微电子器件物理
双极型晶体管

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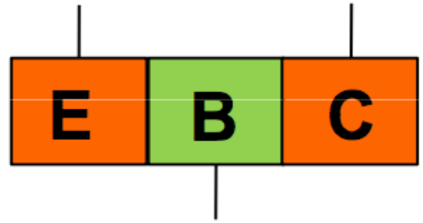
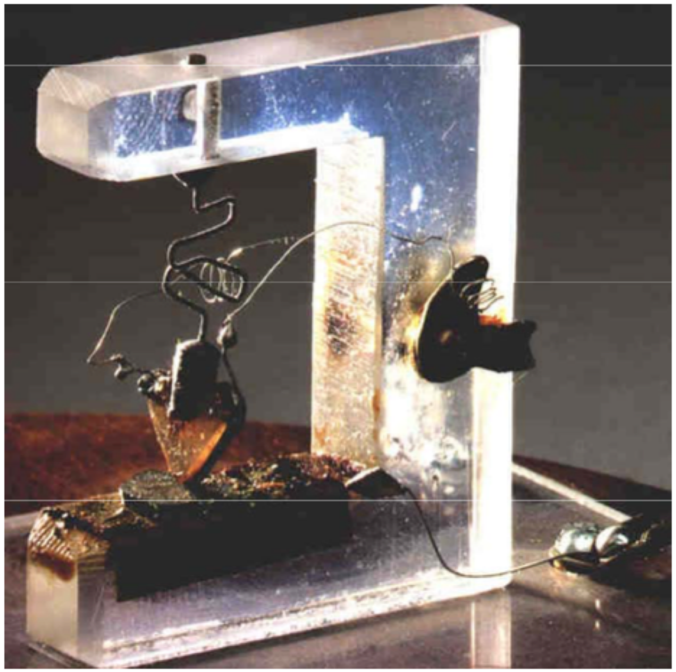
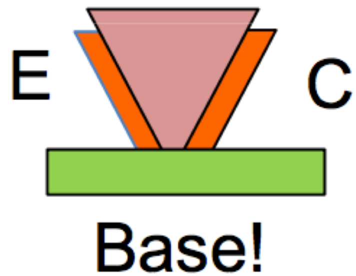
2020/12/04

Background



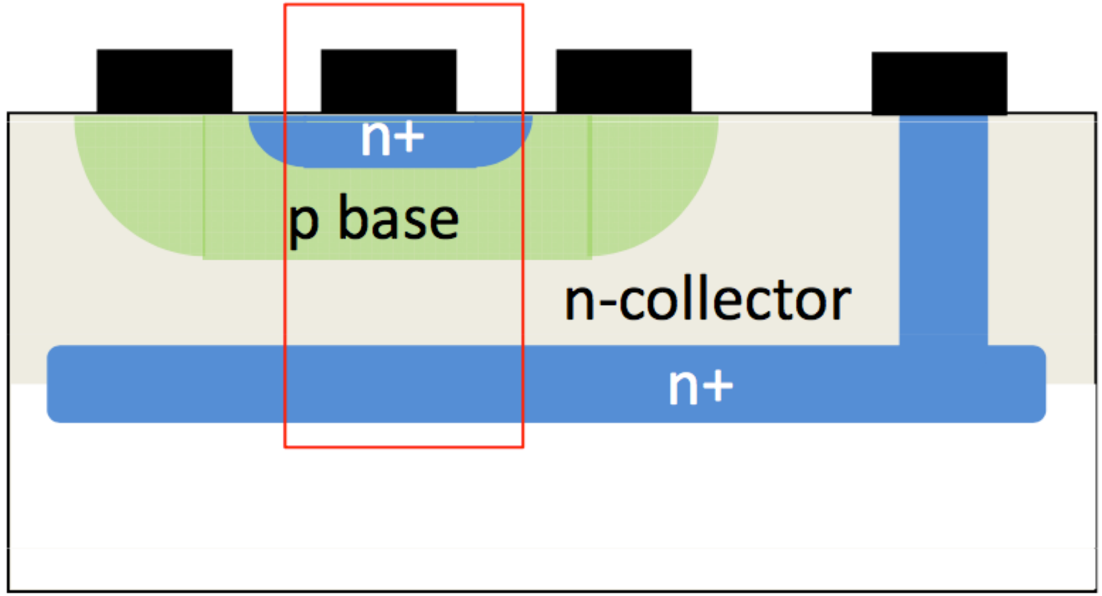


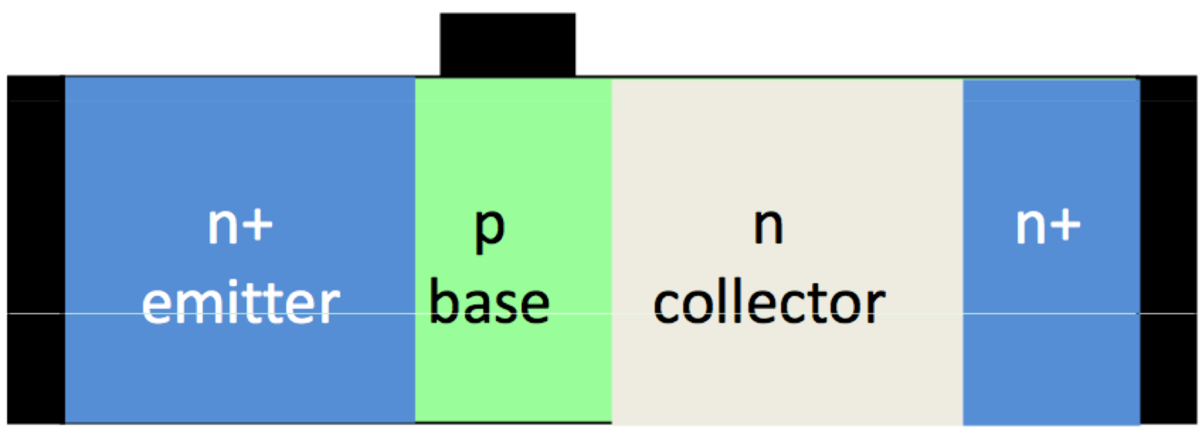


点接触型锗双极型晶体管

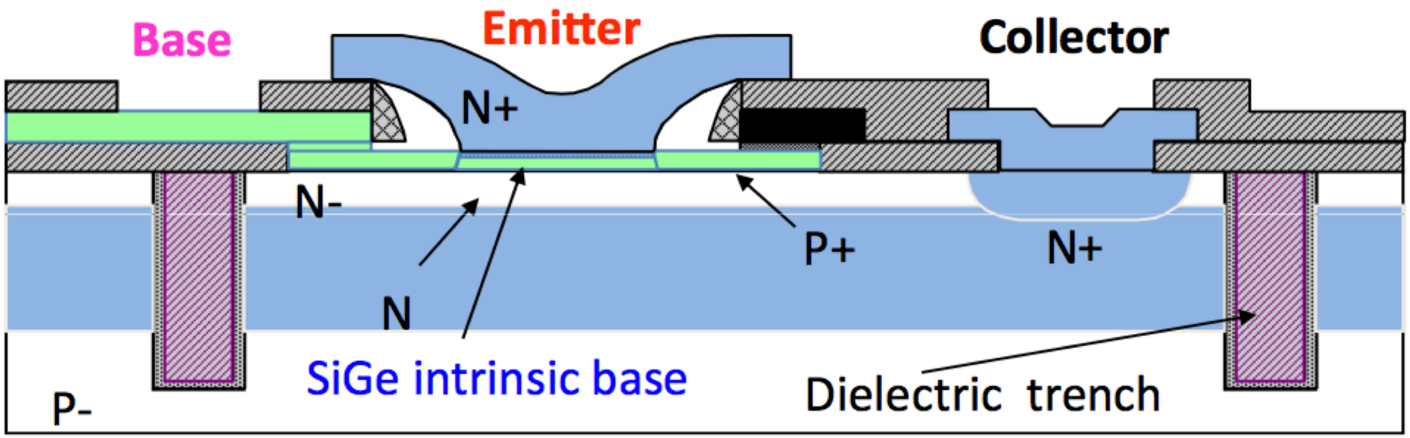
肖克莱的结型晶体管

双扩散双极型晶体管

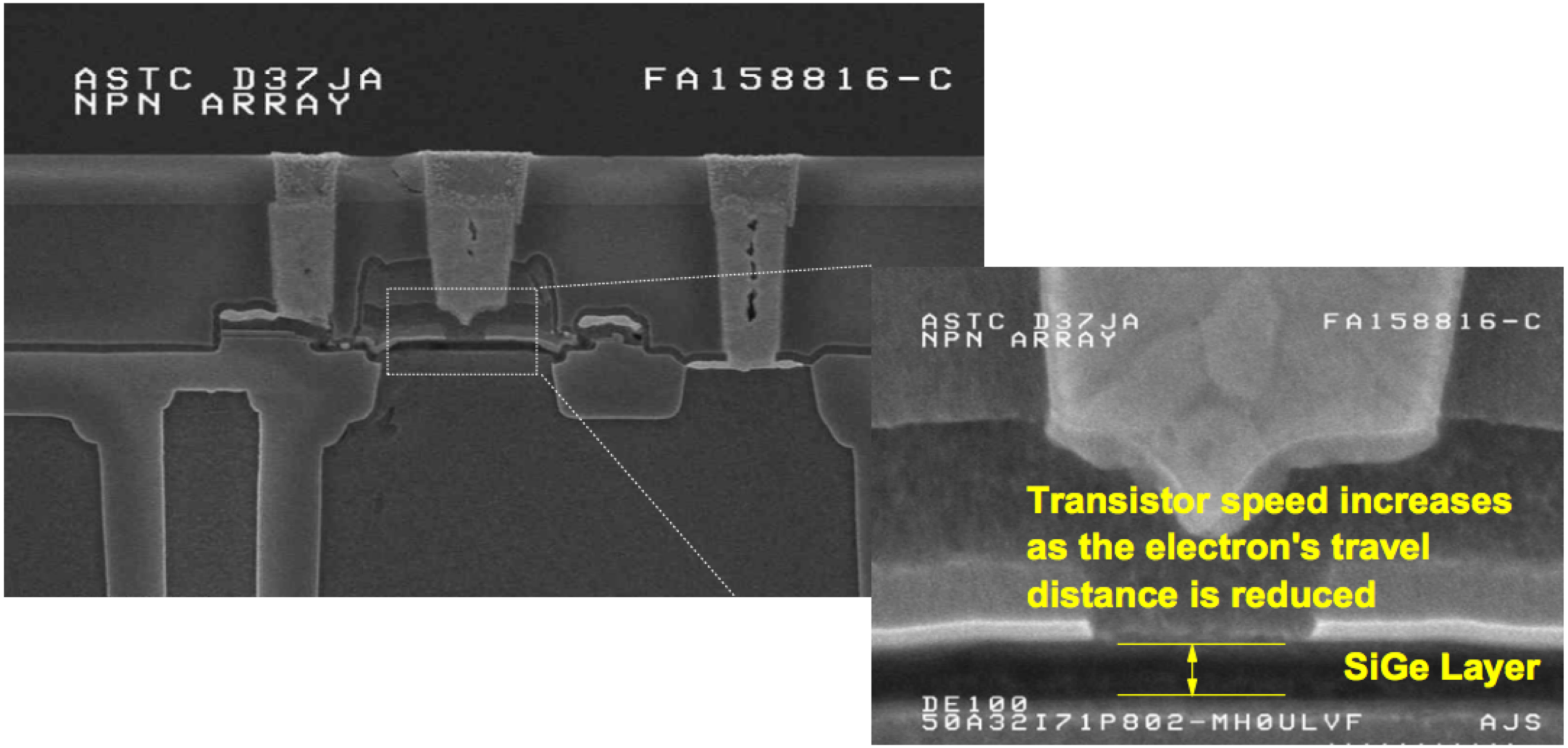




现代的双极型晶体管

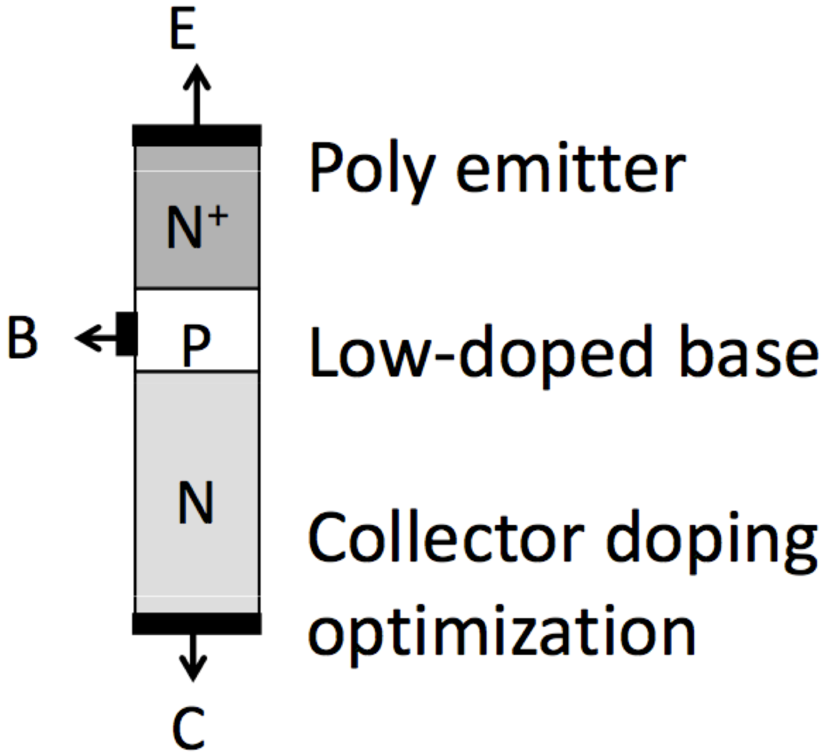


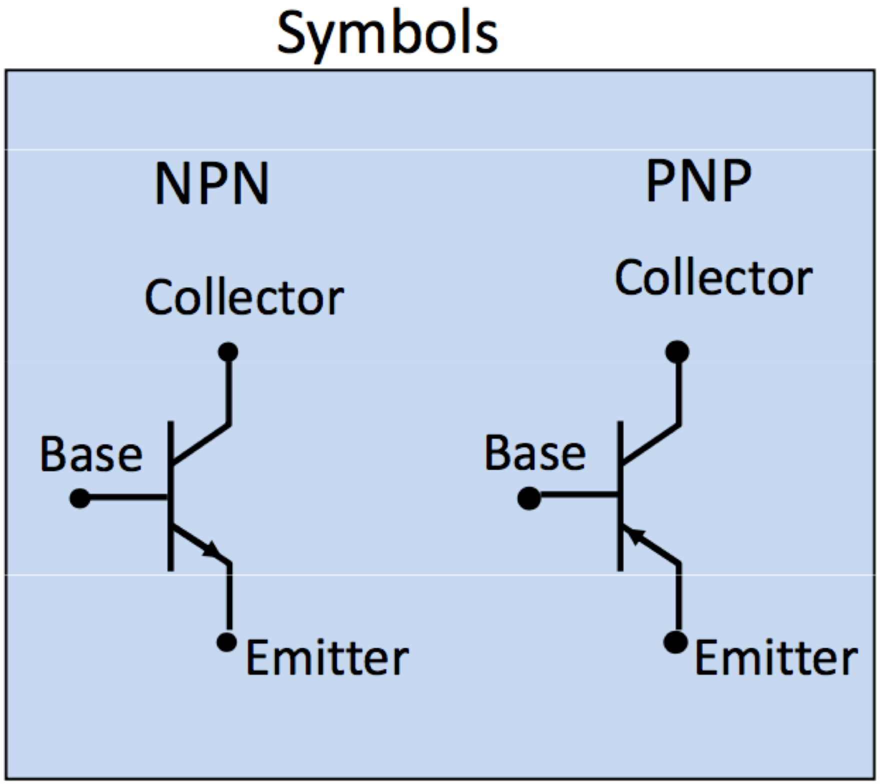
Base
Emitter
Collector
N+
N-
N
P+
N+
SiGe intrinsic base
Dielectric trench
P-



ASTC D37JA
NPN ARRAY
FA158816-C
ASTC D37JA
NPN ARRAY
FA158816-C
Transistor speed increases
as the electron's travel
distance is reduced
SiGe Layer
DE100
50A32I71P802-MH0ULVF
AJS

双极型晶体管的电路符号





$$I_C+I_B+I_E=0$$

$$V_{EB}+V_{BC}+V_{CE}=0$$

本节课提纲

1. 平衡态的能带图
2. 电流特性

平衡态的能带图

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

平衡态

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

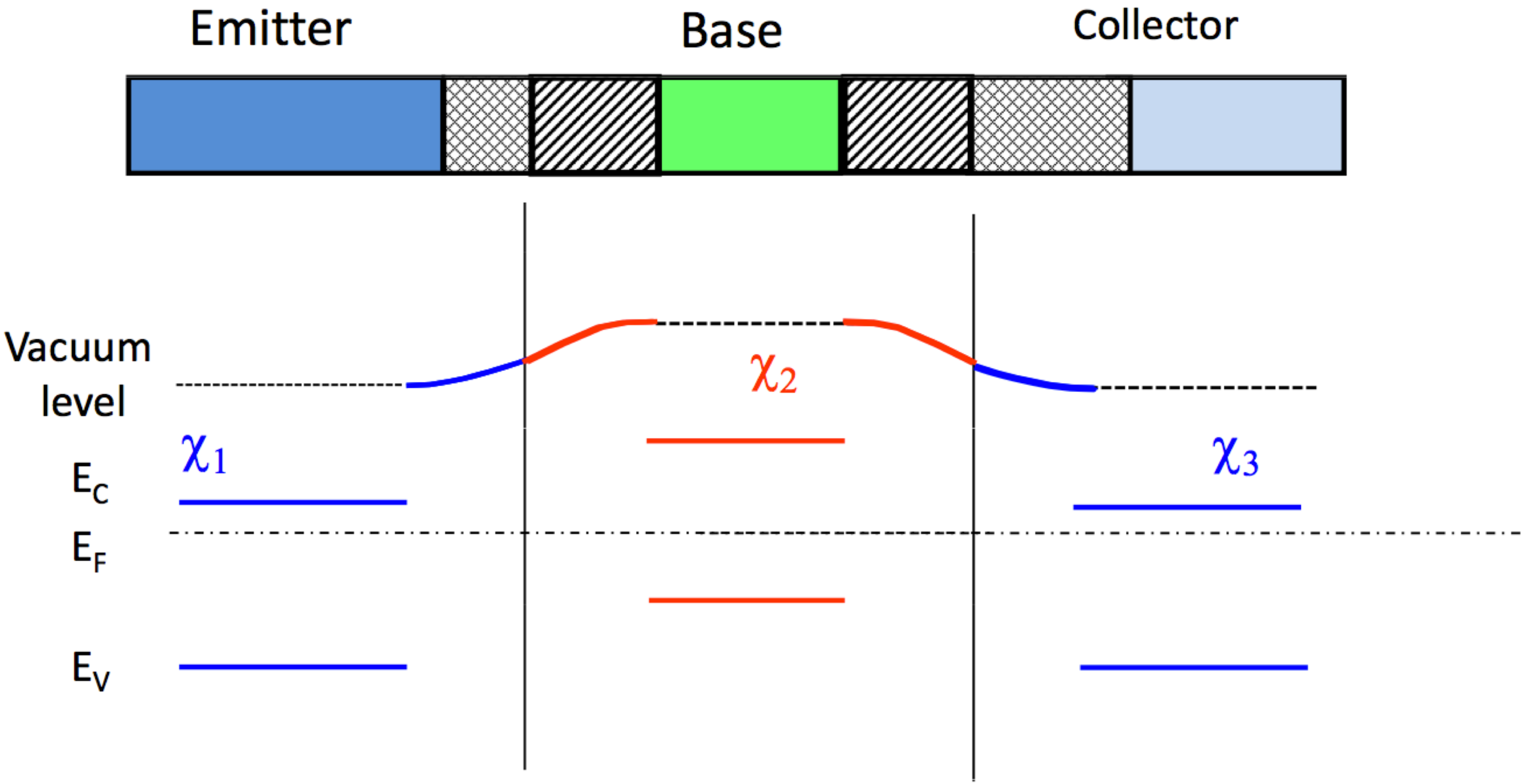
$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- Charge control model

平衡态的能带图



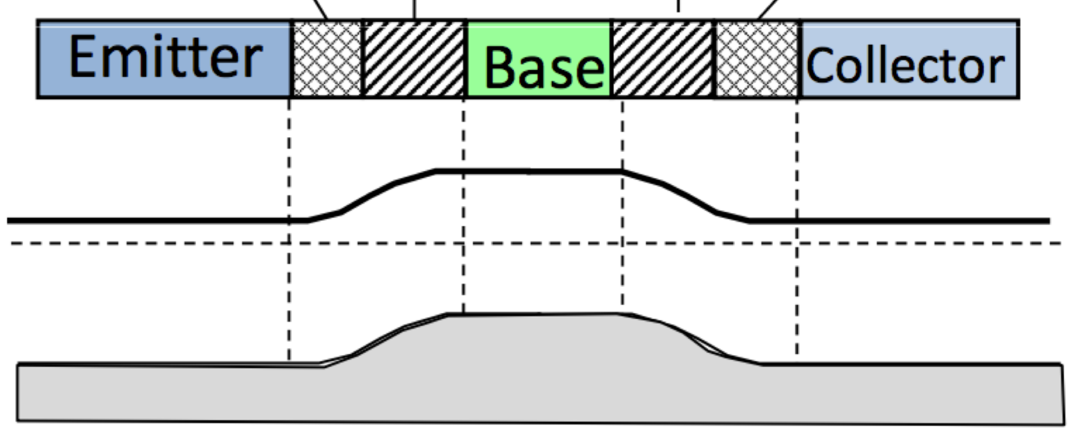
平衡态的电势

$$x_{p,BE}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}V_{bi}}$$

$$x_{p,BC}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}V_{bi}}$$

$$x_{n,E}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}V_{bi}}$$

$$x_{n,C}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_C\left(N_C+N_B\right)}V_{bi}}$$



本节课提纲

1. 平衡态的能带图
2. 电流特性

施加外加电压之后的能带图

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

非平衡态

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- Charge control model

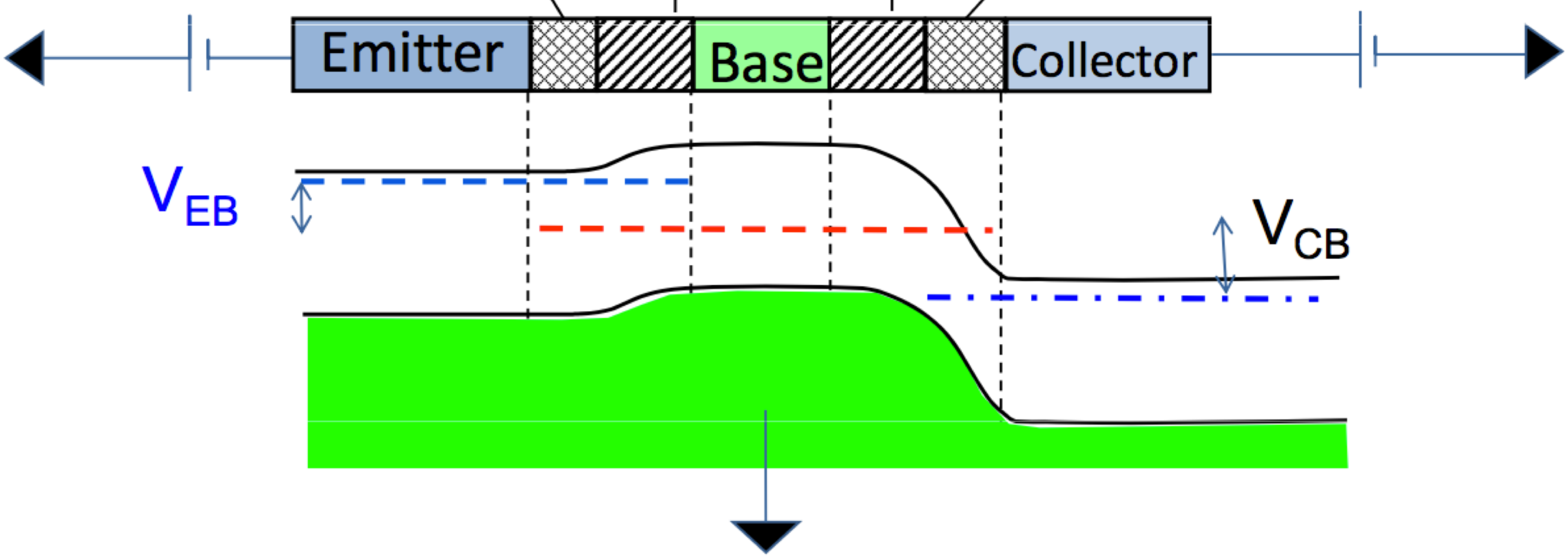
施加外加电压之后

$$x_{p,BE}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{EB}\right)}$$

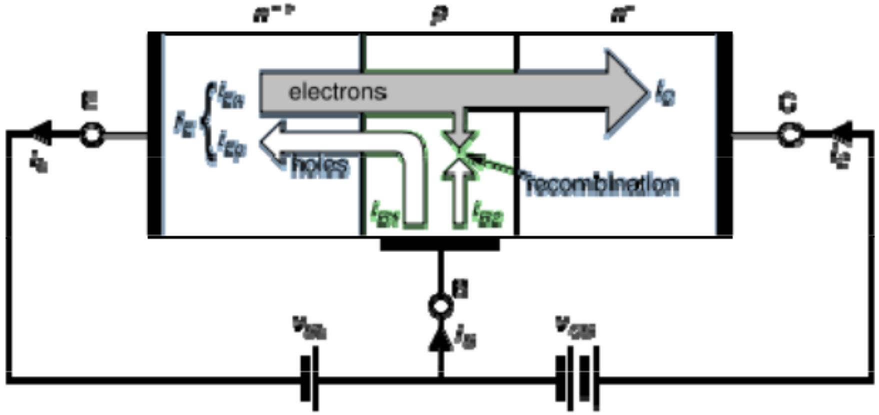
$$x_{p,BC}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$

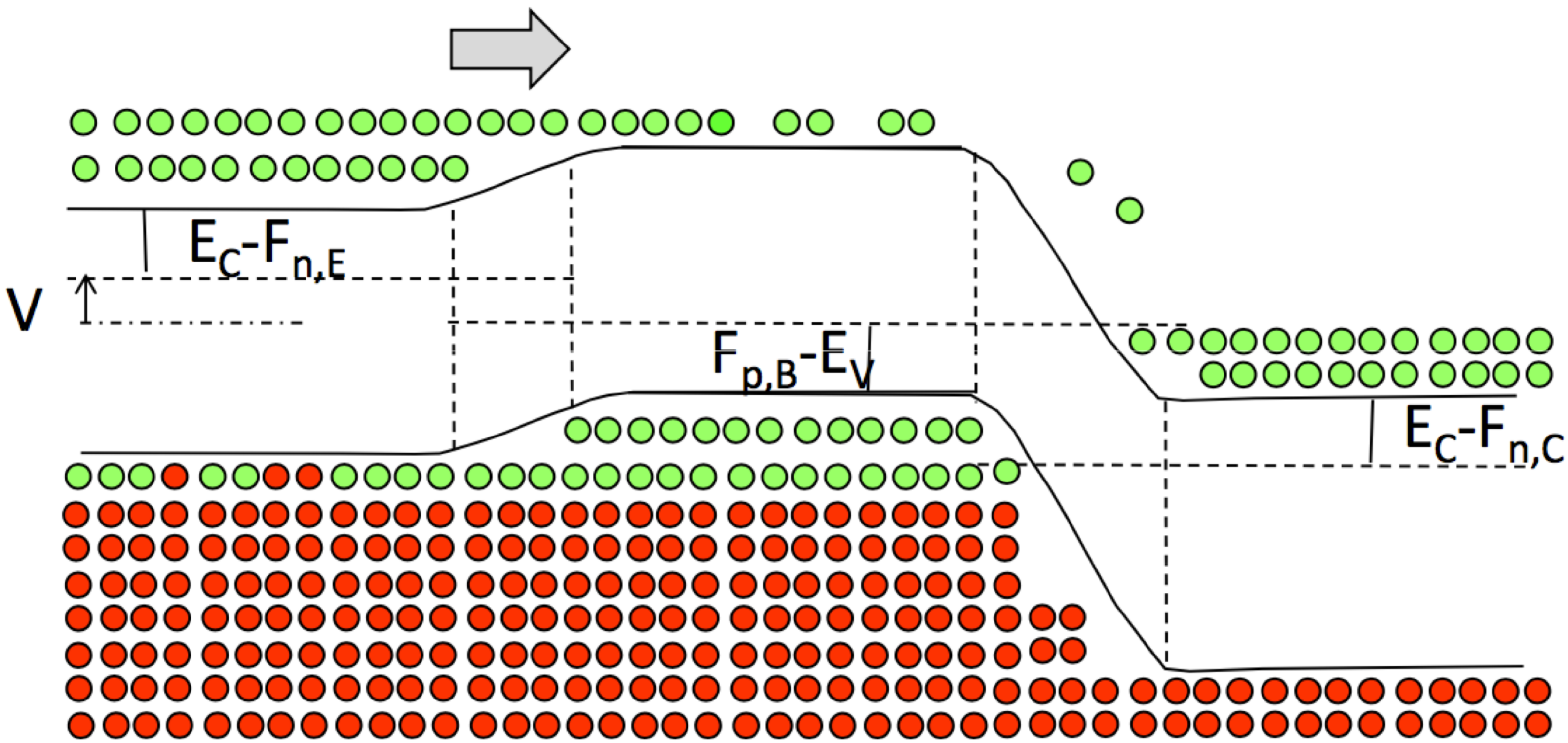
$$x_{n,E}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}\left(V_{bi}-V_{EB}\right)}$$

$$x_{n,C}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_C\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$

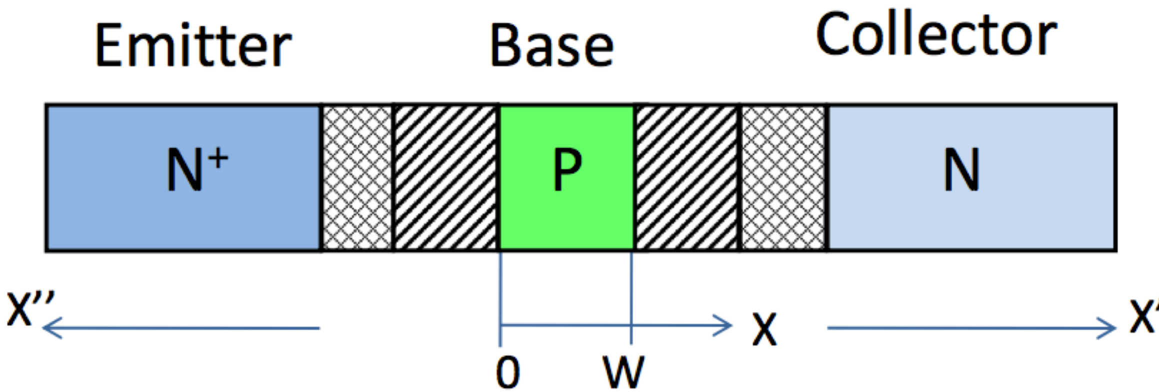


施加外加电压之后的电流





坐标与表示符号



$$N_E = N_{D,E} \qquad N_B = N_{A,B} \qquad N_C = N_{A,C}$$

$$D_E = D_P \qquad D_B = D_N \qquad D_C = D_N$$

$$n_{E0} = n_{p0} \qquad p_{B0} = p_{n0} \qquad n_{C0} = n_{n0}$$

基级的载流子分布

$$\Delta n(x) = Ax + B = C\left(1 - \frac{x}{W_B}\right) + D\left(\frac{x}{W_B}\right)$$

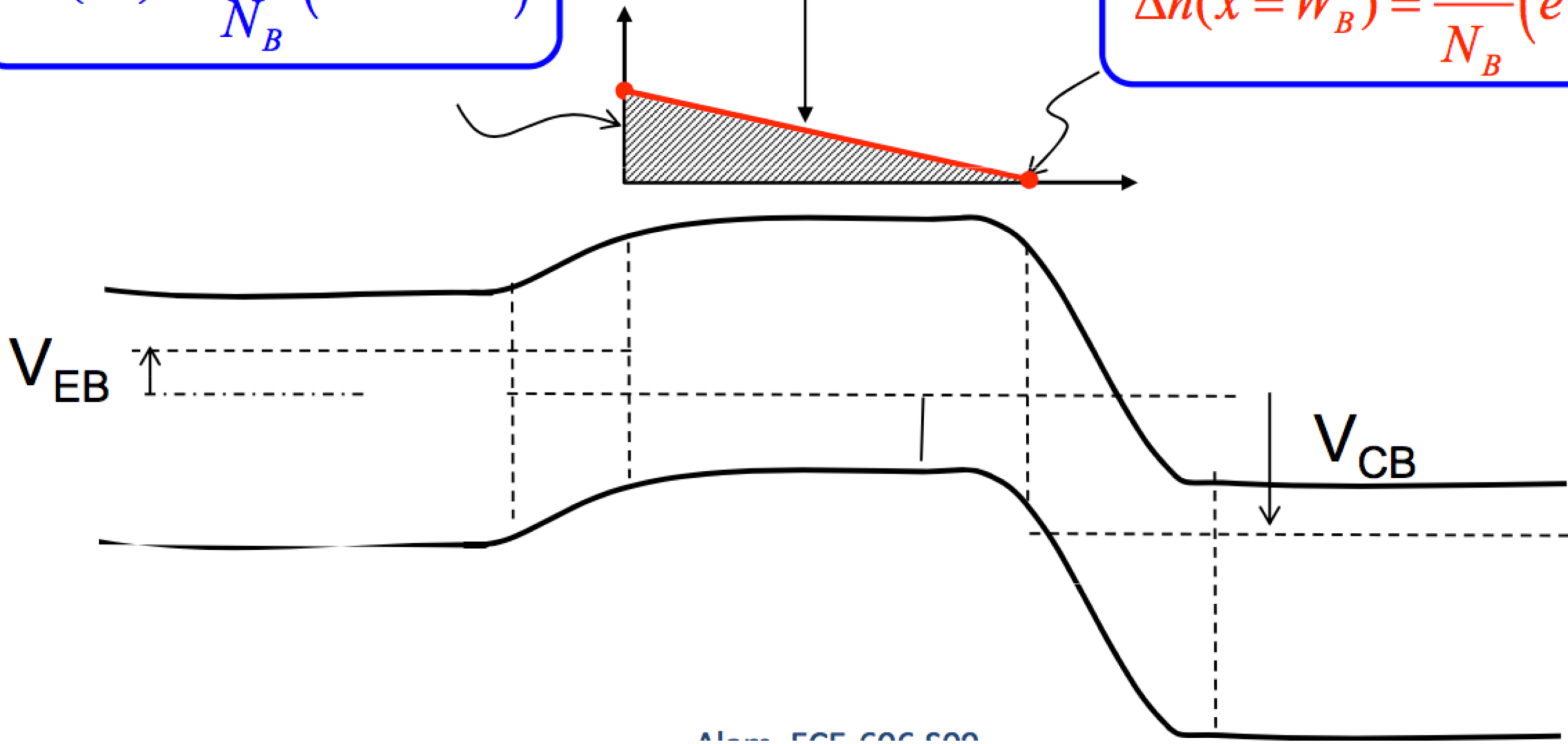
C

D

$$\Delta n(x) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)\left(1 - \frac{x}{W_B}\right) + \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta} - 1\right)\left(\frac{x}{W_B}\right)$$

$$\Delta n(0^+) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)$$

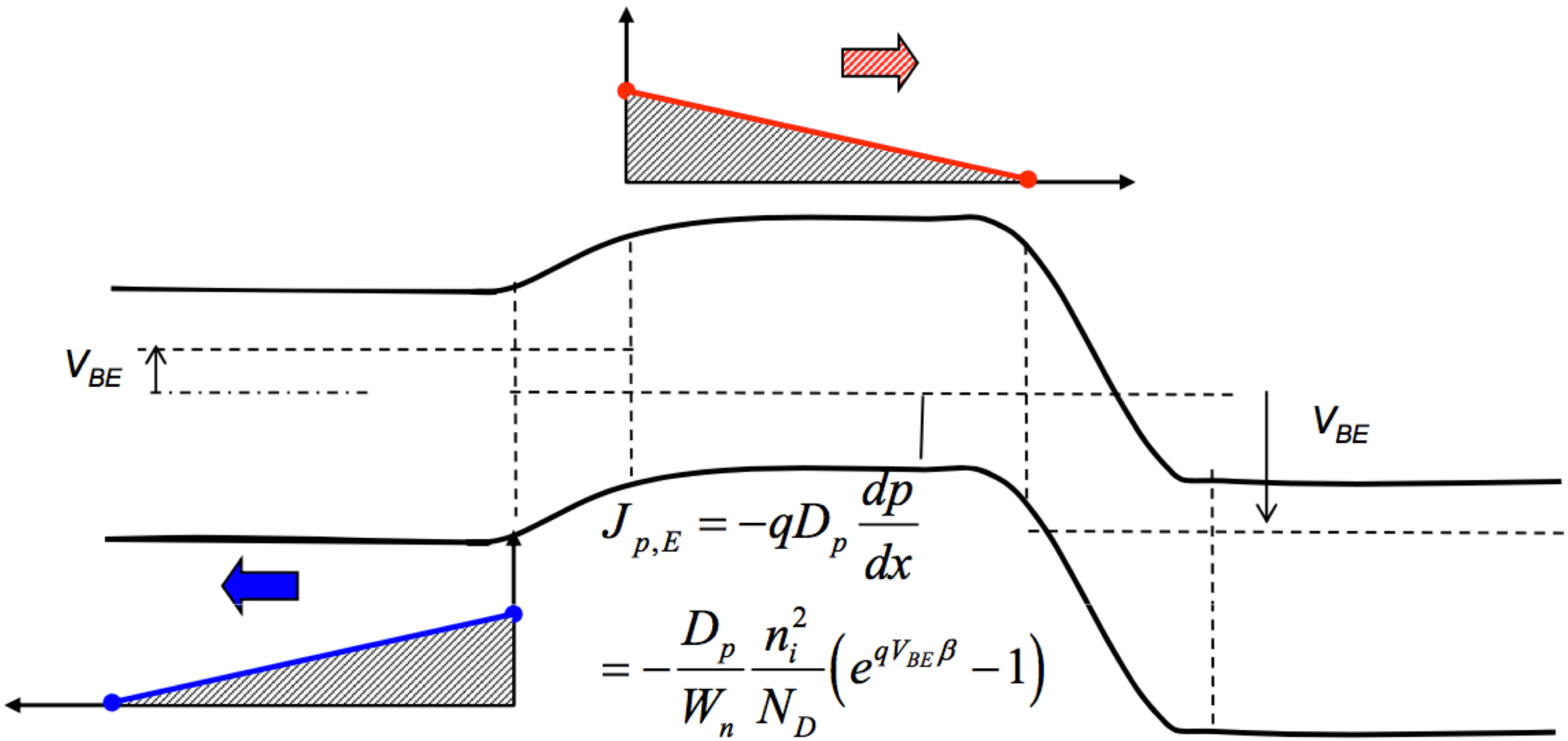
$$\Delta n(x = W_B) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta} - 1\right)$$



集电极和发射极的电流

$$\Delta n(x)=\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)\left(1-\frac{x}{W_B}\right)+\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)\left(\frac{x}{W_B}\right)$$

$$J_{n,C}=qD_n\left.\frac{dn}{dx}\right|_{W_B}=-\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$



$$J_{p,E}=-qD_p\frac{dp}{dx}$$

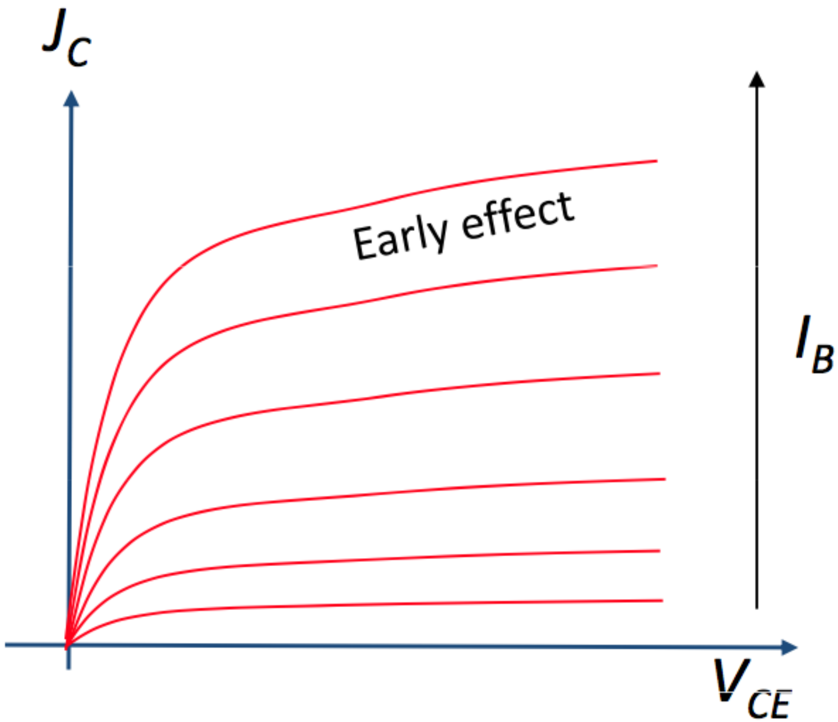
$$=-\frac{D_p}{W_n}\frac{n_i^2}{N_D}\left(e^{qV_{BE}\beta}-1\right)$$

电流特性曲线

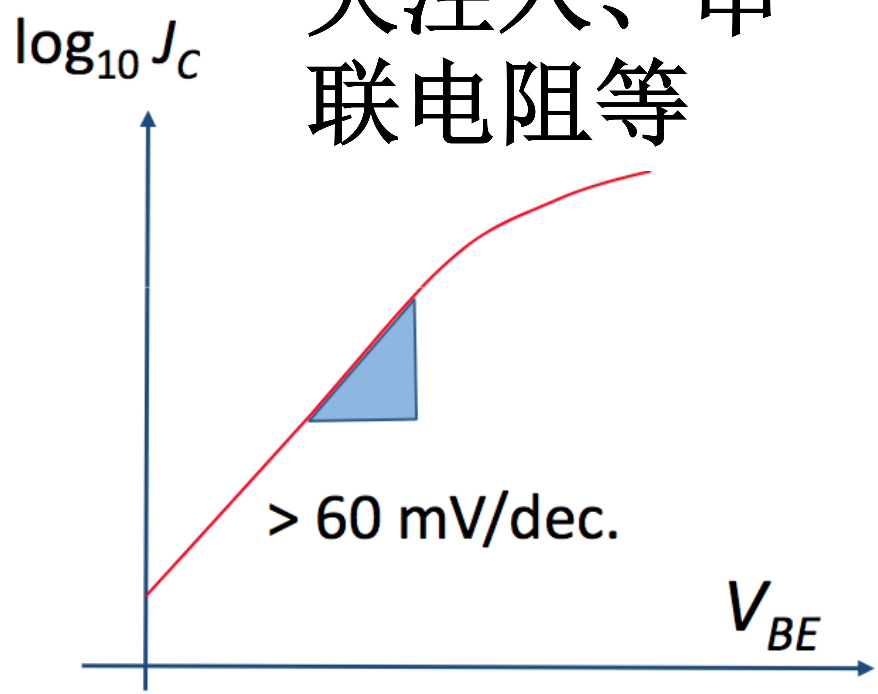
发射结：正偏

集电结：反偏

$$J_{n,C}=-\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$



大注入、串联电阻等



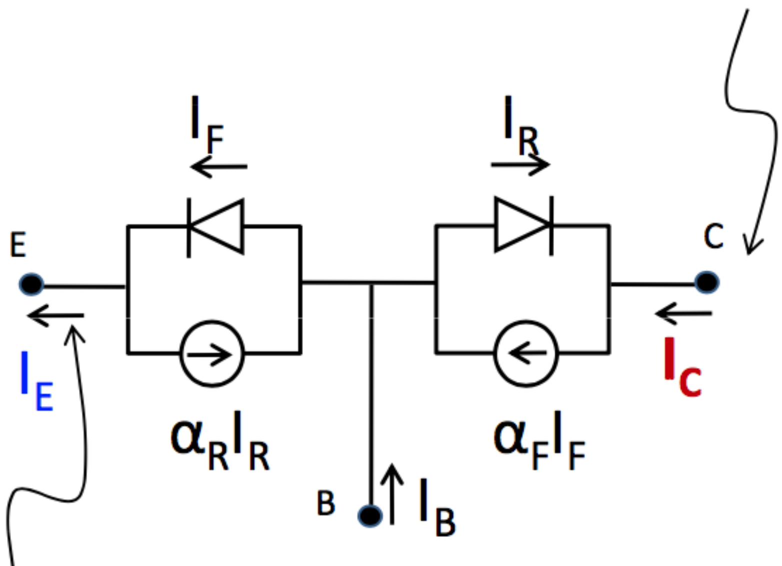
Have you seen this figure before?

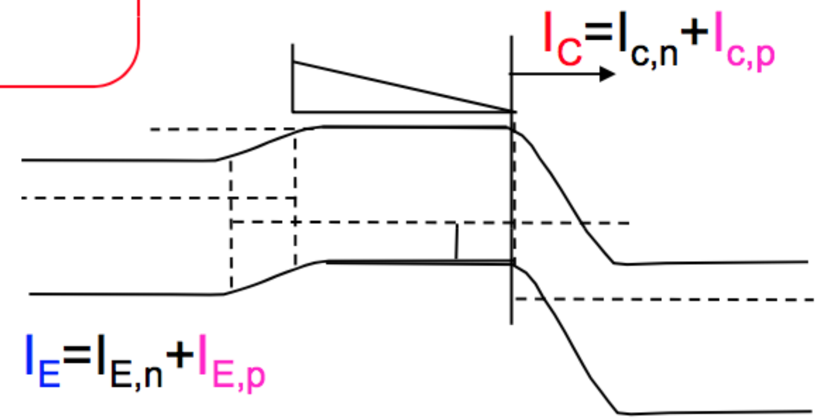
Ebers Moll Model

空穴在集电极中扩散

$$I_C = -A\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)+A\left[\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}+\frac{qD_p}{W_C}\frac{n_{i,C}^2}{N_C}\right]\left(e^{qV_{BC}\beta}-1\right)$$

$$\equiv \alpha_F I_{F0}\left(e^{qV_{BE}\beta}-1\right)-I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$





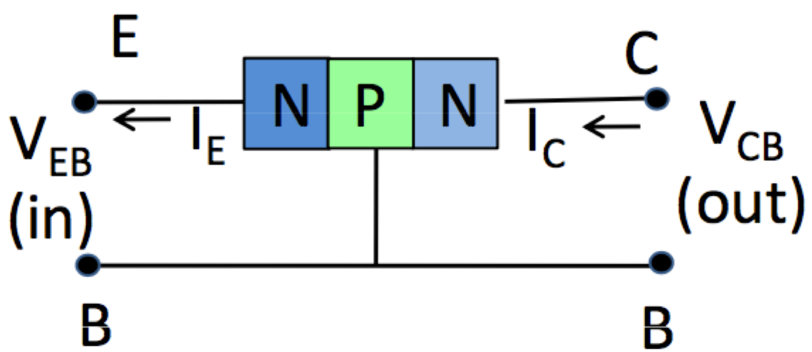
$$I_F = I_{F0}\left(e^{qV_{BE}\beta}-1\right)$$

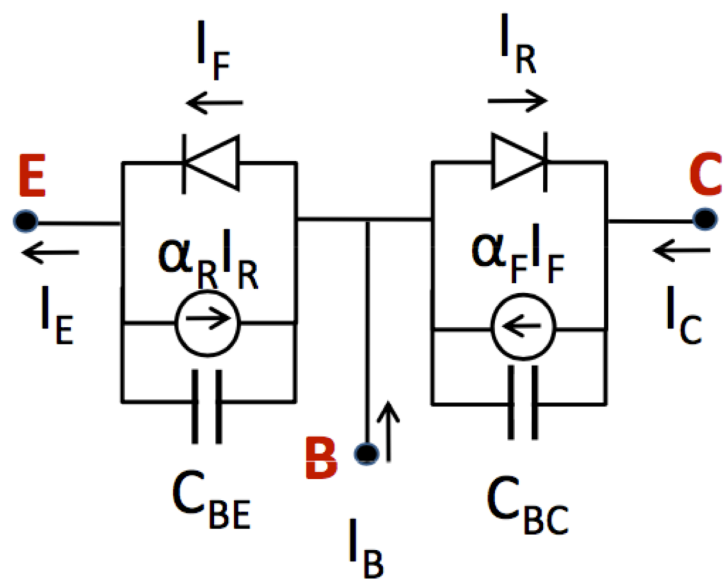
$$I_R = I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

$$I_E = -A\left[\frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\right]\left(e^{qV_{BE}\beta}-1\right)+A\frac{qD_n}{W_E}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$

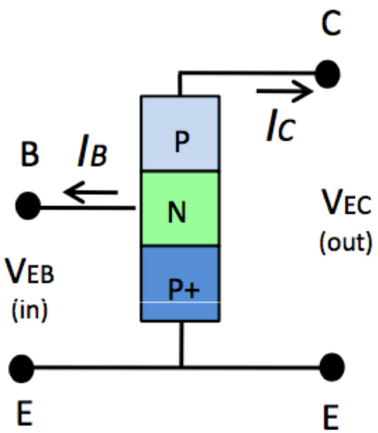
$$\equiv I_{F0}\left(e^{qV_{BE}\beta}-1\right)-\alpha_R I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

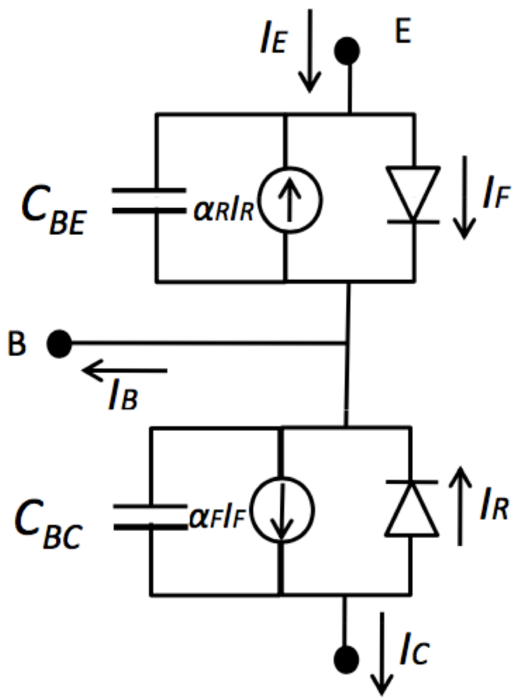
共基极连接

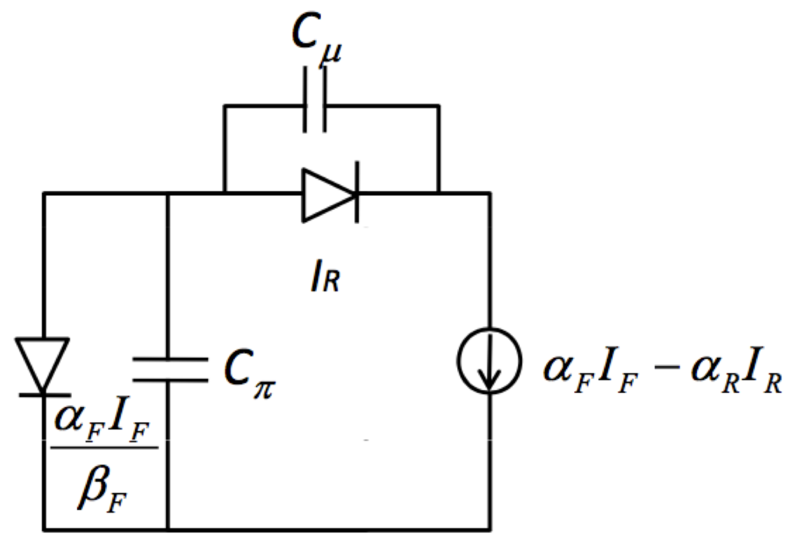

E
N
P
N
C
V_{EB}
(in)
I_E
I_C
V_{CB}
(out)
B
B


I_F
I_R
E
C
$\alpha_R I_R$
$\alpha_F I_F$
I_E
I_C
B
C_{BE}
C_{BC}
I_B

共发射极连接







$$\frac{\alpha_F I_F}{\beta_F} = \frac{\alpha_F I_F}{\frac{\alpha_F}{1-\alpha_F}} = (1-\alpha_F) I_F = I_B$$

Thanks!
Q&A