE}}{N_{AB}}$$

Optimisation ( $\beta_F \rightarrow \infty$ ) :

- base courte  $W \rightarrow 0$
- émetteur fortement dopé  $N_{DE}$  comparé à la base  $N_{AB}$

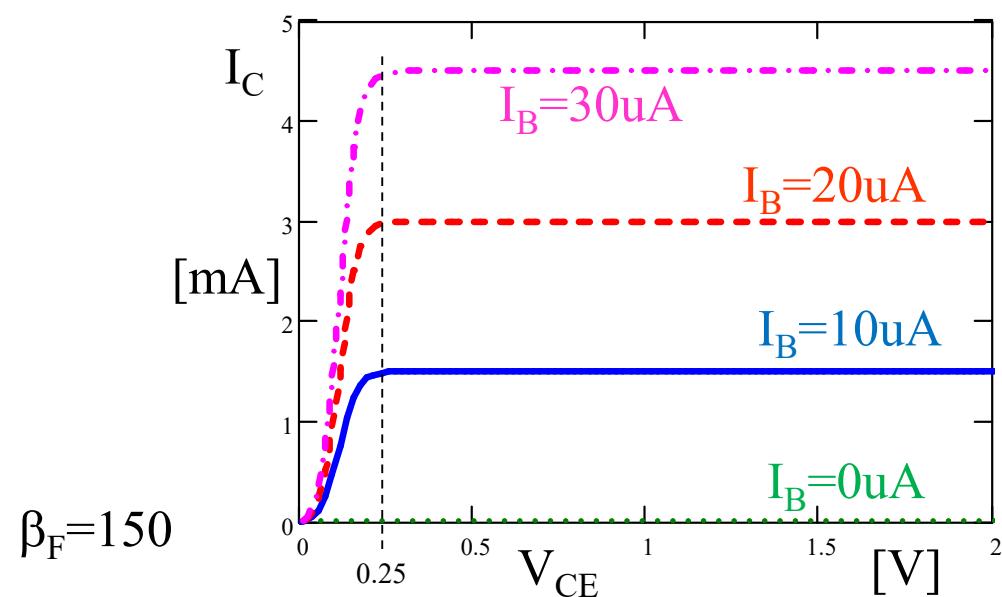
Typique:  $\beta_F = 100 - 300$

# Caractéristiques en émetteur commun: théorie

$$I_c(V_{CE}, I_B) = \beta_F I_B - \left[ (1 + \beta_F + \beta_R) I_{pC0} \left( \frac{I_B + I_{pE0} + I_{pC0}}{I_{pE0} e^{qV_{CE}/kT} + I_{pC0}} - 1 \right) \right]$$

En mode actif: indépendant de la tension de sortie  $V_{CE}$

Négligeable en mode actif



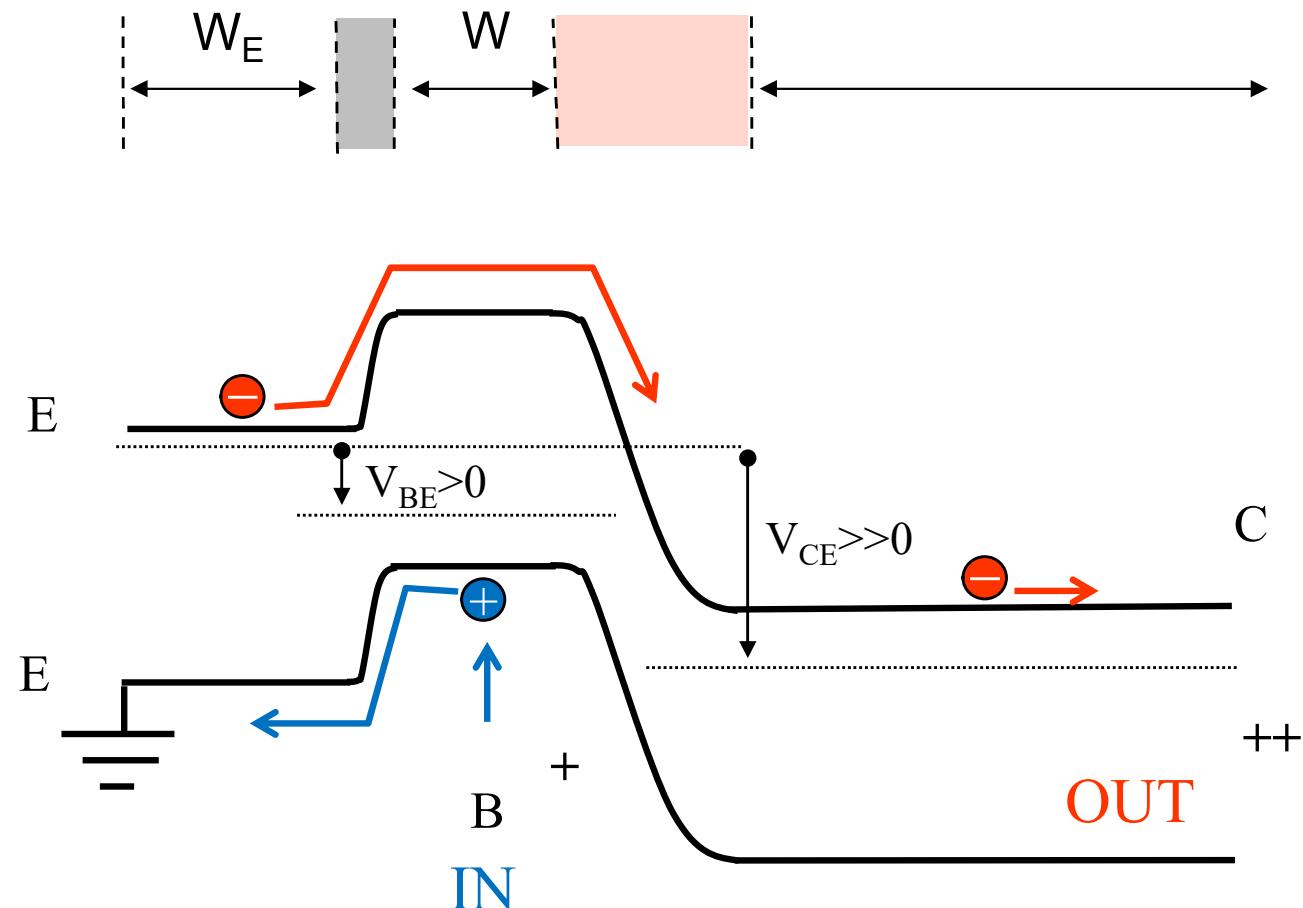
À partir des équations du modèle Ebers-Moll (npn)

# BJT

# Effet Early

# Émetteur commun: schéma de bandes

Transistor npn

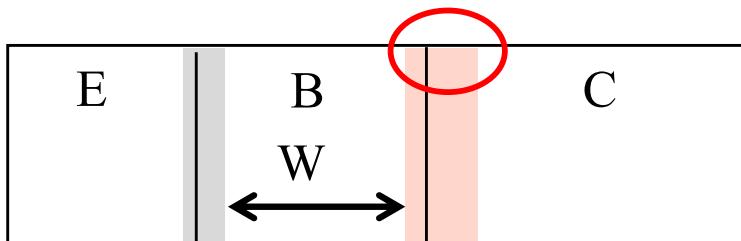


En mode actif:

$$\frac{I_C}{I_B} = \beta_F = \frac{D_{nB}}{D_{pE}} \cdot \frac{W_E}{W} \cdot \frac{N_{DE}}{N_{AB}}$$

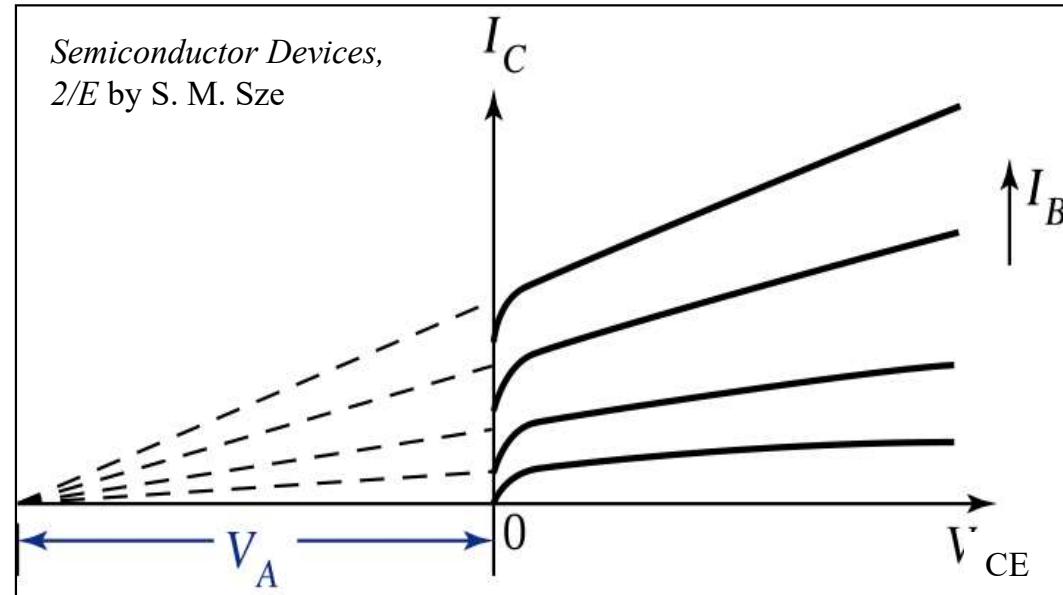
Variation de la largeur W de la base:

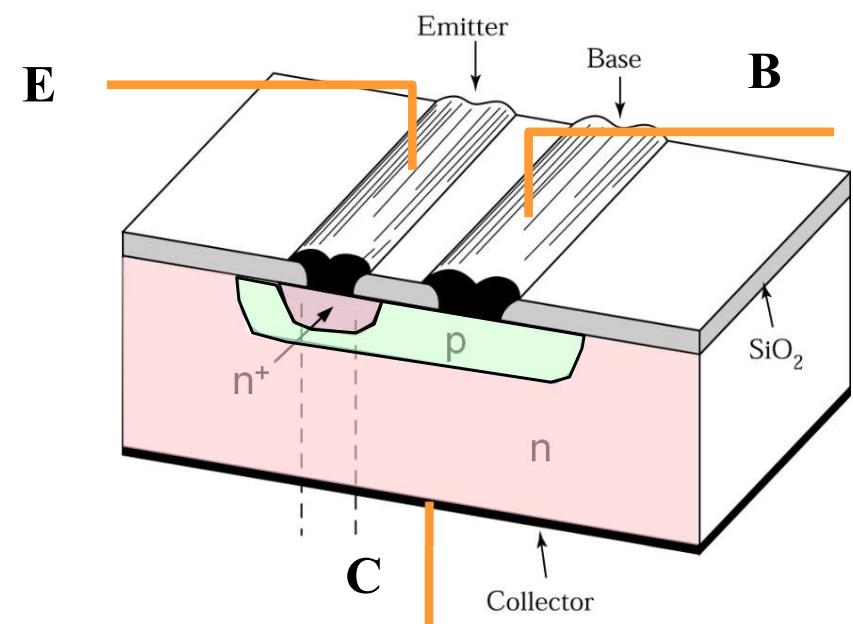
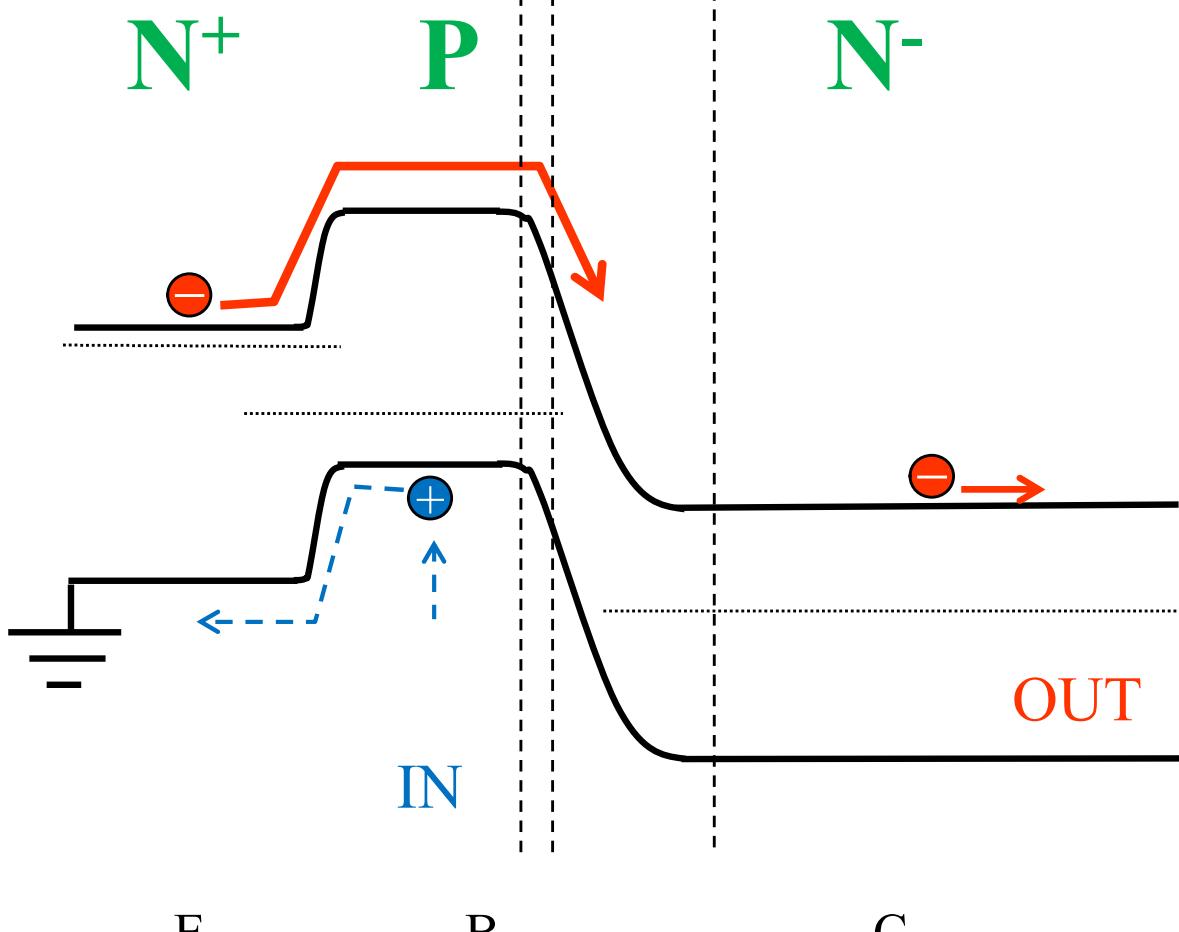
$$V_{CE} \uparrow \Rightarrow W \downarrow \Rightarrow \beta_F \uparrow$$



Optimisation:

- Effet moins fort si le dopage de la base est élevé
- Compromis avec une valeur élevée de  $\beta$  !!!





# BJT

## Conductances et Modèle petit signaux

Conductance

$$g \equiv \frac{\partial \text{courant}}{\partial \text{tension}} = \frac{\partial I}{\partial V}$$

Conductance d'entrée:

$$g_{in} \equiv \frac{\partial \text{courant d'entrée}}{\partial \text{tension d'entrée}} = \frac{\partial I_{in}}{\partial V_{in}}$$

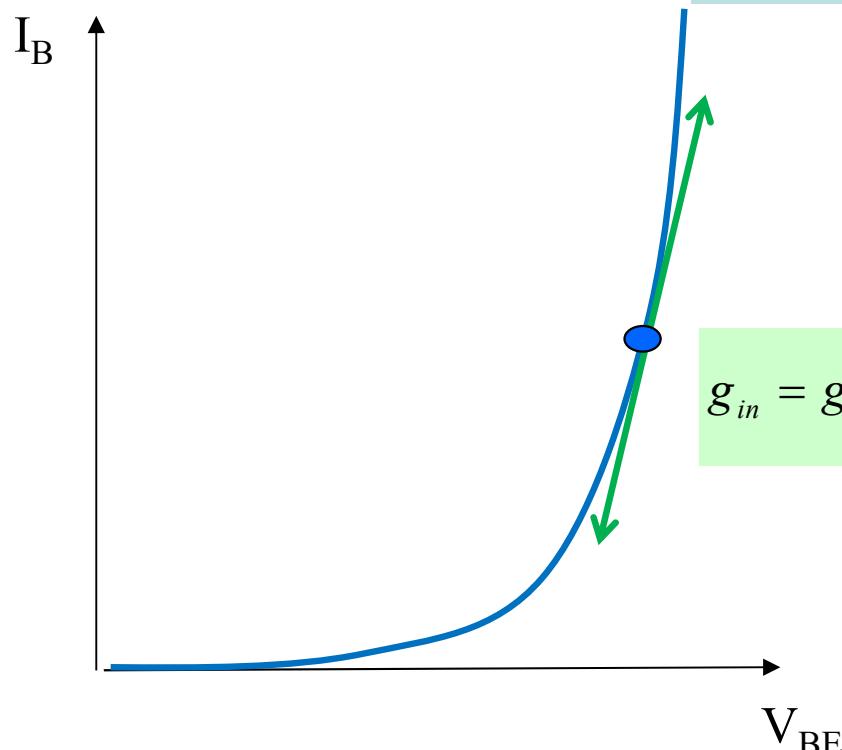
Conductance de sortie:

$$g_{out} \equiv \frac{\partial \text{courant de sortie}}{\partial \text{tension de sortie}} = \frac{\partial I_{out}}{\partial V_{out}}$$

Trans-conductance:

$$g_m \equiv \frac{\partial \text{courant de sortie}}{\partial \text{tension d'entrée}} = \frac{\partial I_{out}}{\partial V_{in}} = \frac{\partial I_{out}}{\partial I_{in}} \cdot \frac{\partial I_{in}}{\partial V_{in}} = \beta \cdot g_{in}$$

# Résumé: BJT actif – caractéristique d'entrée en émetteur commun



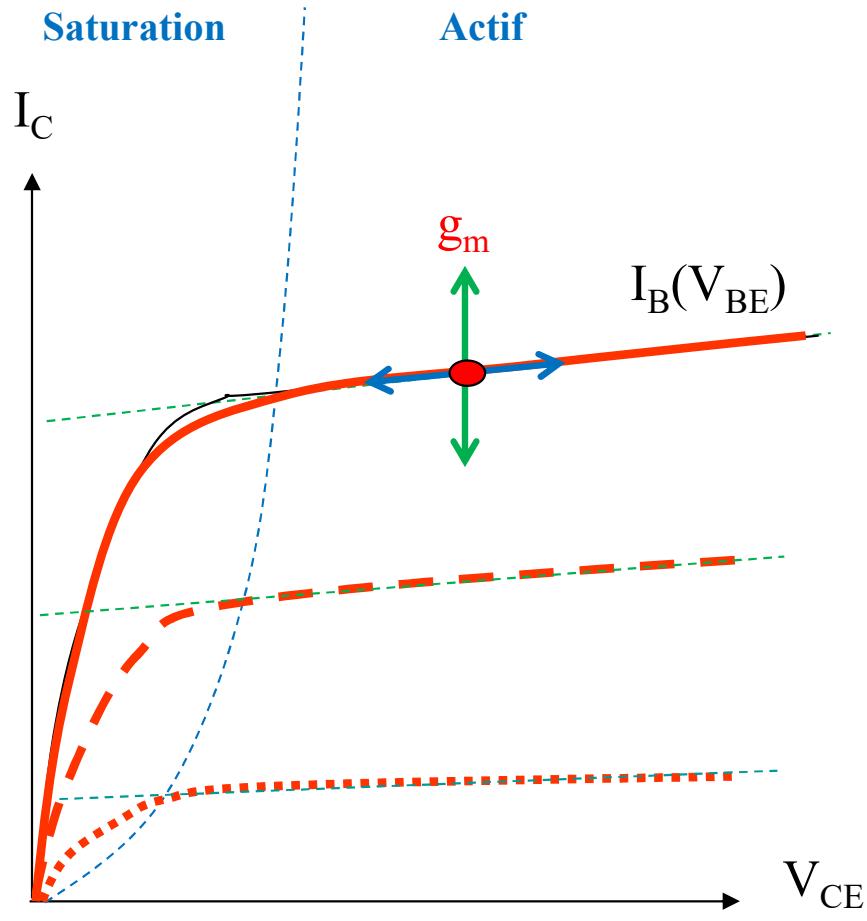
$$I_B = I_{pE0} (e^{qV_{BE}/kT} - 1)$$

$$I_{pE0} = A \frac{qD_{pE}}{W_E} \frac{n_i^2}{N_{DE}}$$

$$g_{in} = g_{BE} \equiv \frac{\partial I_B}{\partial V_{BE}} \cong \frac{q}{kT} I_B = \frac{I_B}{U_{th}}$$

**Conductance d'entrée**

# Résumé: BJT actif – caractéristique de sortie en émetteur commun



$$I_C = \beta_F I_B \cdot (1 + \lambda V_{CE})$$

$$\beta_F = \frac{D_{nB}}{D_{pE}} \frac{W_E}{W} \frac{N_{DE}}{N_{AB}} \quad \lambda = \frac{1}{|V_A|}$$

## Transconductance

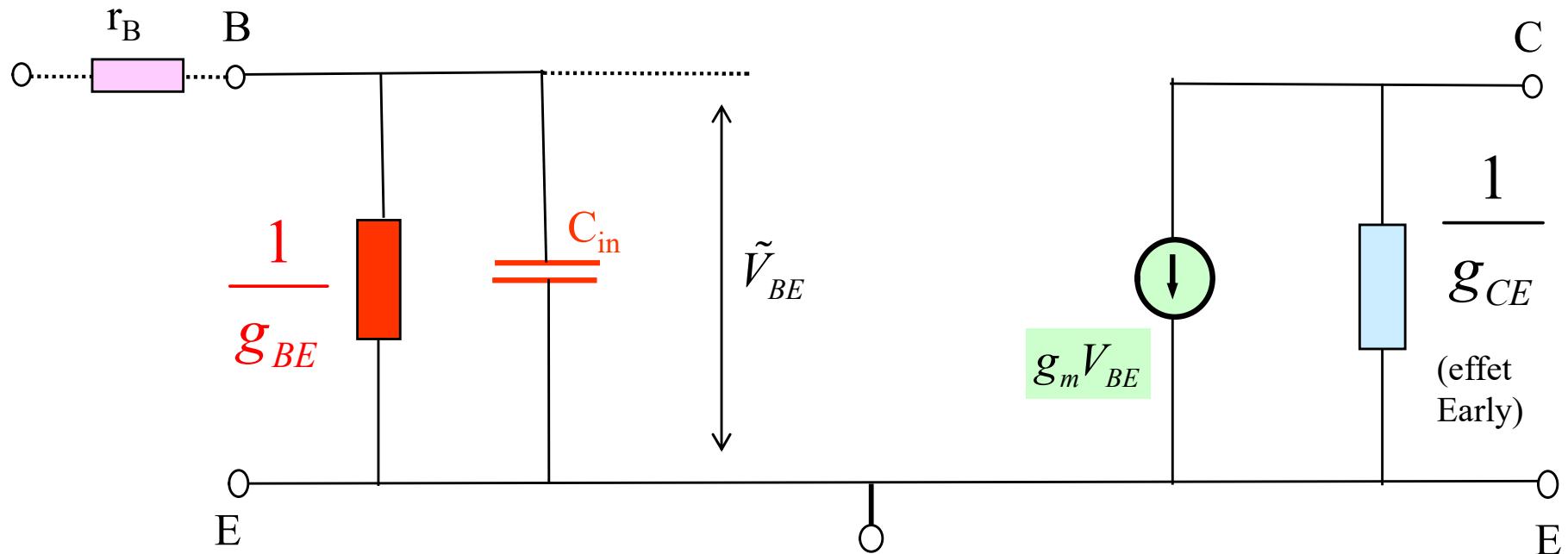
$$g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{q}{kT} I_C = \beta_F \cdot g_{BE}$$

$$g_{CE} = \frac{\partial I_C}{\partial V_{CE}} = \lambda \cdot I_C \cong \frac{I_C}{|V_A|}$$

## Conductance de sortie

# Circuit équivalent simplifié en émetteur commun

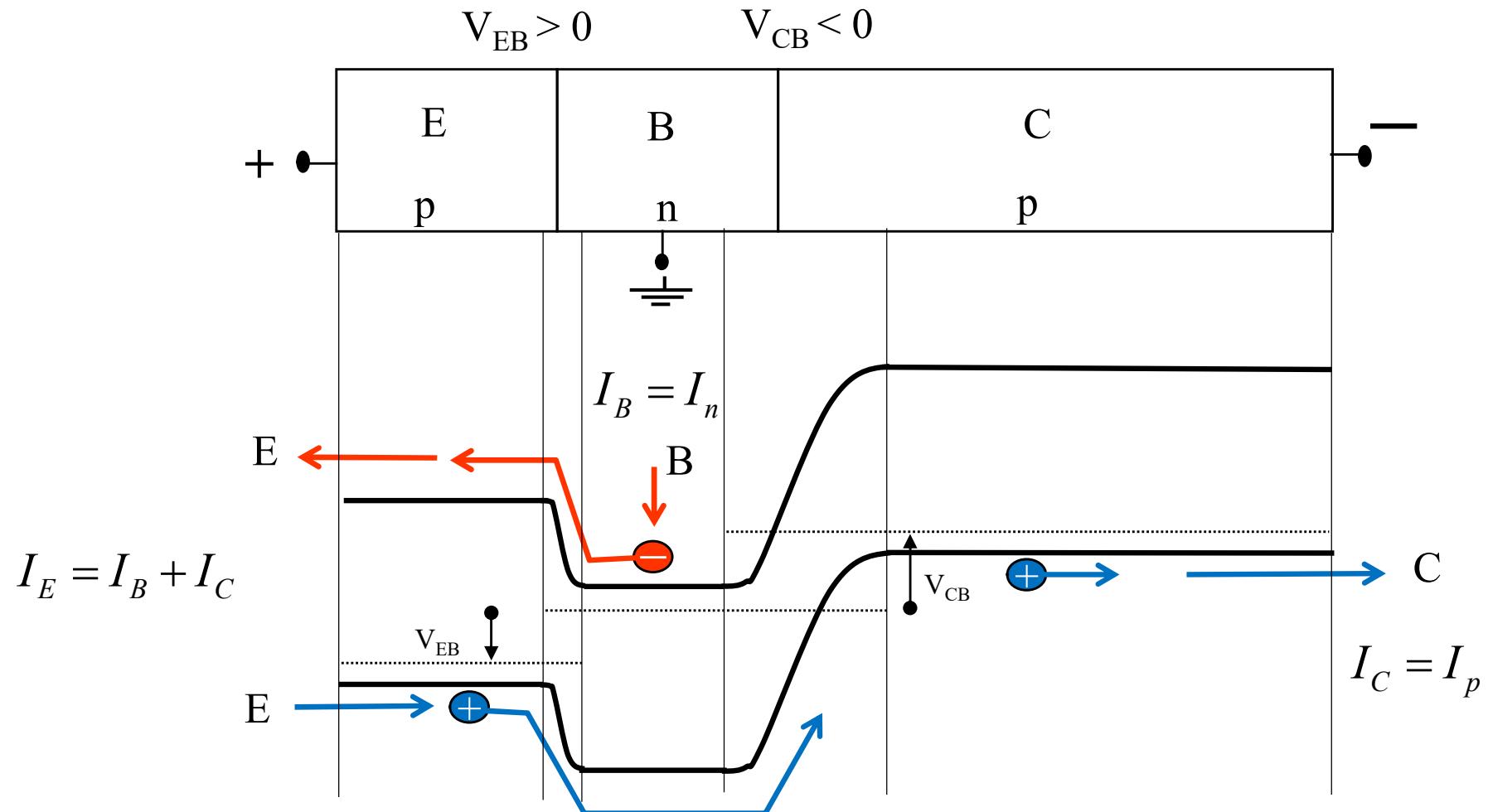
Modèle petits signaux en émetteur commun, mode actif



$$g_{BE} = \frac{q}{kT} I_B$$

$$g_m = \beta_F \cdot g_{BE} = \frac{q}{kT} I_C$$

$$g_{CE} = \lambda \cdot I_C \cong \frac{I_C}{|V_A|}$$

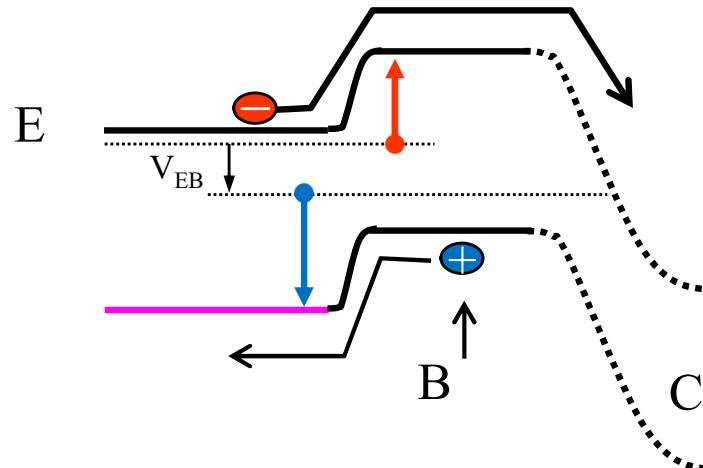


**HBT**

# Hétéro Bipolar Transistor

Homo-jonction

npn

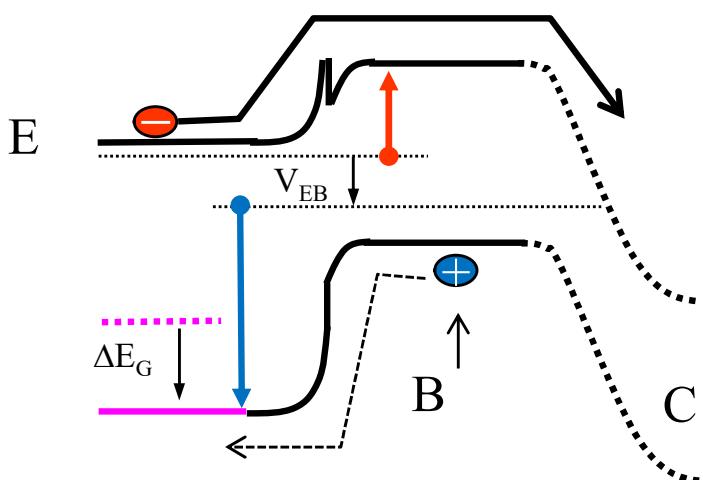


La barrière pour les électrons est plus petite que pour les trous à cause du dopage élevé dans l'émetteur.

→  $\beta_F$  élevé mais pas optimal.

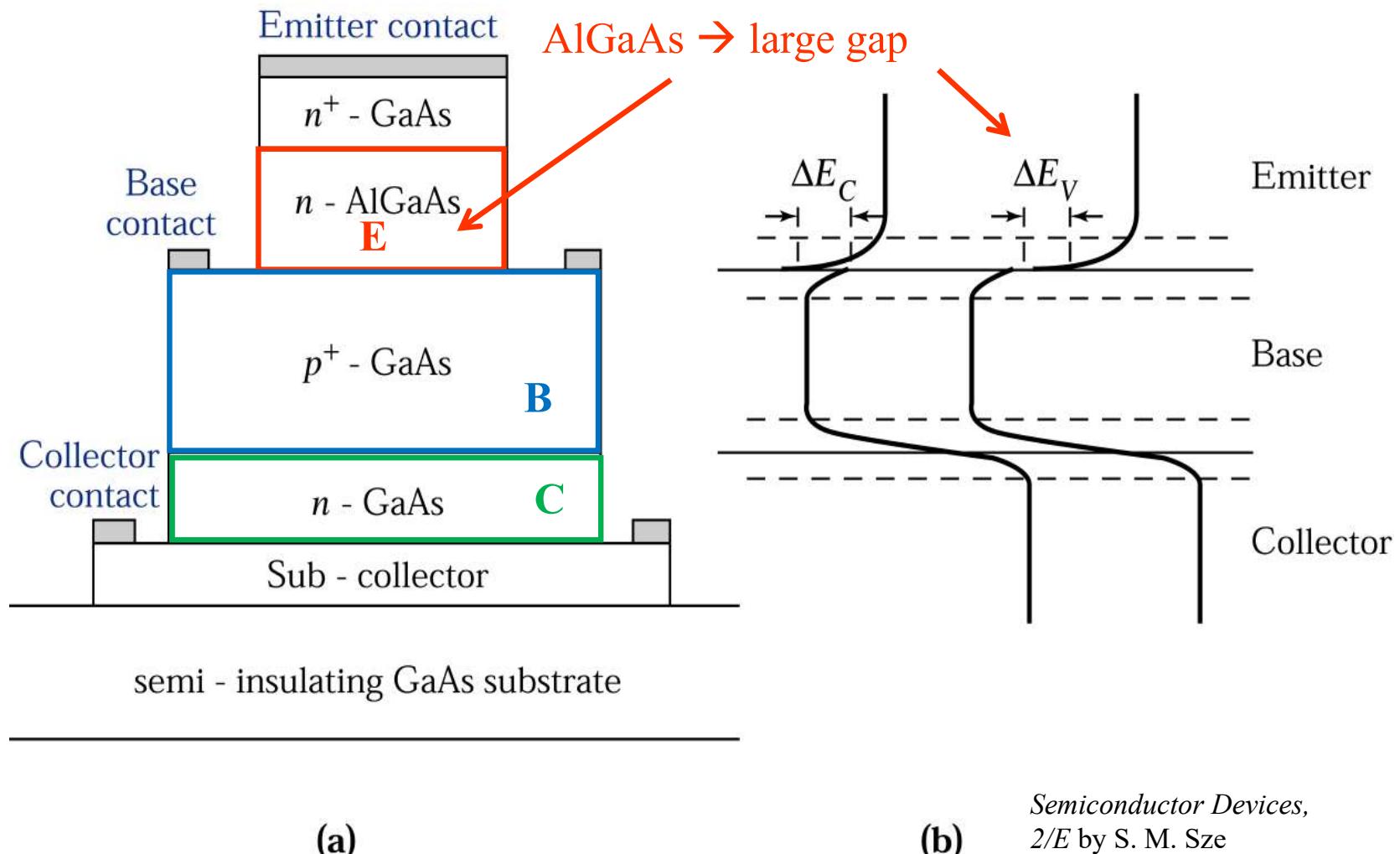
Hétéro-jonction

npn



La barrière pour les trous est augmentée par l'agrandissement du gap  $\Delta E_g$  dans l'émetteur.

→  $\beta_F$  optimal et très élevé.



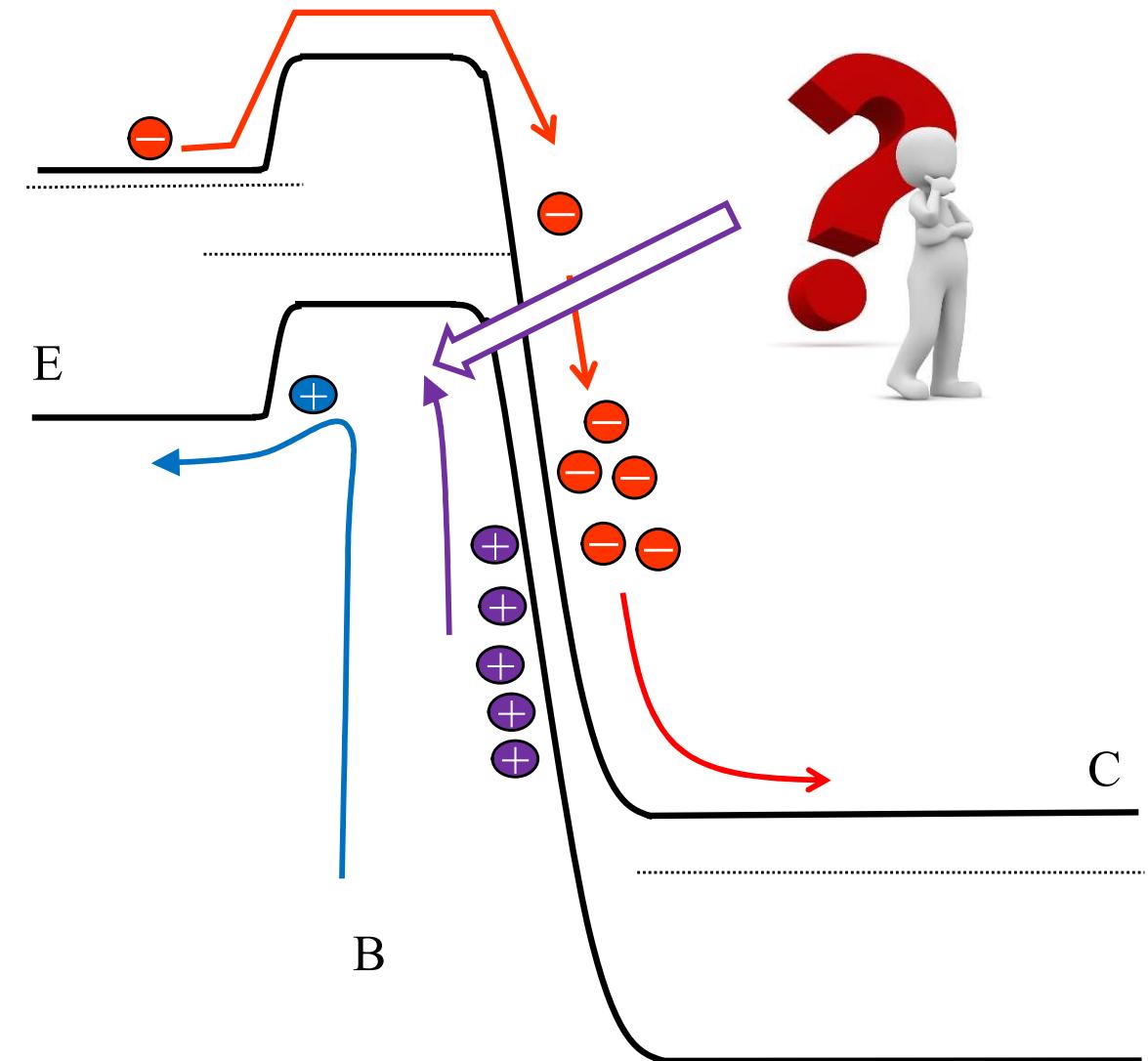
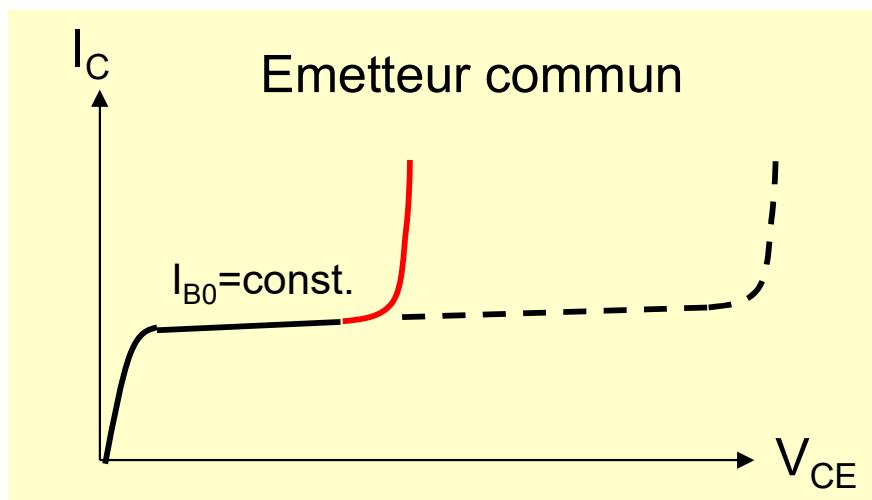
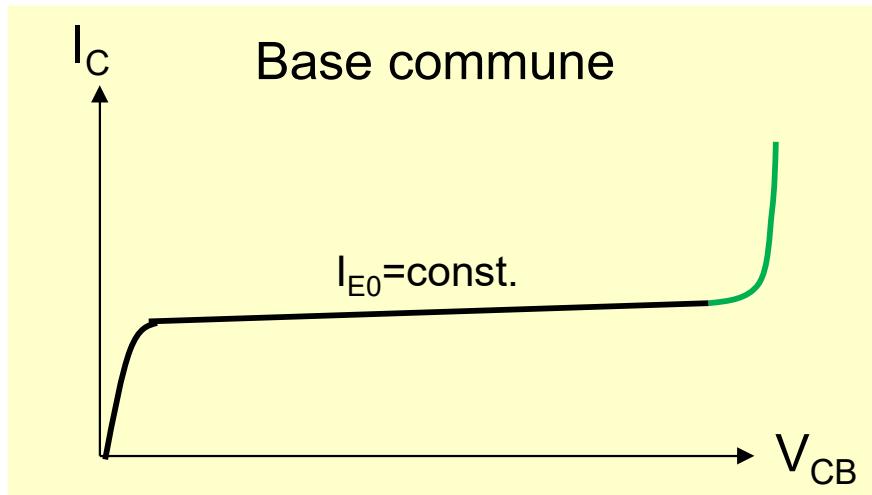
(a)

(b)

*Semiconductor Devices,  
2/E by S. M. Sze*

# BJT

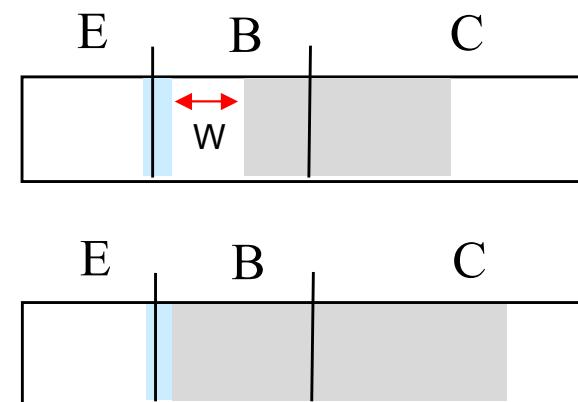
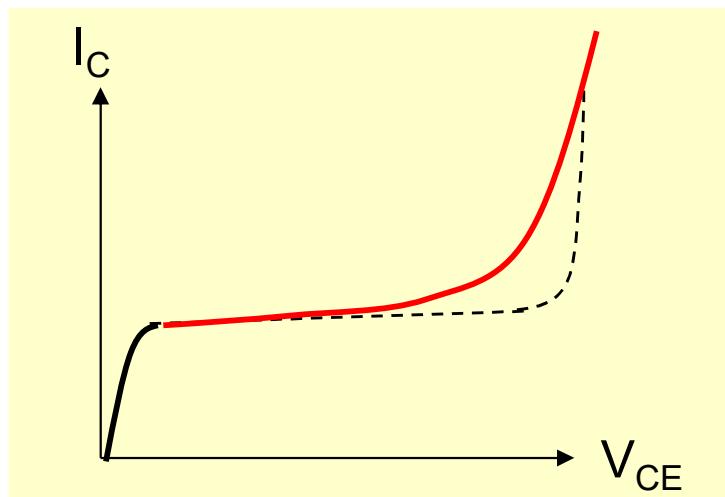
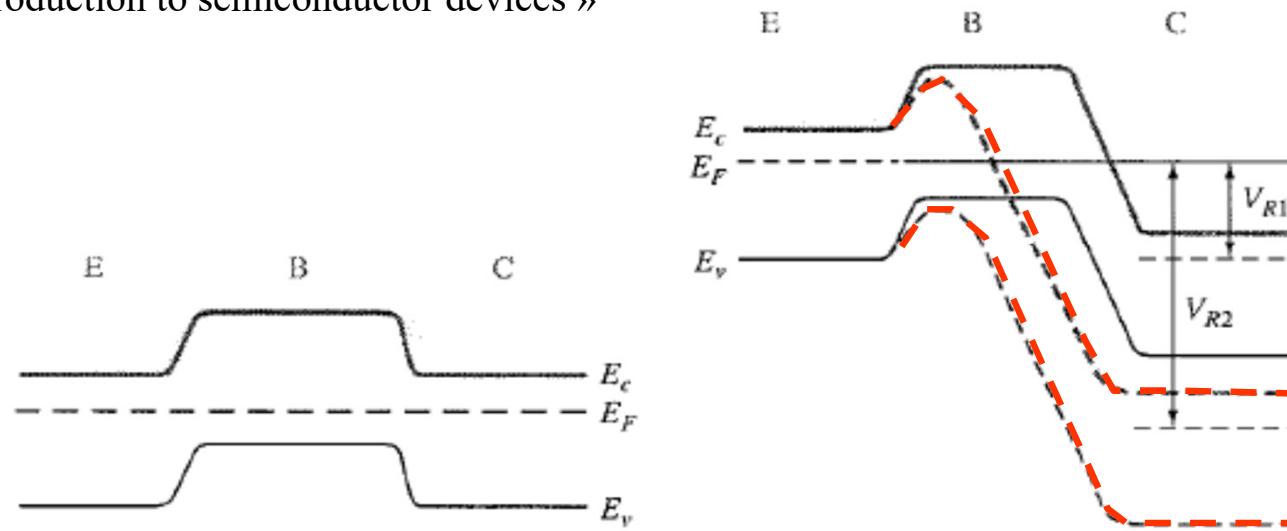
# Parasitic effects





## Punch-through

Neamen, « an introduction to semiconductor devices »

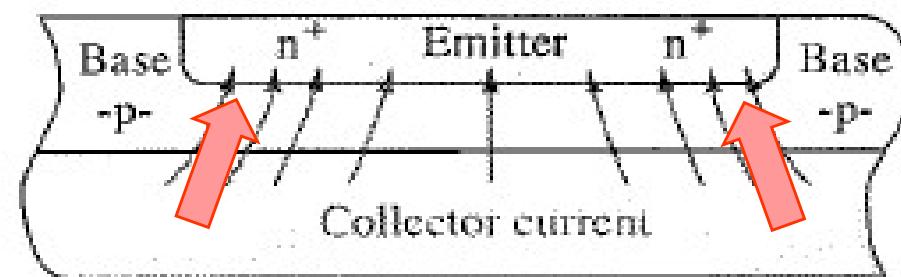
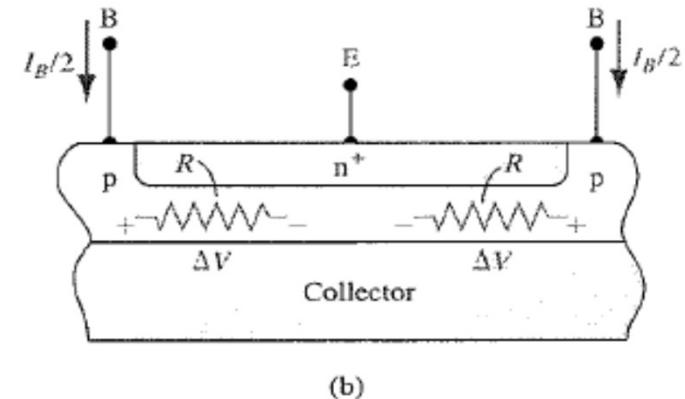
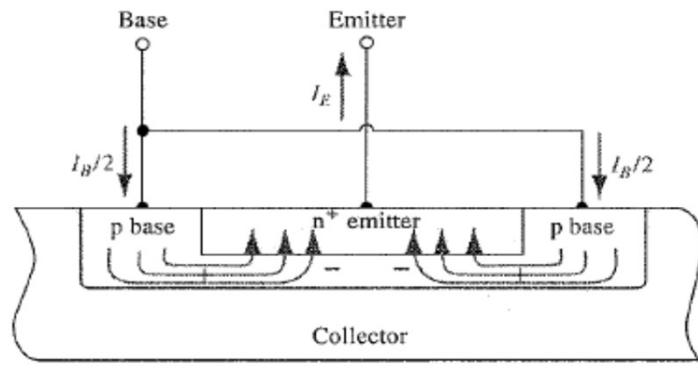


Normal

Punch-through

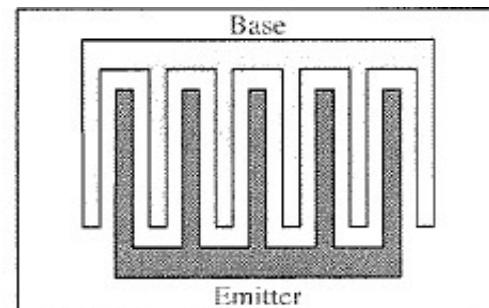


## Current crowding

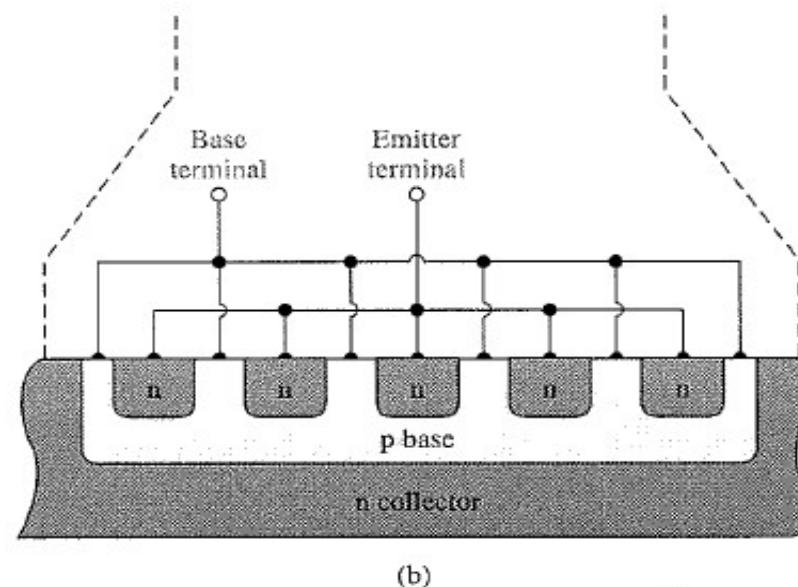


Neamen, « an introduction to semiconductor devices »

# Transistor BJT de puissance, structure en peigne



(a)



(b)

Neamen,  
« an introduction to  
semiconductor devices »



Répondez aux questions de réflexion ci-dessous :

Attention la première question utilise un pnp, la seconde un npn !

7.1b	<p>Esquissez le schéma de bandes d'un transistor bipolaire <b>pnp</b>. À partir de ce schéma, expliquez les concepts de gain en configurations « base commune » et « émetteur commun ». Comment optimiser le gain ? Quel est l'effet limitant et pourquoi ?</p>
7.5b	<p>Définissez la transconductance d'un transistor bipolaire en mode émetteur commun. Utilisez un transistor <b>npn</b> comme amplificateur de tension. Comment fixer le point de travail ? Comment introduire le signal AC ? Quel est le gain ? (Esquissez si possible une explication graphique).</p>