Semiconductor Physics

Chapter 5, Bipolar transistors

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Outline

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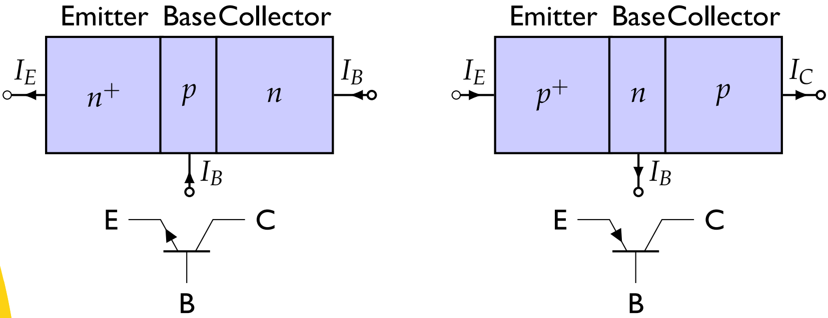
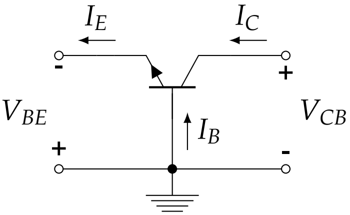
Static characteristics

Symbols and nomenclature: npn- and pnp-transistors



Static characteristics

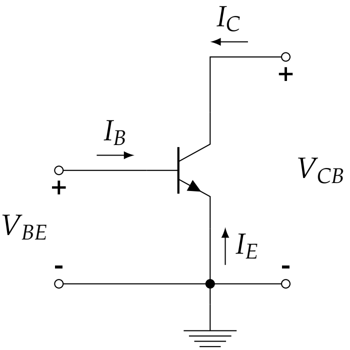
Biasing configurations



Common-Base

Static characteristics

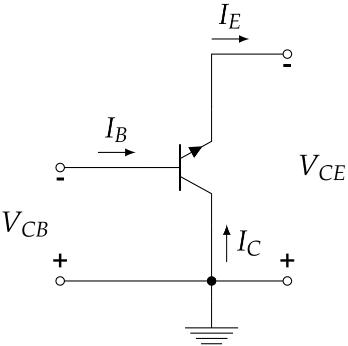
Biasing configurations



Common-Emitter

Static characteristics

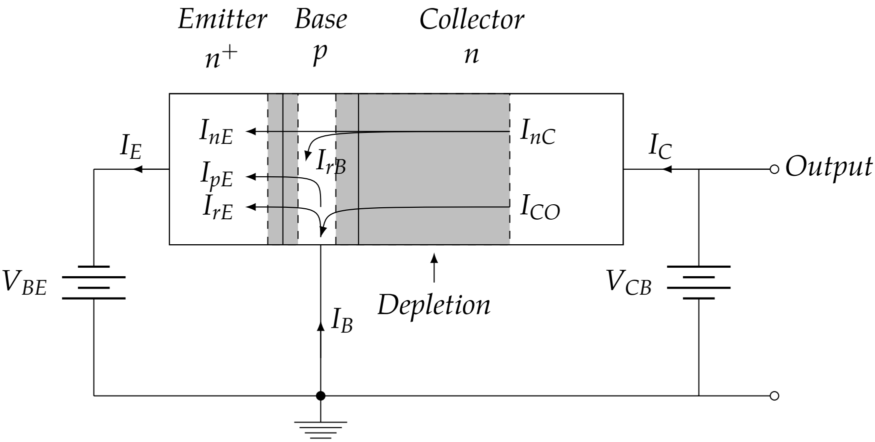
Biasing configurations



Common-Collector

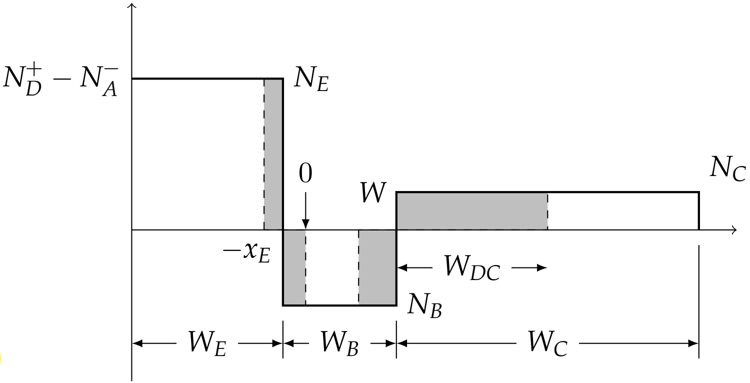
Static characteristics

Connection and biases in common-base configuration



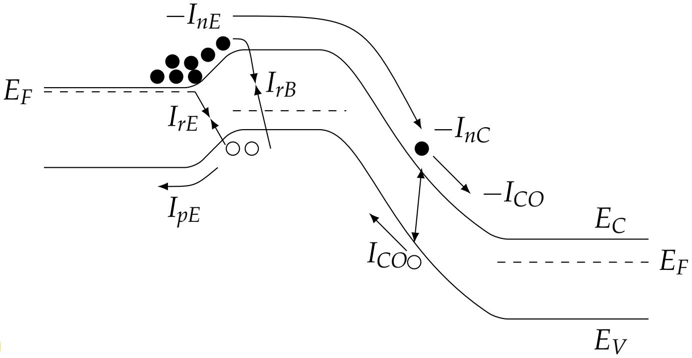
Static characteristics

Doping profiles and critical dimensions



Static characteristics

Energy band diagram of a npn transistor



Electron currents

Emitter and collector edge

$$
\begin{aligned}
0 &= -\frac{n_p - n_{po}}{\tau_n} + D_n \frac{d^2 n_p}{dx^2} \\
n_p(x) &= n_{po} + C_1 exp\left(\frac{x}{L_n}\right) + C_2 exp\left(\frac{-x}{L_n}\right)
\end{aligned}
$$

C_1 and C_2 are constants and $L_{\equiv}\sqrt{D_n \tau_n}$

$$
\begin{aligned}
C_1 &= \left\{ n_p(W) - n_{po} - \left[n_p(0) - n_{po} \right] exp\left(\frac{-W}{L_n}\right) \right\} / 2 \sinh \frac{W}{L_n} \\
C_2 &= \left\{ \left[n_p 0 - n_{po} \right] exp\left(\frac{W}{L_n}\right) \left[n_p(W) - n_{po} \right] \right\} / 2 \sinh \frac{W}{L_n}
\end{aligned}
$$

Electron currents

Emitter and collector edge

Boundary conditions for the two edges of the base:

$$\begin{aligned} n_p(0) &= n_{po} exp\left(\frac{qV_{BE}}{kT}\right) \\ n_p(W) &= n_{po} exp\left(\frac{qV_{BC}}{kT}\right) \\ I_{nE} &= \frac{A_E q D_n n_{po}}{L_n} coth \frac{W}{L_n} exp\left(\frac{qV_{BE}}{kT}\right) \\ I_{nC} &= \frac{A_E q D_n n_{po}}{L_n} cosech \frac{W}{L_n} exp\left(\frac{qV_{BE}}{kT}\right) \end{aligned}$$

The ratio of I_{nC}/I_{nE} is called **base transport factor** α_T

Electron currents

Emitter and collector edge

$$I_{nE} \approx I_{nC} \approx \frac{A_E q D_n n_{po}}{W} exp\left(\frac{qV_{BE}}{kT}\right) \approx \frac{A_E q D_n n_i^2}{W N_B} exp\left(\frac{qV_{BE}}{kT}\right)$$

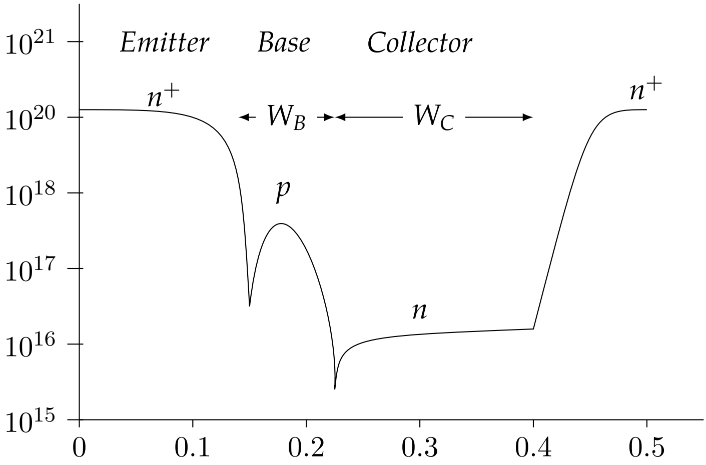
Can be reduced to:

$$I_{nE} \approx I_{nC} \approx \frac{2 A_E D_N Q_B}{W^2}$$

Q_B is the injected excess charge in the base:

$$Q_B = q \int_0^W [n_p(x) - n_{po}] dx$$

Doping profile



Electron Currents

A build-in electric field enhances electron transport.

$$p(x) \approx N_B(x) = n_i exp\left(\frac{E_i - E_F}{kT}\right)$$

built-in field

$$\mathscr{E}(x) = \frac{dE_i}{qdx} = \frac{kT}{qN_B}\frac{dN_B}{dx}$$

Electron Currents

$$I_n(x) = A_E q \left(\mu_n \mu_p \mathscr{E} + D_n \frac{dn_p}{dx} \right)$$

substituting $\mathscr{E}$

$$I_n(x) = A_E q D_n \left(\frac{n_p}{N_B} \frac{dN_B}{dx} + \frac{dn_p}{dx} \right)$$

steady state solution with boundary condition $n_p(W) = 0$

$$n_p(x) = \frac{I_n(x)}{A_E q D_n N_B(x)} \int_x^W N_B(x) dx$$

Electron Currents

total impurity dose per area in the base

$$N_b^{\prime} \equiv \int_x^W N_B(x)dx$$

called Gummel number. (Si: $10^{12}\, to\, 10^{13} cm^{-2}$)

Hole Currents

diffusion current injected from base to emitter

$$I_{pE} = \frac{A_E q D_p E p_{noE}}{W_E} \left[exp\left(\frac{qV_{BE}}{kT}\right) - 1 \right]$$

Recombination

- Shockley-Read-Hall recombination
- Auger recombination

$$\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_A}$$

Base-emitter recombination

$$I_{rE} \propto \frac{1}{\tau} exp\left(\frac{qV_{BE}}{mkT}\right)$$

Collector base junction

$$I_{CO} \approx A_C q \left(\frac{D_{pC} p_{noC}}{W_C - W_{DC}} + \frac{D_n n_{po}}{W} \right)$$

Current gain

$$\begin{aligned} I_E &= I_{nE} + I_{rE} + I_{pE} \\ I_C &= I_{nC} + I_{CO} \\ I_B &= I_{pE} + I_{rE} + (I_{nE} - I_{nC}) - I_{CO} \end{aligned}$$

It holds true that

$$I_E = I_C + I_B$$

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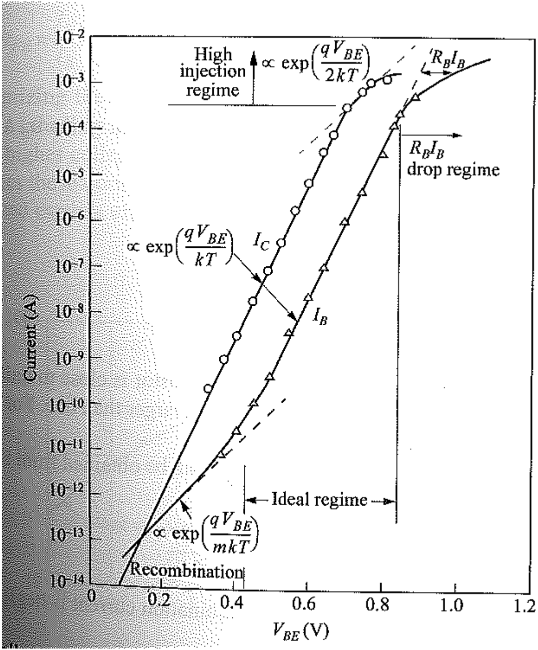


Current (A)
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
0
0.2
0.4
0.6
0.8
1.0
1.2
V_{BE} (V)
High injection regime
$\propto \exp\left(\frac{qV_{BE}}{2kT}\right)$
$R_B I_B$
$R_B I_B$ drop regime
$\propto \exp\left(\frac{qV_{BE}}{kT}\right)$
I_C
I_B
Ideal regime
$\propto \exp\left(\frac{qV_{BE}}{mkT}\right)$
Recombination

Parameters for a bipolar transistor

Parameters for a Bipolar Transistor	
Emitter injection efficiency	$\gamma \equiv I_{nE}/I_E$
Base transport factor	$\alpha_T \equiv I_{nC}/I_{nE}$
Common-base current gain, h_{FB}	$\alpha_0 \equiv I_{nC}/I_E = \gamma\alpha_T \approx I_C/I_E$
" small signal h_{fb}	$\alpha \equiv dI_C/dI_E$
Common-emitter current gain, h_{FE}	$\beta_0 \equiv \alpha_0/(1-\alpha_0) \approx I_C/I_B$
" small signal h_{fe}	$\beta \equiv dI_C/dI_E$

Parameters for a bipolar transistor

Common base current gain

I_{CBO}

$$\alpha_0 \equiv h_{FB} = \frac{I_C - I_{CB0}}{I_E} = \frac{I_{nC}}{I_E} = \frac{I_{nC}}{I_nE}\frac{I_{nE}}{I_E} = \alpha_T \gamma$$

γ is defined as emitter injection efficiency

Parameters for a bipolar transistor

Common emitter configuration

$$I_C = \beta_0 I_B + I_{CEO}$$

I_{CEO} is I_{CO} when $I_B = 0$, or open base:

$$\begin{aligned} I_C &= \alpha_0(I_B + I_{CO}) + I_{CBO} \\ &= \frac{\alpha_0}{1-\alpha_0} I_B + \frac{I_{CBO}}{1-\alpha_0} \\ \Rightarrow & \quad \beta_0 \equiv h_{FE} = \frac{\alpha_0}{1-\alpha_0} \end{aligned}$$

Parameters for a bipolar transistor

Base transport factor, emitter injection efficiency

Base transport factor

$$\alpha_T \equiv \frac{I_{nC}}{I_{nE}} = \frac{1}{\cosh(W/L_n)} \approx 1 - \frac{W}{2L_n^2}$$

Emitter injection efficiency

$$\gamma \equiv \frac{I_{nE}}{I_E} \approx \frac{I_{nE}}{I_{nE} + I_{pE}} \approx \left[1 + \frac{p_{noE} D_{pE} L_n}{N_{PO} D_n W_E} \tanh\left(\frac{W}{L_n}\right)\right]^{-1}$$

$$h_{FE} = \frac{\gamma}{1-\gamma} = \frac{n_{po} D_n W_E}{p_{noE} D_{pE} L_n} \coth\left(\frac{W}{L_n}\right) \propto \frac{n_{po}}{p_{noE} W} \propto \frac{N_E}{N_B W} \propto \frac{N_E}{N_b^{‘}}$$

Output Characteristics

1. applied voltages control the boundary densities through the term $exp(qv/kT)$
2. emitter and collector currents are given by minority density gradients at x=0 and x=W (junction boundaries)
3. base current is the difference between emitter and collector current

Nonideal Effects

Emitter bandgap narrowing

To improve h_{FE}, the emitter should be much more heavily doped than the base, that is $N_E >> N_B$.At high doping concentrations bandgap narrowing has to be considered.
Bandgap reduction:

$$\Delta E_g = 18.7 \ln\left(\frac{N}{7 \cdot 10^{17}}\right)$$

N larger than $7 \cdot 10^{17}$ Intrinsic carrier density in the emitter is:

$$n_{iE}^2 = N_C N_V \exp\left(-\frac{E_g - \Delta E_g}{kT}\right) = n_i^2 \exp\left(\frac{\Delta E_g}{kT}\right)$$

n_i: intrinsic carrier density

Nonideal Effects

Emitter bandgap narrowing

Minority carrier concentration becomes

$$p_{noE} = \frac{n_{iE}^2}{N_E} = \frac{n_i^2}{N_E} \exp\left(\frac{\Delta E_g}{kT}\right)$$

Increased minority carrier concentration in the emitter.
The net result is an increased hole diffusion current and the current gain is recuded

$$h_{FE} \propto \frac{n_{po}}{p_{noE}} \propto \exp\left(-\frac{\Delta E_g}{kT}\right)$$

Nonideal Effects

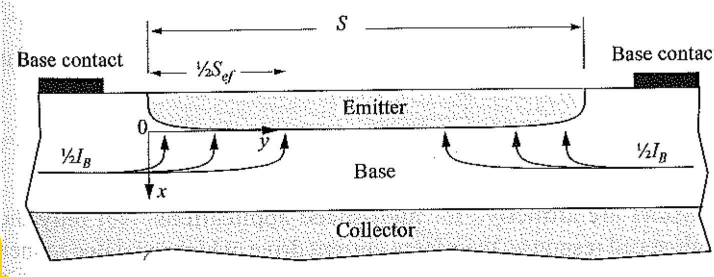
Kirk Effect

In modern bipolar transistors with a lightly doped collector region, the net charge is changed significantly under high-current condition. The high-field region is relocated from the base-collector junction towards the n+-substrate.
It is referred to as the Kirk effect and increases the effective Gummel number and causes a reduction of h_{FE} (current gain).

Nonideal Effects

Current Crowding

Minimization of the emitter resistance results in non-uniform current passing through the emitter area.



S_{ef} effective width carries most of the current.

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