VE 320 Summer 2019

Introduction to Semiconductor Devices

Instructor: Rui Yang （杨睿）

Office: JI Building 434

rui.yang@sjtu.edu.cn

Lecture 9

BJT
(Chapter 12)

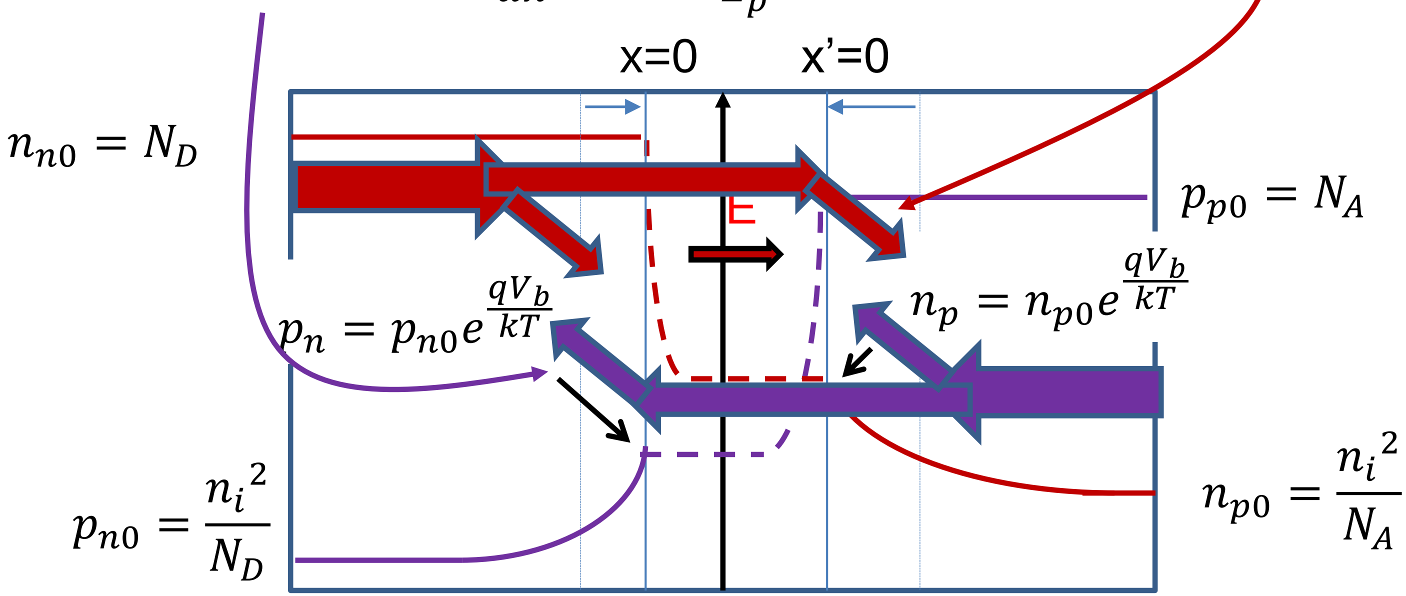
Previously: pn Junction Current

- charge carrier transport: <u>forward bias: current ratio</u>

$$J_n = -qD_n \frac{dn_p}{dx} = -\frac{qD_n n_{p0}}{L_n}(e^{\frac{qV_b}{kT}} - 1)e^{-x/L_n}$$

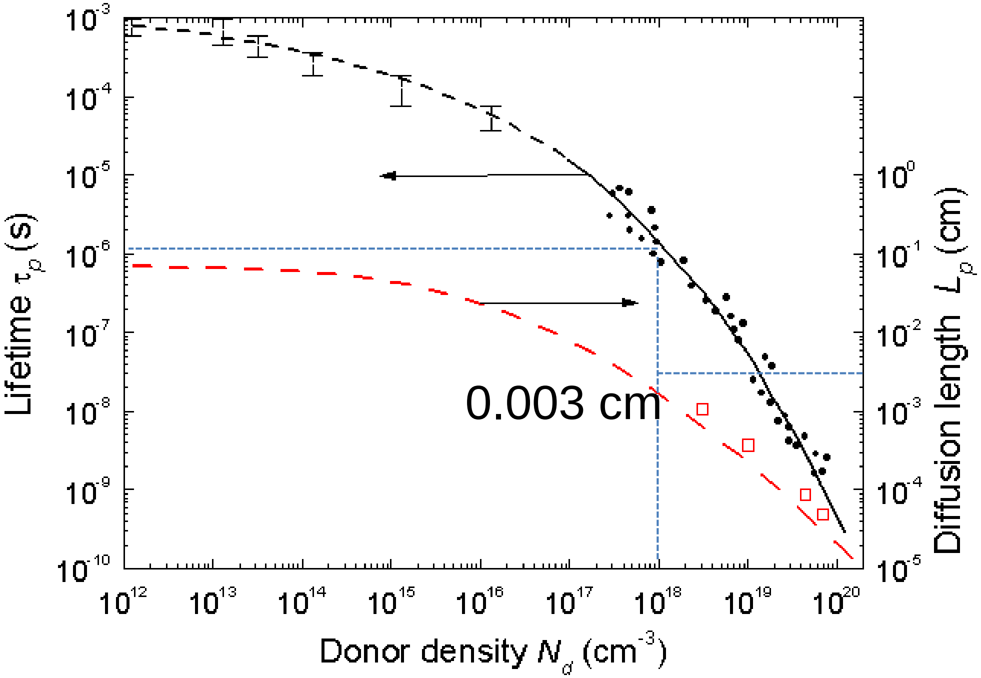
$$J_p = -qD_p \frac{dp_n}{dx} = -\frac{qD_p p_{n0}}{L_p}(e^{\frac{qV_b}{kT}} - 1)e^{x/L_p}$$

$$\boxed{\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}}$$



Assumption: No recombination-generation in depletion region.

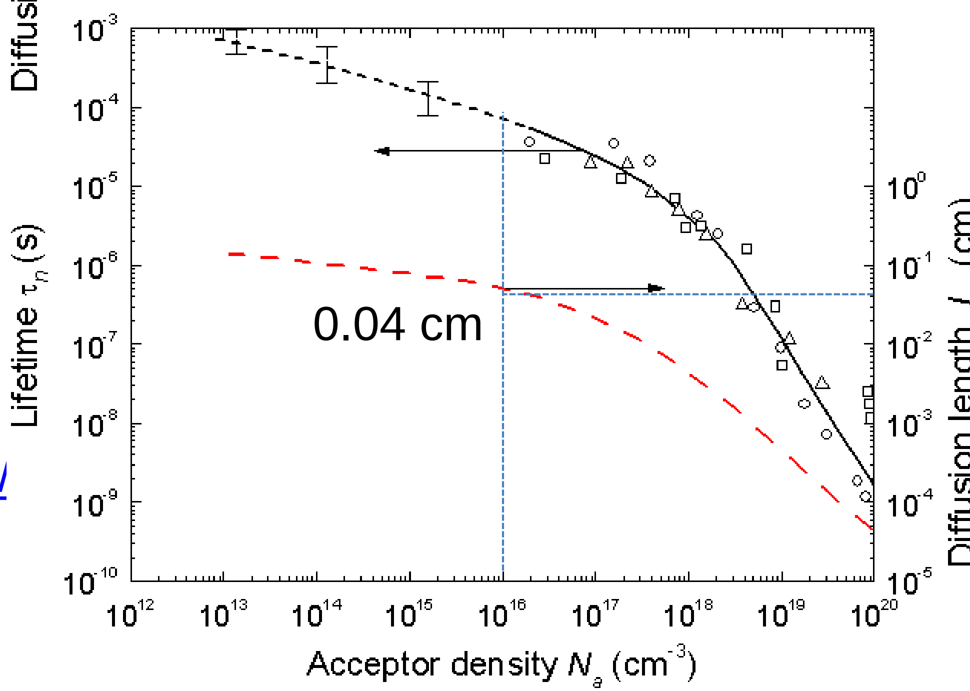
Example: pn Junction Current



$N_D = 10^{18}$ cm^{-3}, $N_A = 10^{16}$ cm^{-3}

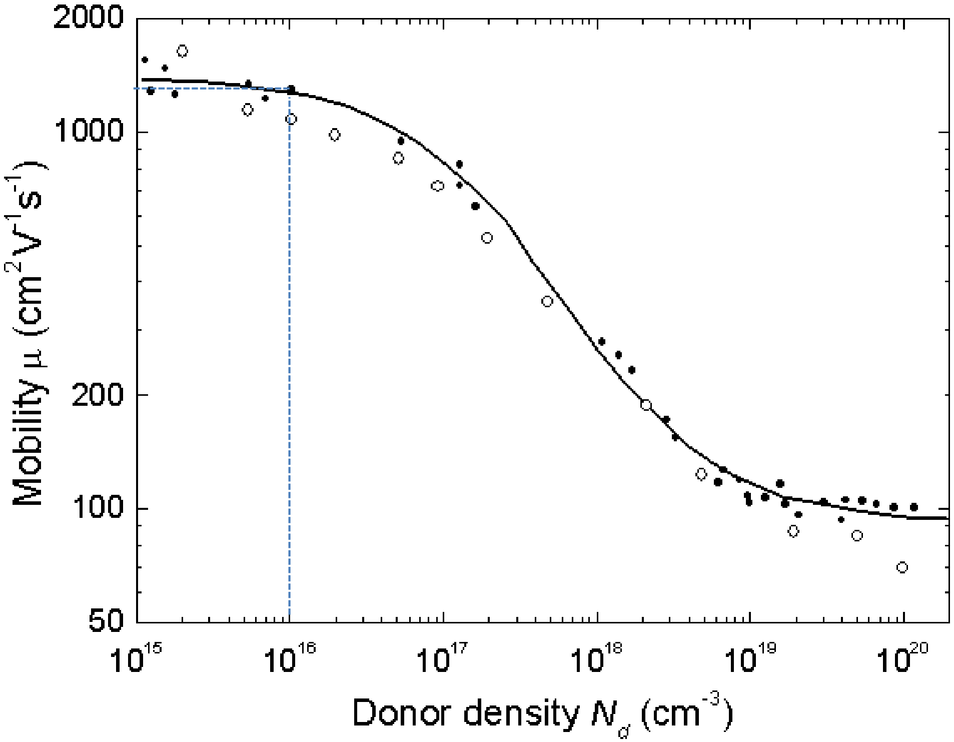
L_n = 0.04cm, L_p=0.003cm

$$\boxed{\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}}$$



http://www.ioffe.ru/SVA/NSM/Semicond/Si/

Example: pn Junction Current

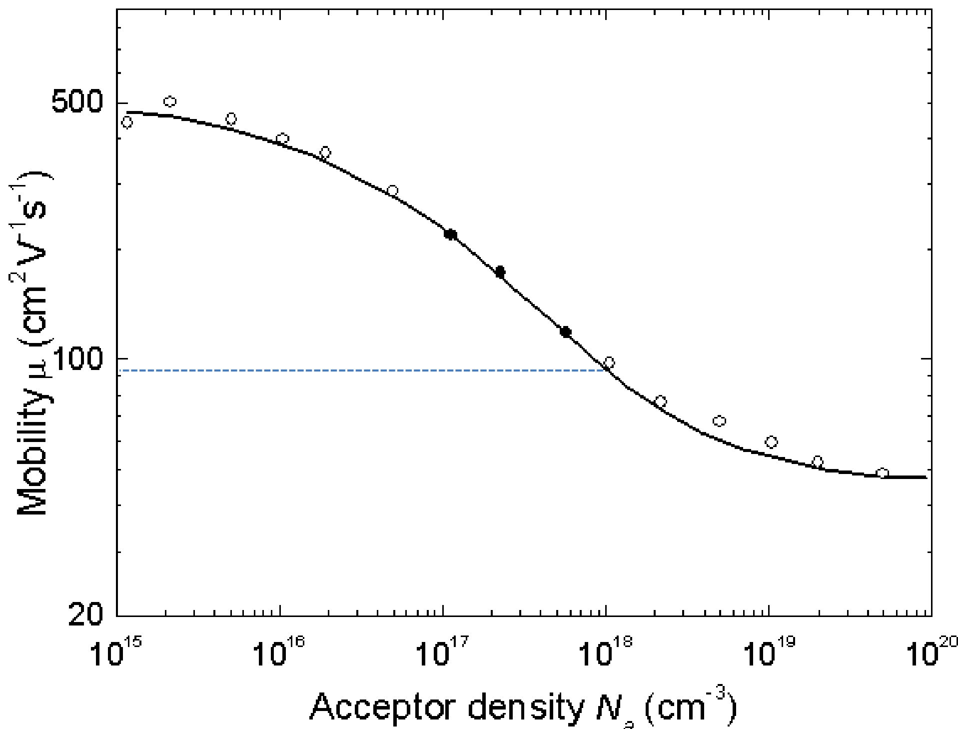


$N_D = 10^{18}$ cm^{-3}, $N_A = 10^{16}$ cm^{-3}

$L_n = 0.04$cm, $L_p = 0.003$cm

$\mu_p = 100$cm^2/Vs $\mu_n = 1300$ cm^2/Vs

$$\boxed{\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}}$$



http://www.ioffe.ru/SVA/NSM/Semicond/Si/

Example: pn Junction Current

$N_D = 10^{18}\ cm^{-3}$, $N_A = 10^{16}\ cm^{-3}$

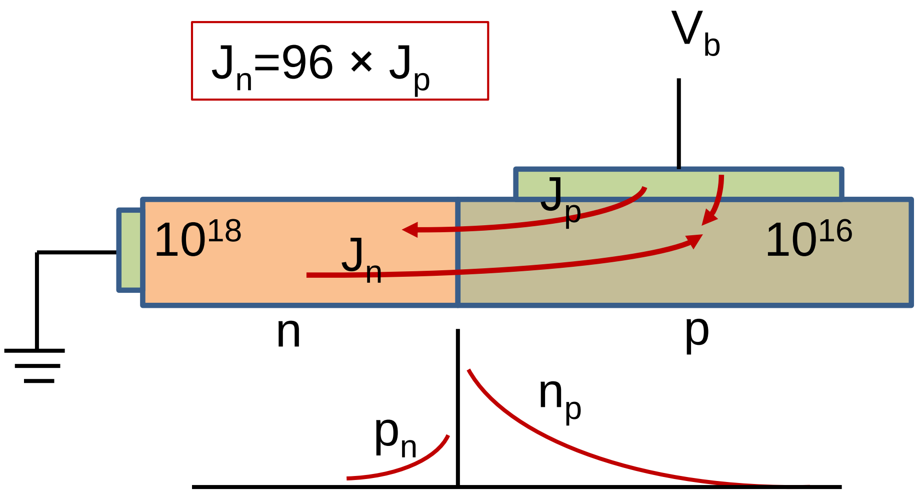
$L_n = 0.04cm$, $L_p = 0.003cm$

$\mu_p = 100 cm^2/Vs$ $\mu_n = 1300\ cm^2/Vs$

$$\boxed{\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p} = \frac{1300 \times 10^{18} / 0.04}{100 \times 10^{16} / 0.003} = 97.5}$$

Bipolar Junction transistor

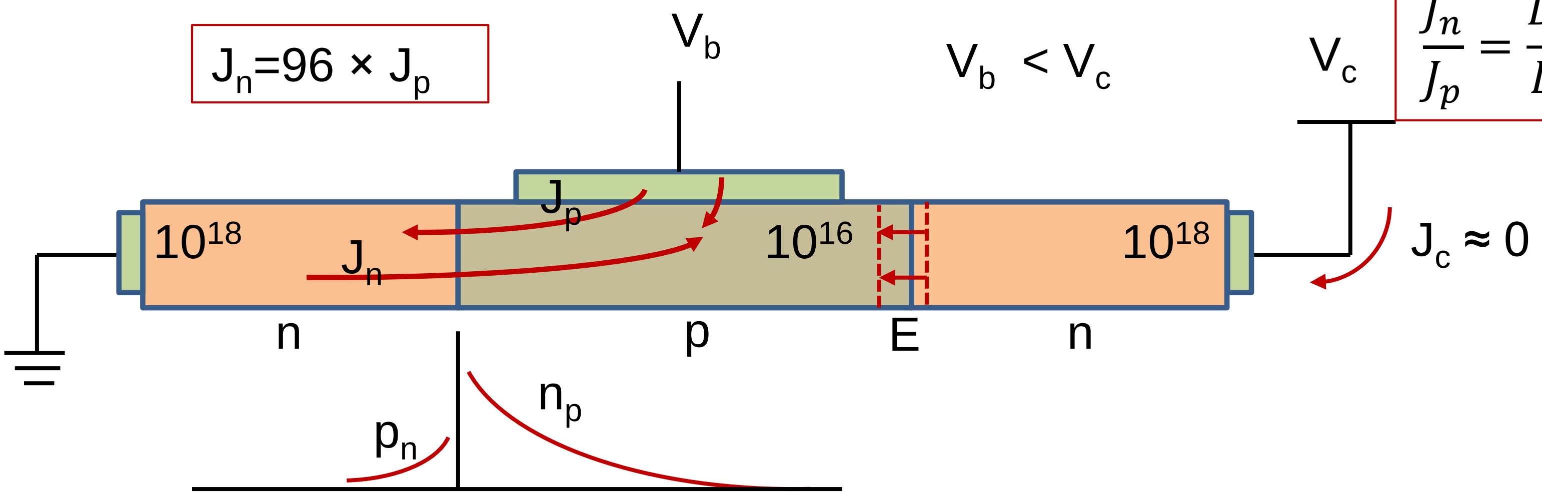
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$



Bipolar Junction transistor

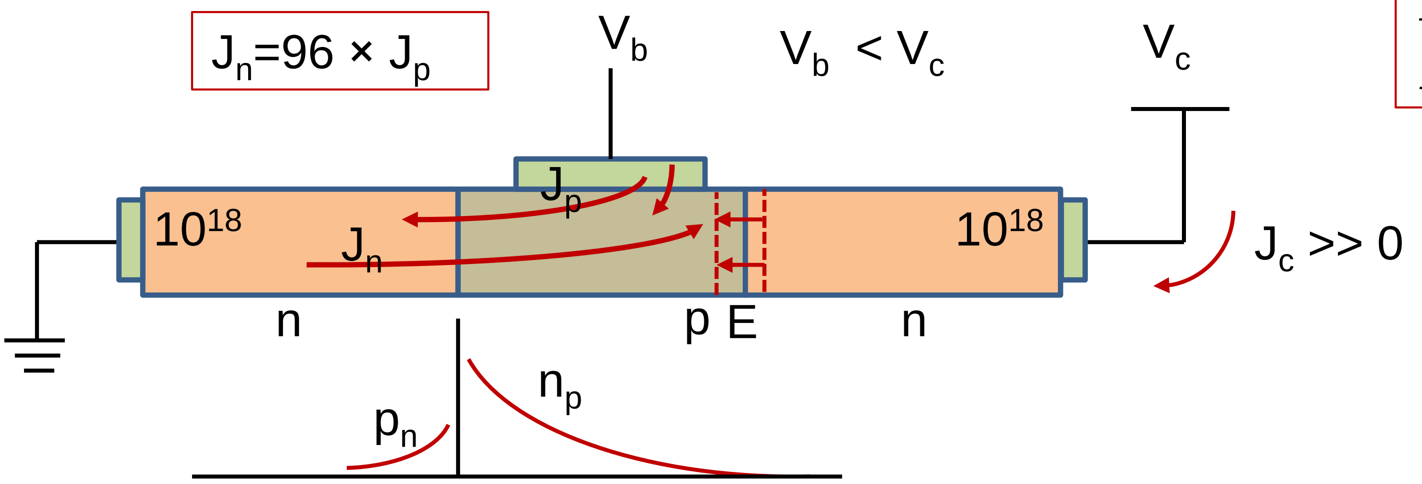
$J_n = 96 \times J_p$

$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$



Bipolar Junction transistor

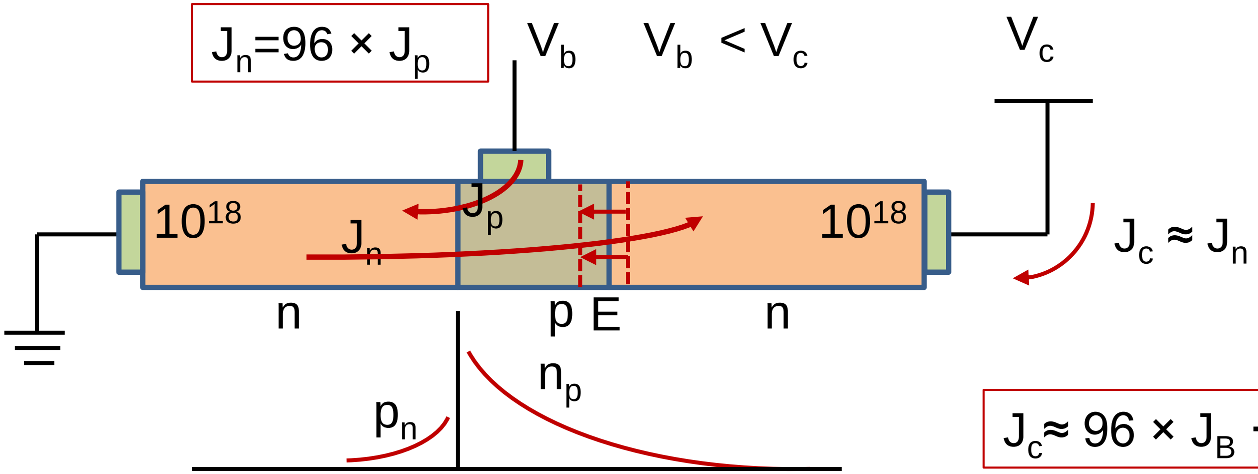
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$



Bipolar Junction transistor

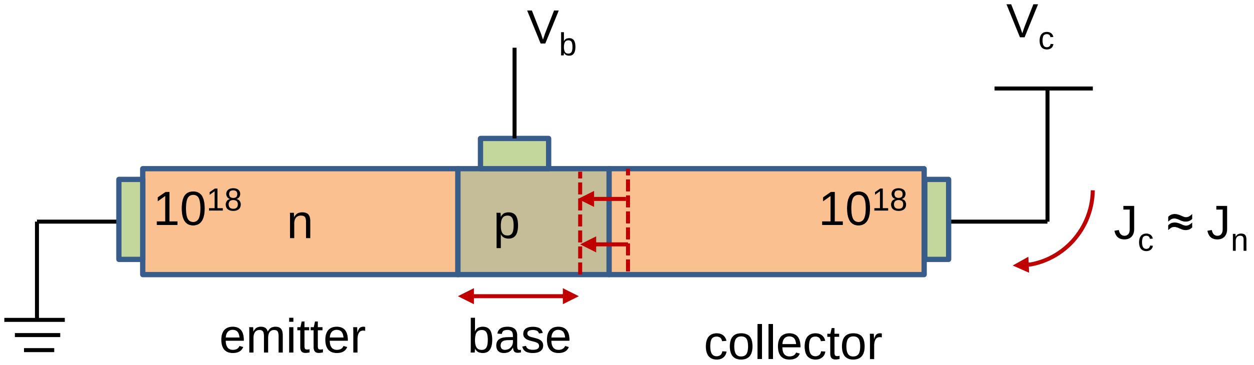
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

$J_n = 96 \times J_p$



$J_c \approx 96 \times J_B \rightarrow$ Gain β=96

Bipolar Junction transistor



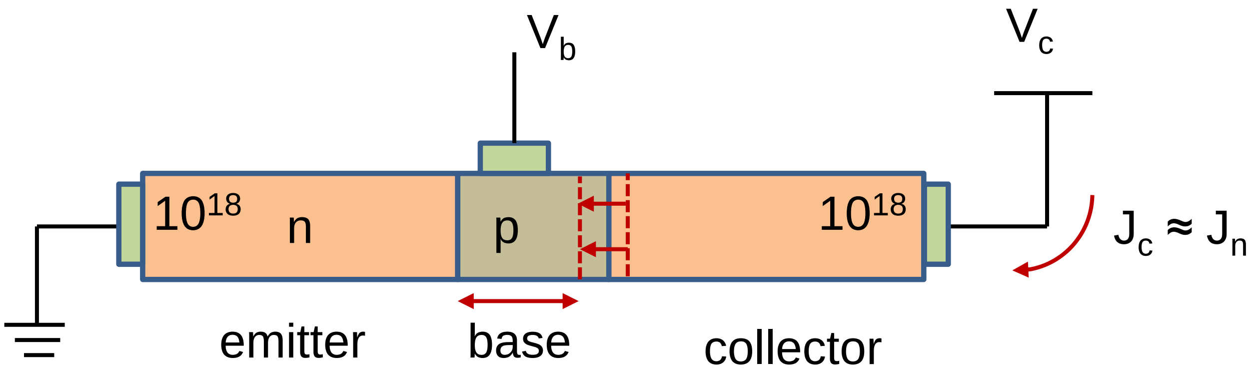
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

$J_c \approx 96 \times J_B$ → Gain β=96

BJT Charateristics:

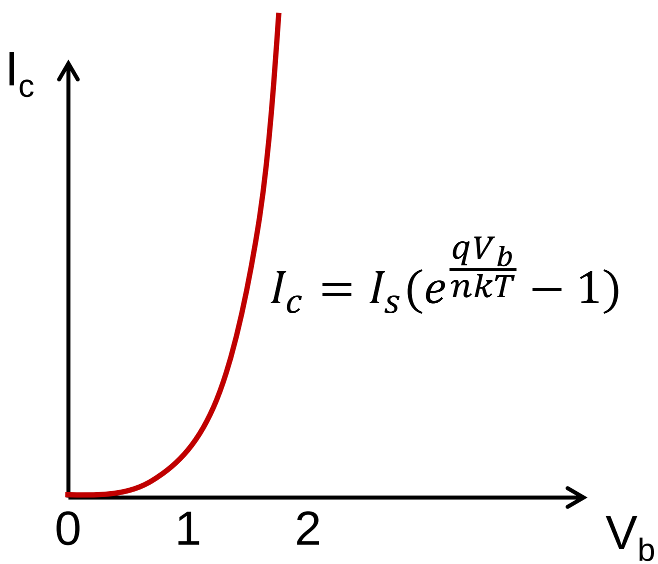
1. Base width smaller → higher gain
2. Larger emitter-base concentration ratio → higher gain

Bipolar Junction transistor: I-V



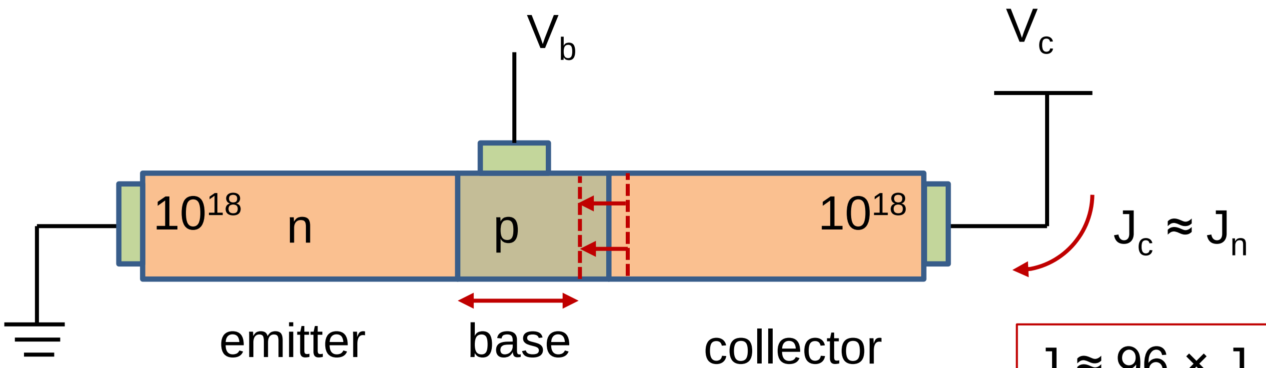
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

$\boxed{J_c \approx 96 \times J_B \rightarrow \text{Gain } \beta = 96}$



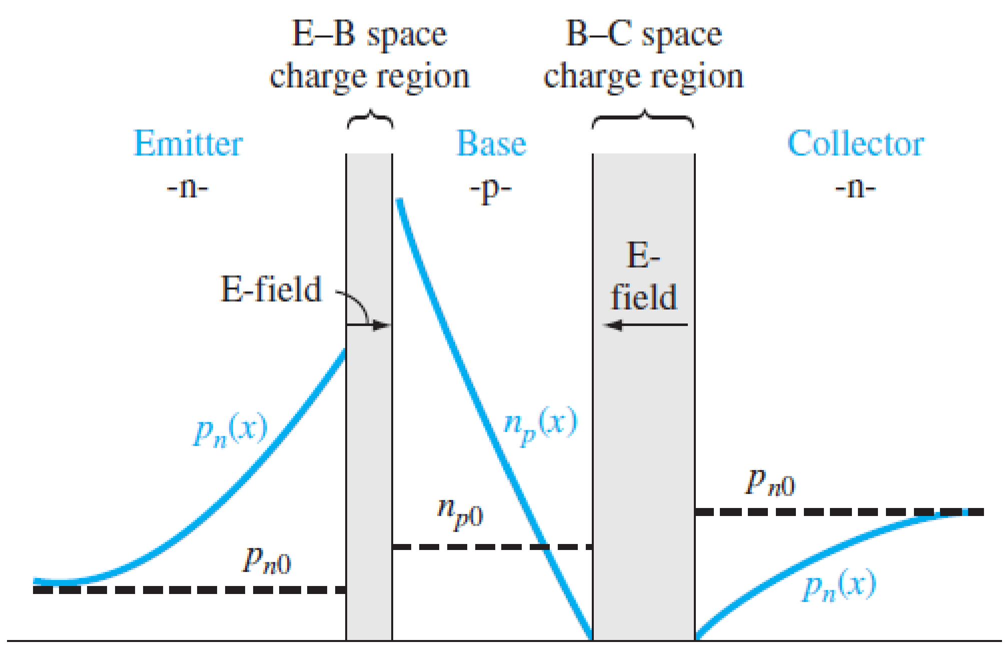
B-E junction forward biased, B-C junction reverse biased: forward-active operating mode

Bipolar Junction transistor: I-V



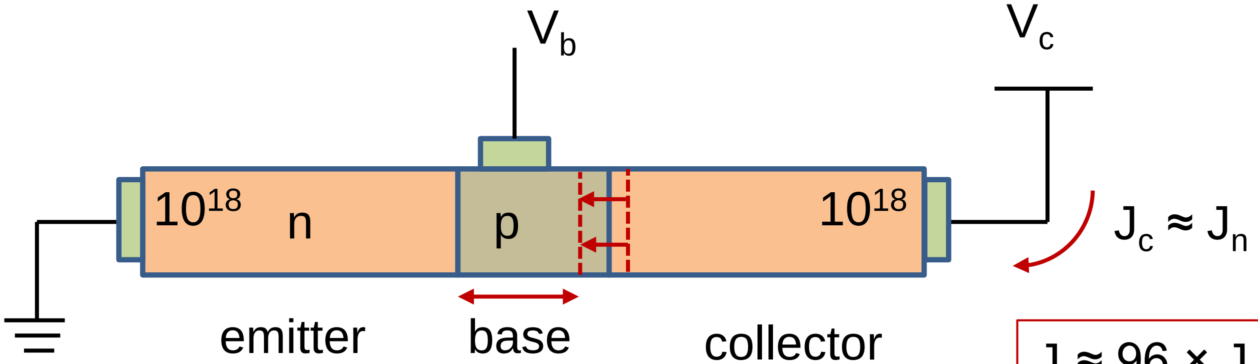
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

$J_c \approx 96 \times J_B$ → Gain β=96

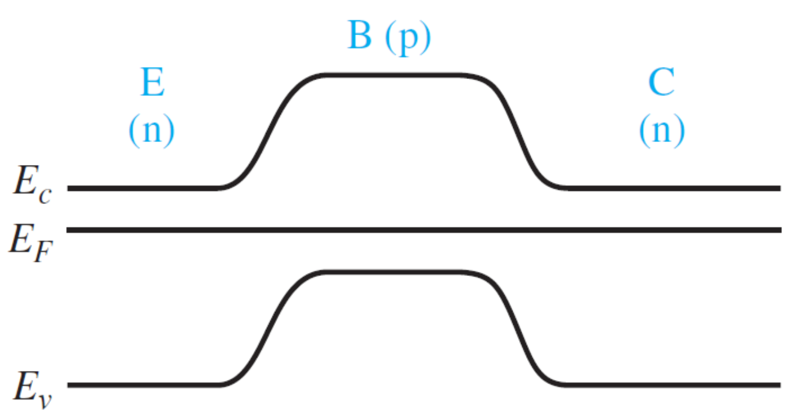


Bipolar Junction transistor: I-V

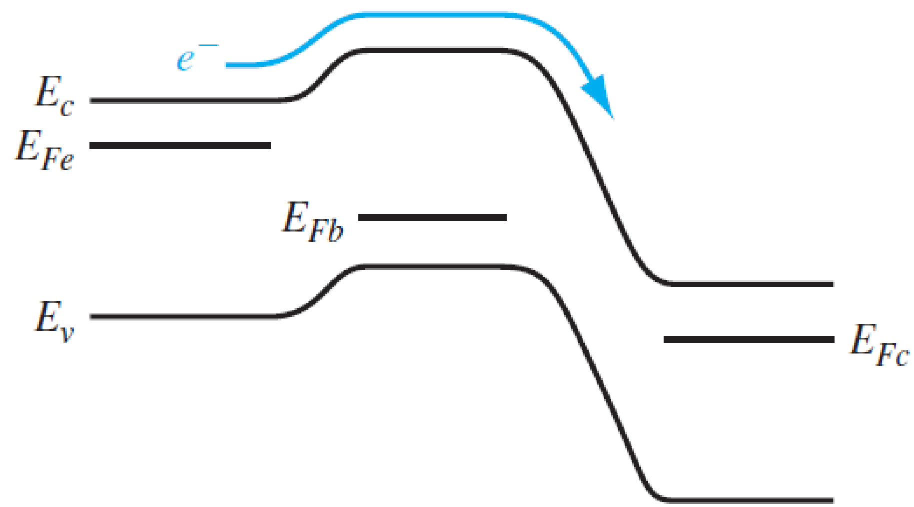
$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$



$J_c \approx 96 \times J_B \rightarrow$ Gain $\beta=96$

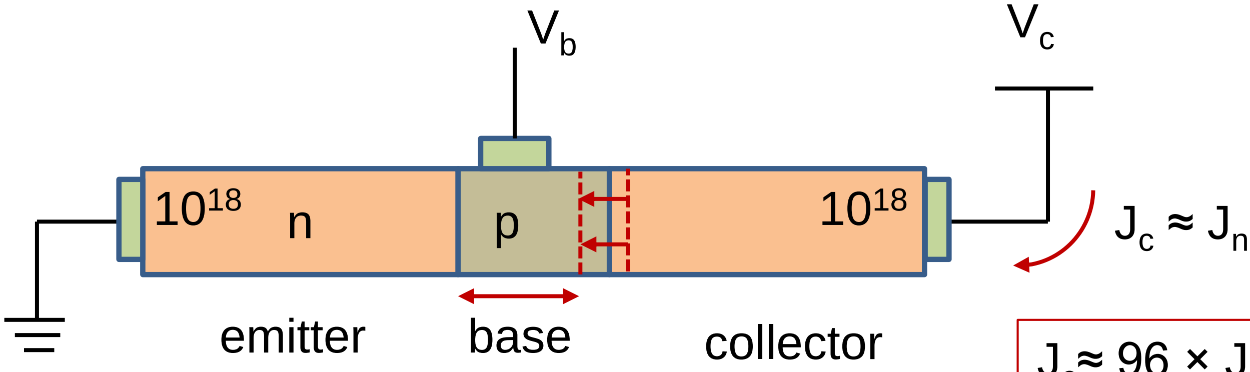


Zero bias



Forward active

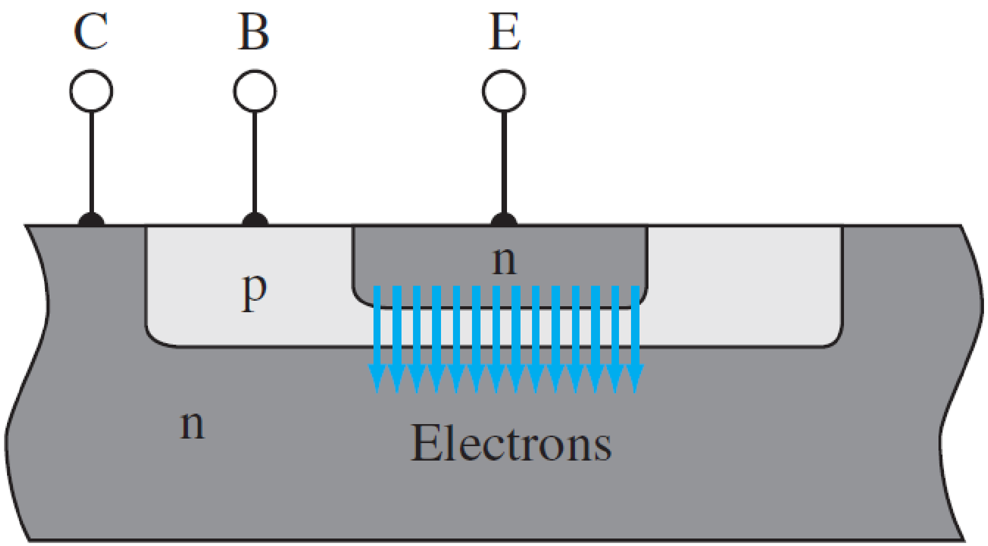
Bipolar Junction transistor: I-V



$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

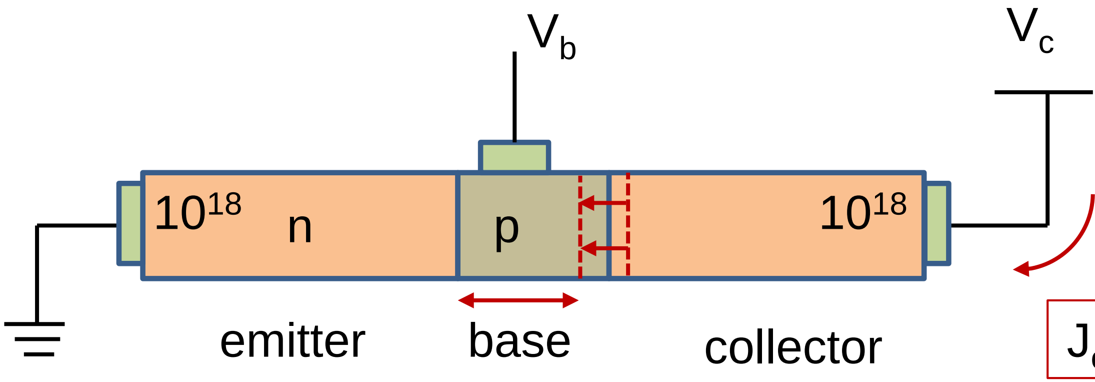
$J_c \approx 96 \times J_B \rightarrow$ Gain $\beta = 96$

Physically:



Bipolar Junction transistor: I-V

$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

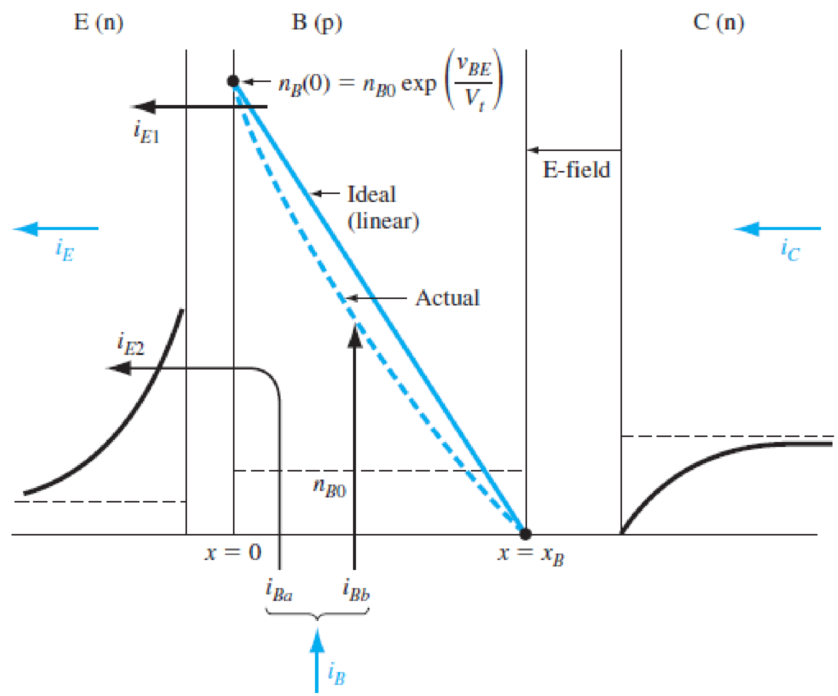


$J_c \approx J_n$

$J_c \approx 96 \times J_B \rightarrow$ Gain β=96

Qualitative *I-V*:

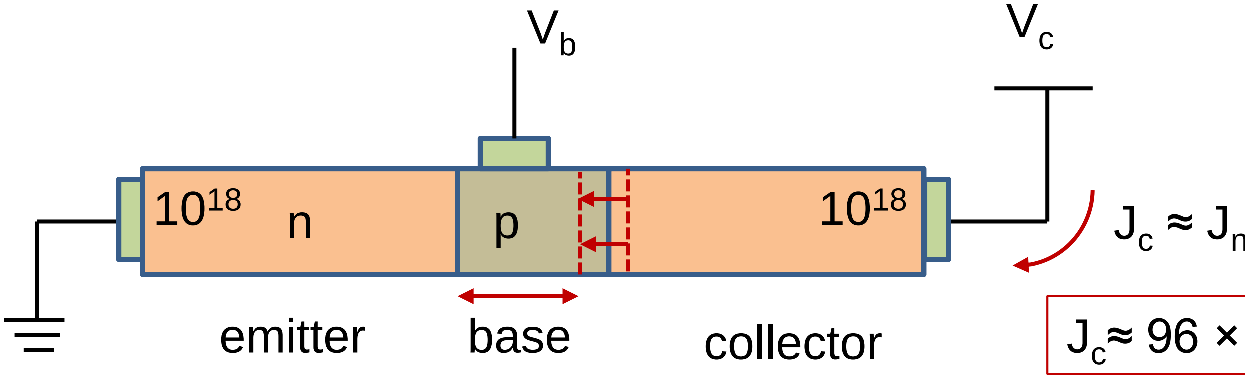
$$i_C = I_S \exp\left(\frac{v_{BE}}{V_t}\right)$$



The collector current is controlled by the base–emitter voltage: the current at one terminal of the device is controlled by the voltage applied to the other two terminals of the device

Bipolar Junction transistor: I-V

$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$



$J_c \approx 96 \times J_B \rightarrow$ Gain $\beta = 96$

Qualitative *I-V*:

Injected holes produce i_{E2}

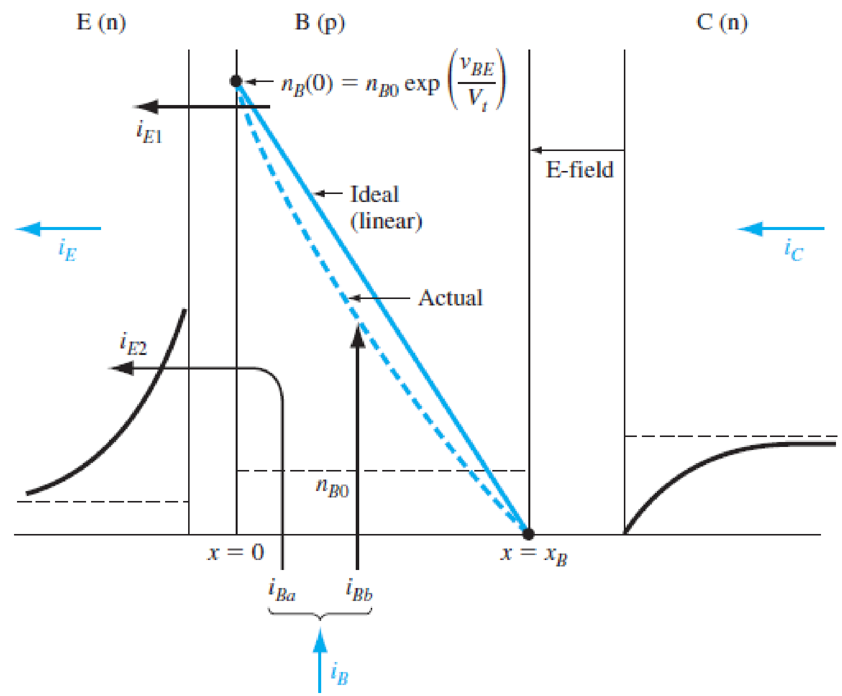
$$i_{E2} = I_{S2} \exp\left(\frac{v_{BE}}{V_t}\right)$$

Injected electrons produce i_{E1}

$$i_E = i_{E1} + i_{E2} = i_C + i_{E2} = I_{SE} \exp\left(\frac{v_{BE}}{V_t}\right)$$

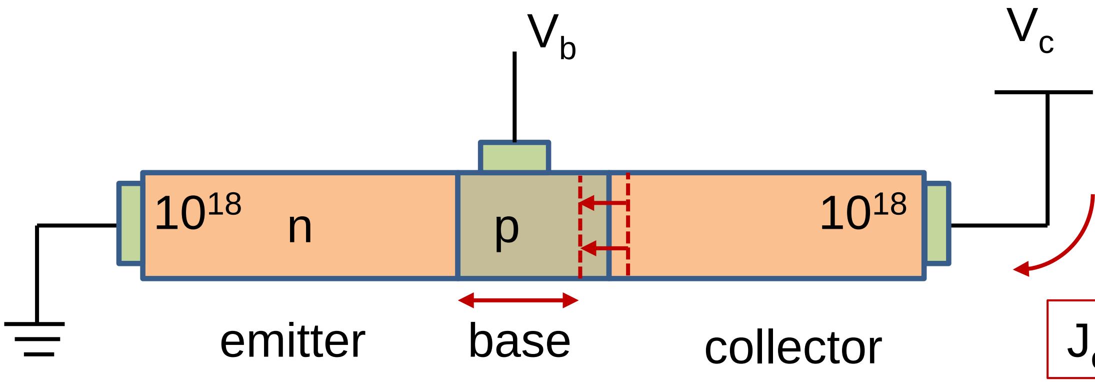
Common-base current gain

$$\frac{i_C}{i_E} \equiv \alpha$$



Bipolar Junction transistor: I-V

$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$



$J_c \approx J_n$

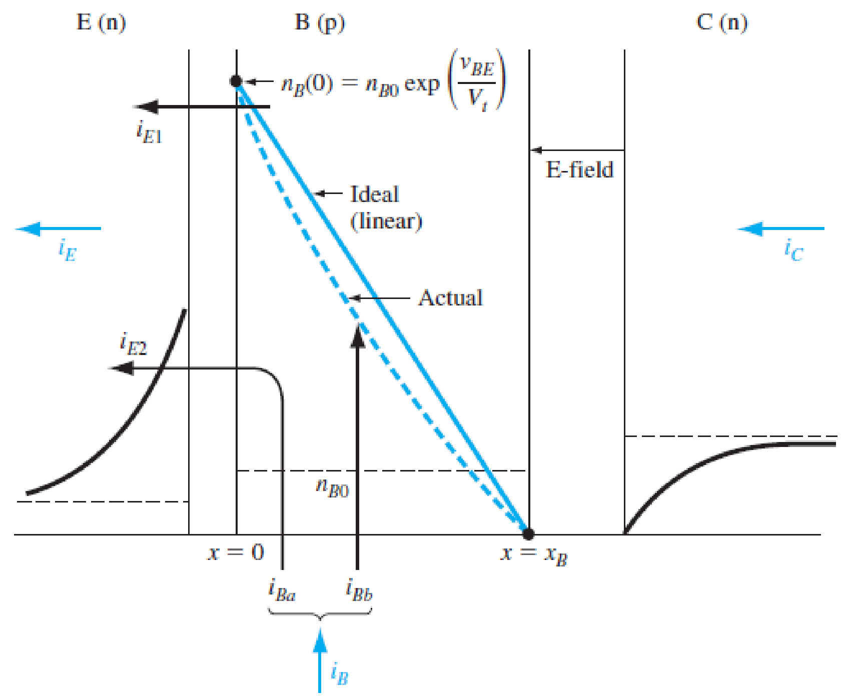
$J_c \approx 96 \times J_B \rightarrow$ Gain β=96

Qualitative *I-V*:

Injected holes produce $i_{E2=}i_{Ba}$

Recombination in the base: re-supply of holes by flow of positive charge, current i_{Bb}

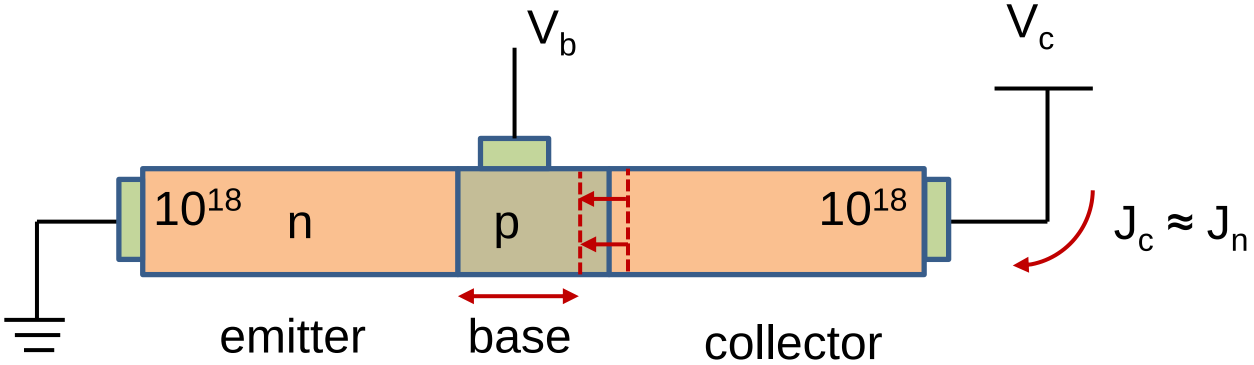
The number of holes per unit time recombining in the base is directly related to the number of minority carrier electrons in the base, so i_{Bb} is also proportional to $\exp(v_{BE}/V_t)$



Common-emitter current gain

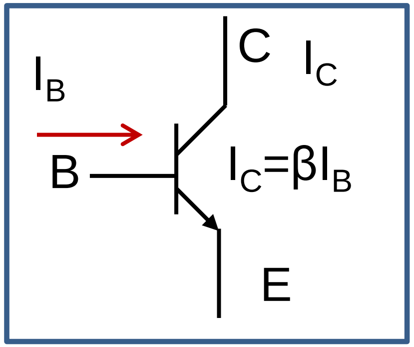
$$\frac{i_C}{i_B} \equiv \beta$$

Bipolar Junction transistor: I-V



$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

$J_c \approx 96 \times JB$ → Gain $\beta=96$

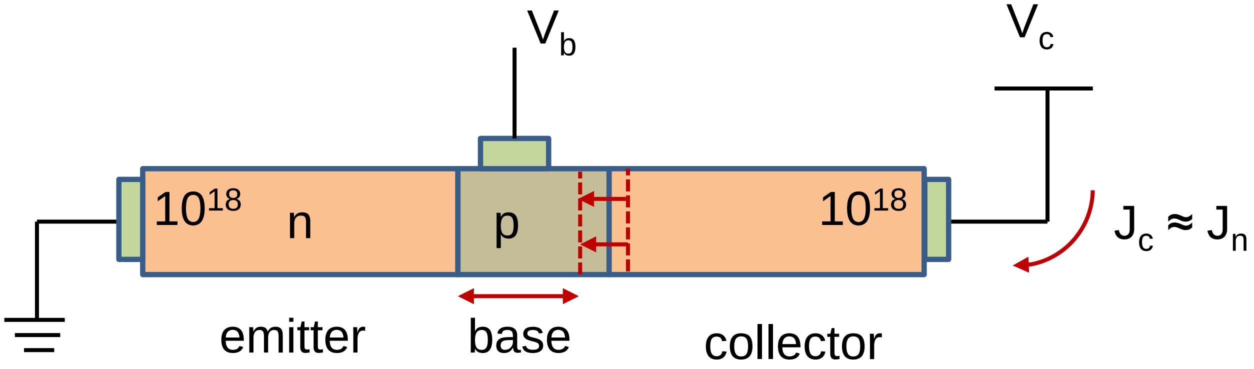


Basic facts:

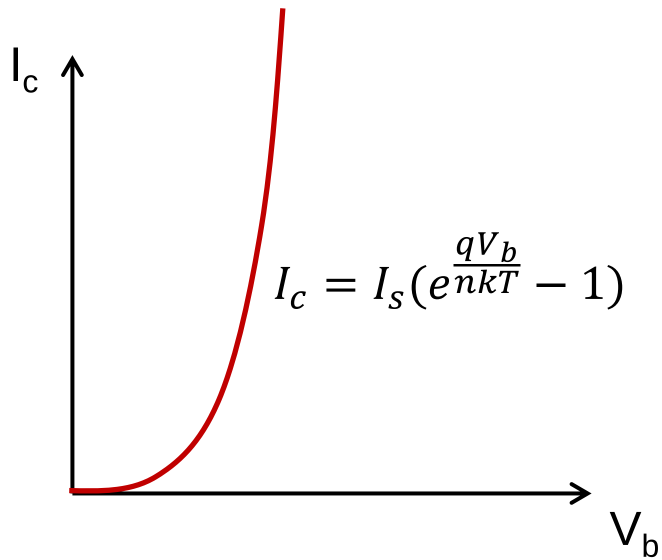
1. Narrower base → larger gain
2. $\beta \approx N_d/N_a$, higher emitter-to-base doping ratio → higher gain

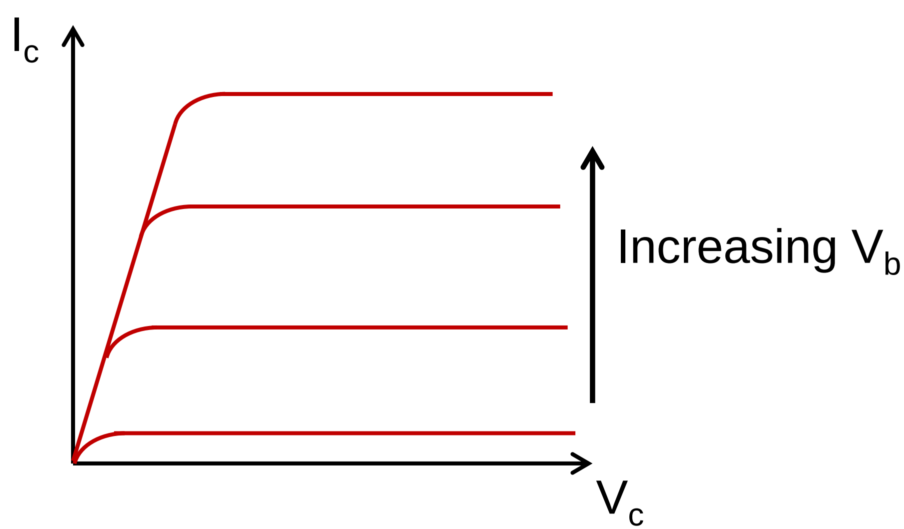
Bipolar Junction transistor: I-V

$$\frac{J_n}{J_p} = \frac{D_n N_D / L_n}{D_p N_A / L_p}$$

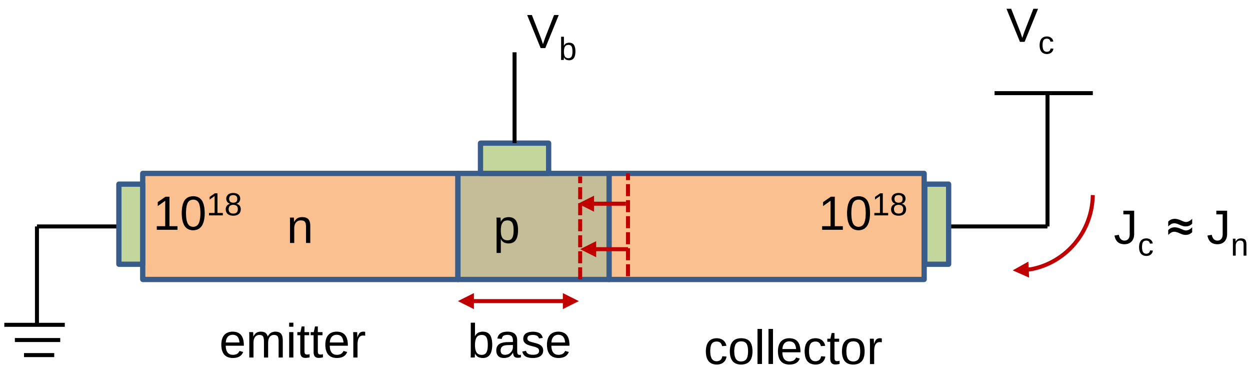


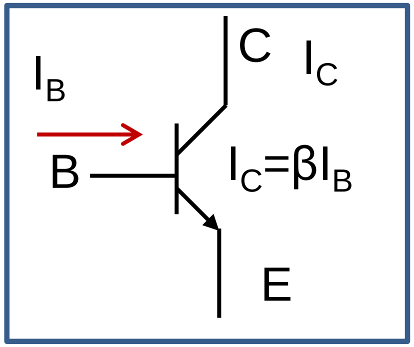
$J_c \approx 96 \times J_B \rightarrow$ Gain β=96



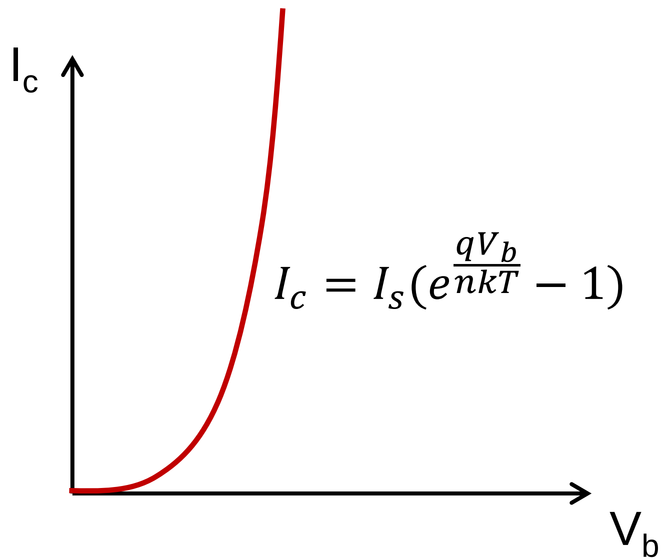


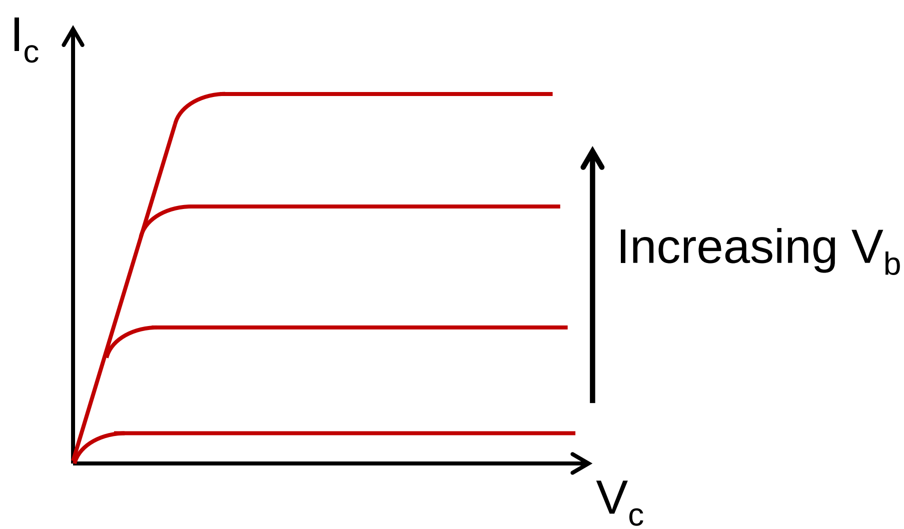
Bipolar Junction transistor: I-V



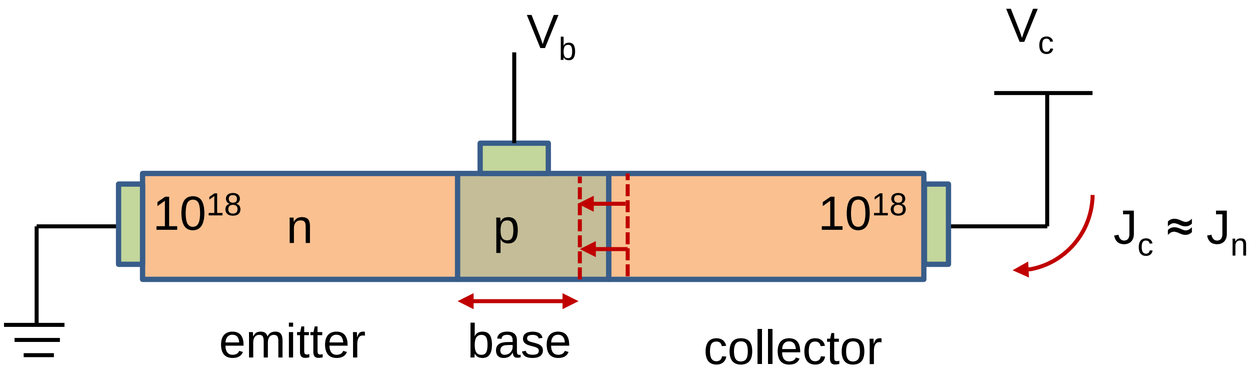


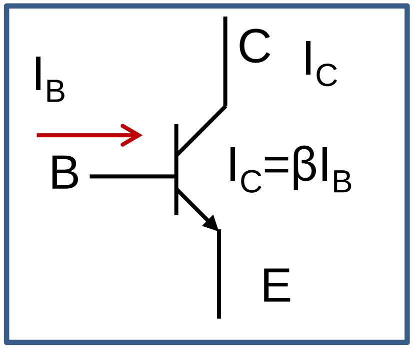
$J_c \approx 96 \times J_B \rightarrow$ Gain $\beta=96$





Bipolar Junction transistor: I-V

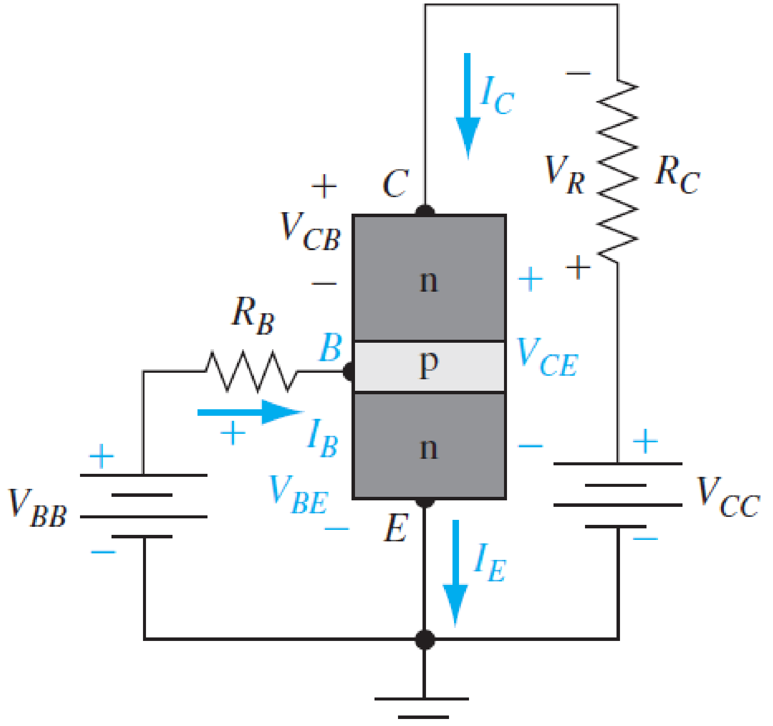




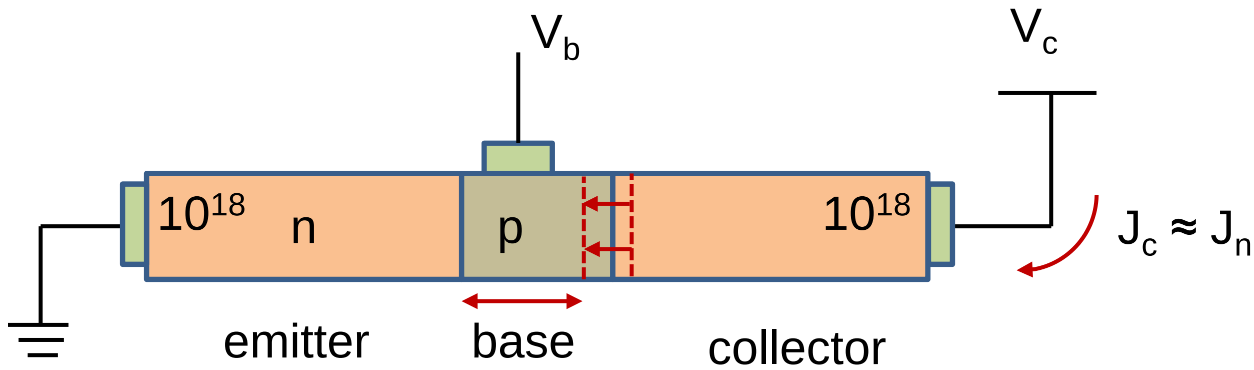
Three modes of operation:
1. Cutoff: B-E zero or reverse biased, B-C reverse biased.
Emitter and collector currents are zero
2. Forward-active: B-E forward biased, B-C reverse biased. V_{cc} large enough, V_R small enough, V_{CB}>0.   KVL

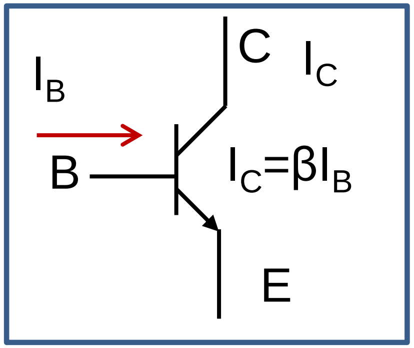
$$V_{CC} = I_C R_C + V_{CB} + V_{BE} = V_R + V_{CE}$$

3. Saturation: both B-E and B-C junctions are forward-biased, so that I_C is no longer controlled by V_{BE}. V_{BE} increase, V_R increases and I_C increases

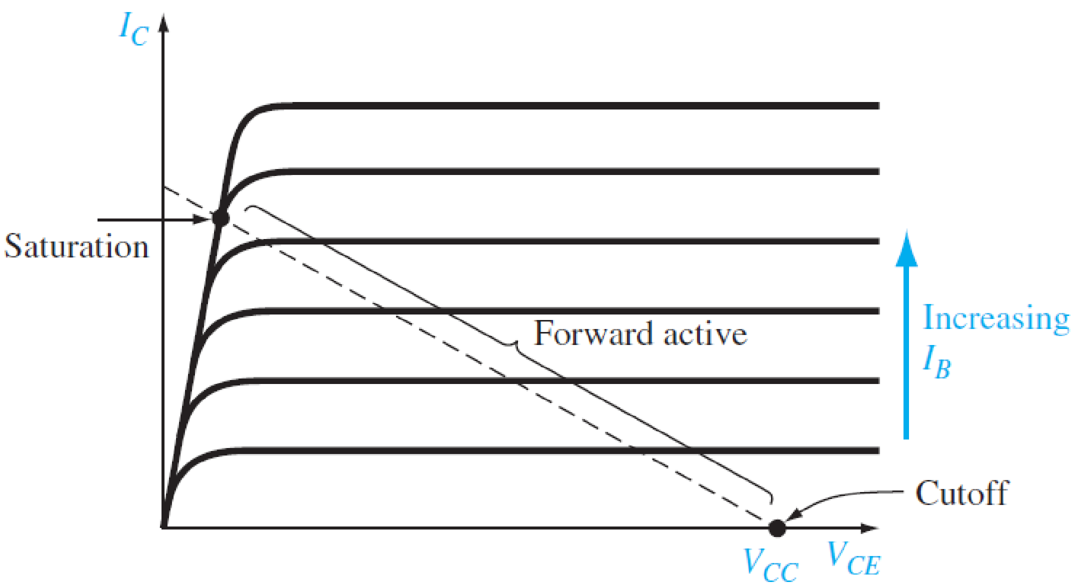


Bipolar Junction transistor: I-V





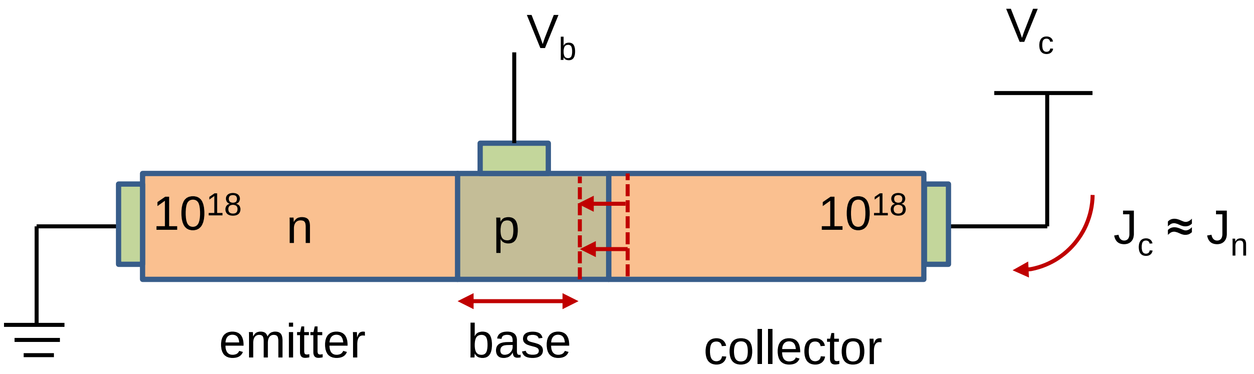
I_C-V_{CE}:

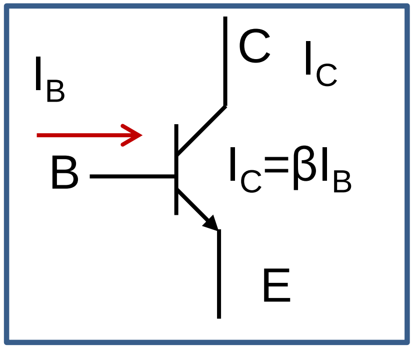


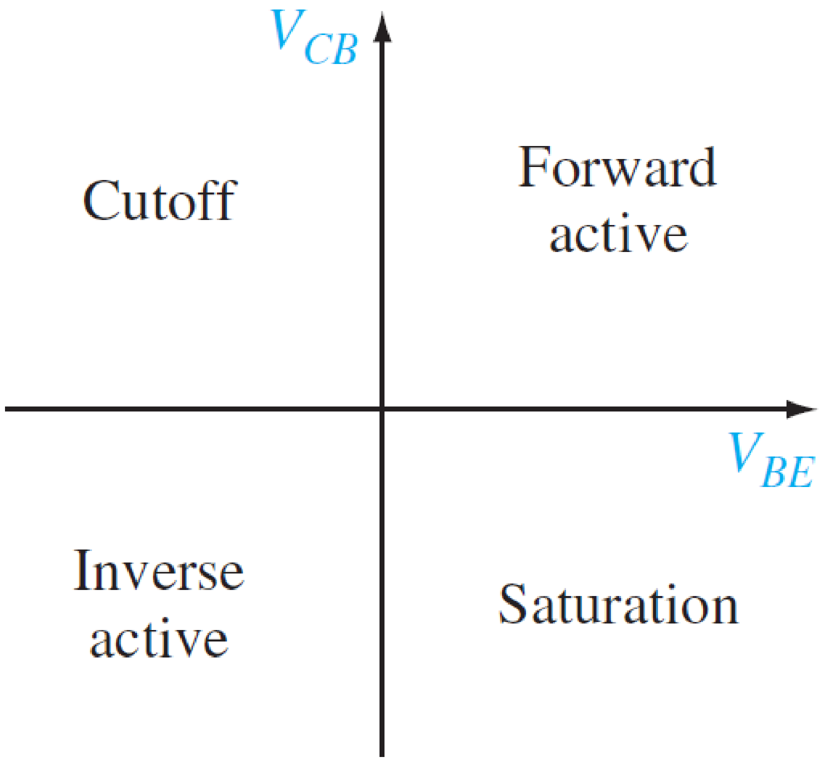
Load line

$$V_{CE} = V_{CC} - I_C R_C$$

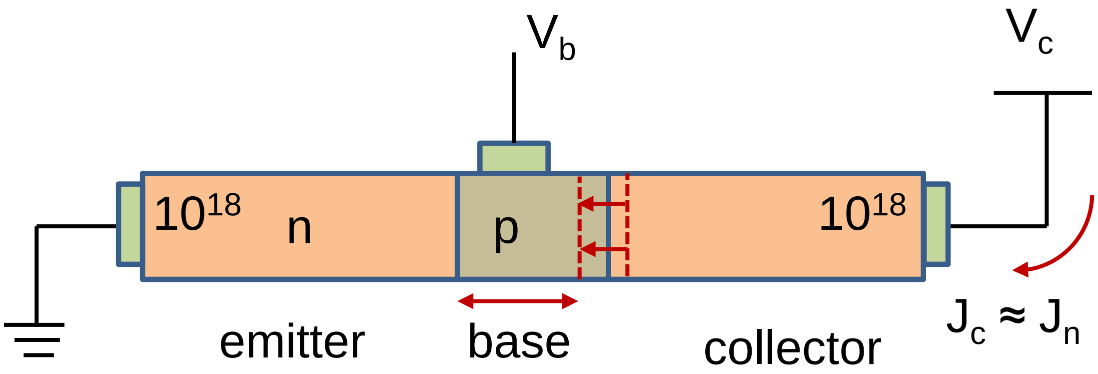
Bipolar Junction transistor: I-V



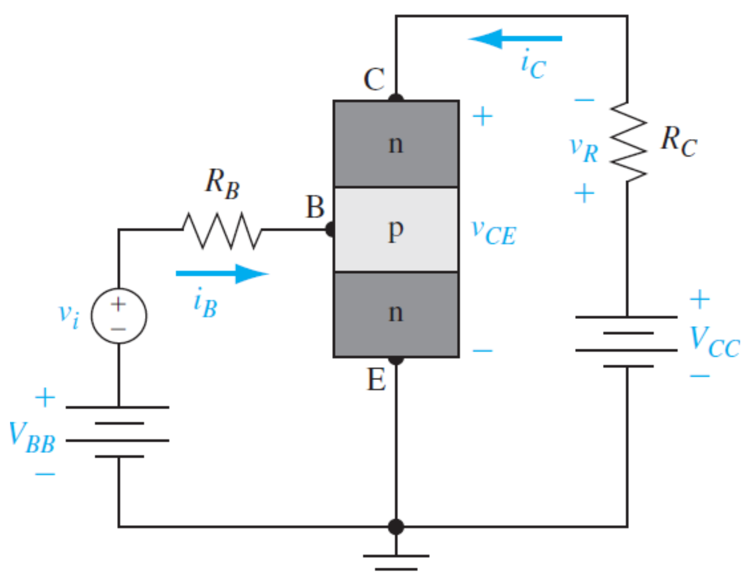


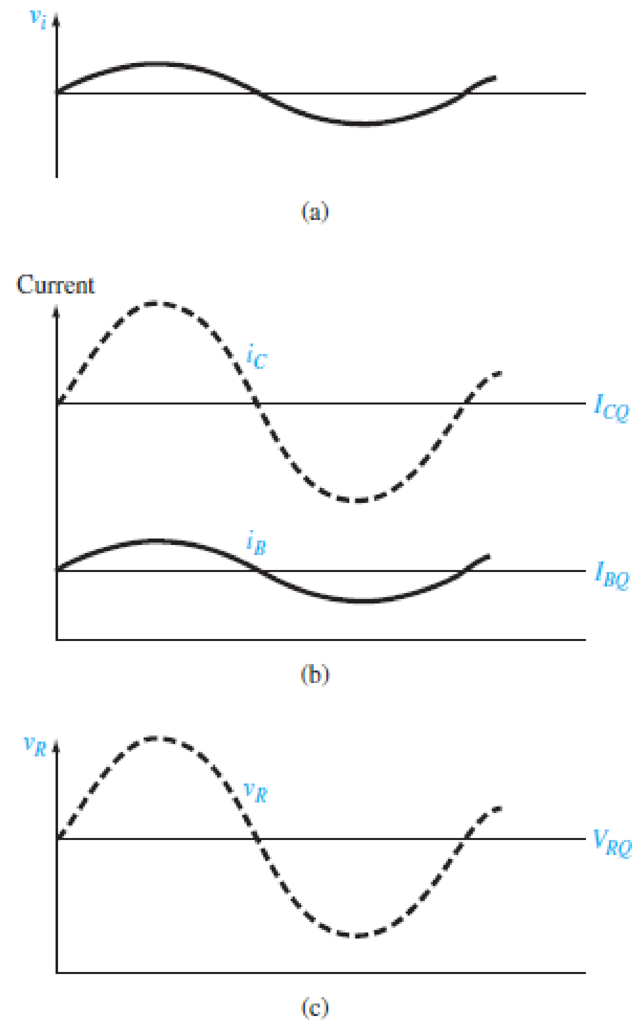


Bipolar Junction transistor: I-V

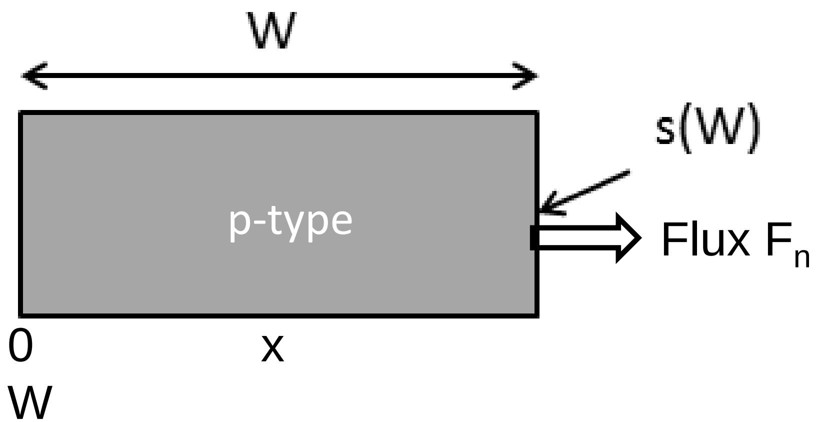


Small signal voltage gain





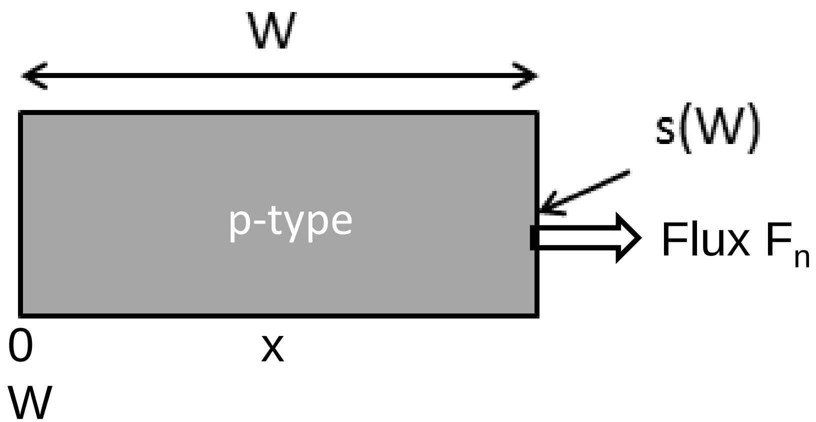
Quantitative analysis of BJT gain



$N_a = 10^{17}$ cm^{-3}, $D_n = 10$ cm^2/s, $\tau_n = 10^{-7}$ s, SRV $s(x=W)= \infty$
$\delta n\ (x=0) = 10^{14}$ cm^{-3}

Find the electron flux Fn at x=0 and W, if
1) W=20um
2) W=2um

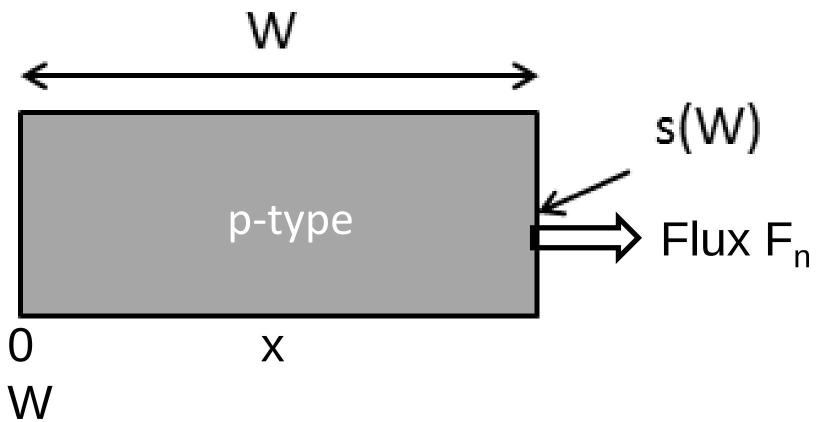
Quantitative analysis of BJT gain



Consider simple case:

$$\boxed{0 = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau}} \quad \Rightarrow \delta n = Aexp\left(-\frac{x}{L_n}\right) + Bexp(\frac{x}{L_n})$$

Quantitative analysis of BJT gain

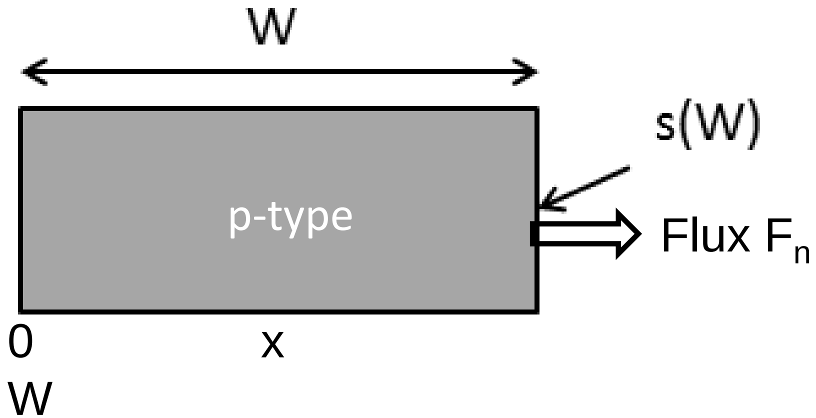


$$\boxed{0 = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau}}$$

$$\Rightarrow \delta n = Aexp\left(-\frac{x}{L_n}\right) + Bexp(\frac{x}{L_n})$$

$$\begin{cases} x = 0 \Rightarrow \delta n_0 = \delta n(x = 0) = A + B \\ x = W \Rightarrow \ \delta n = Aexp\left(-\frac{W}{L_n}\right) + Bexp\left(\frac{W}{L_n}\right) = 0 \end{cases}$$

Quantitative analysis of BJT gain



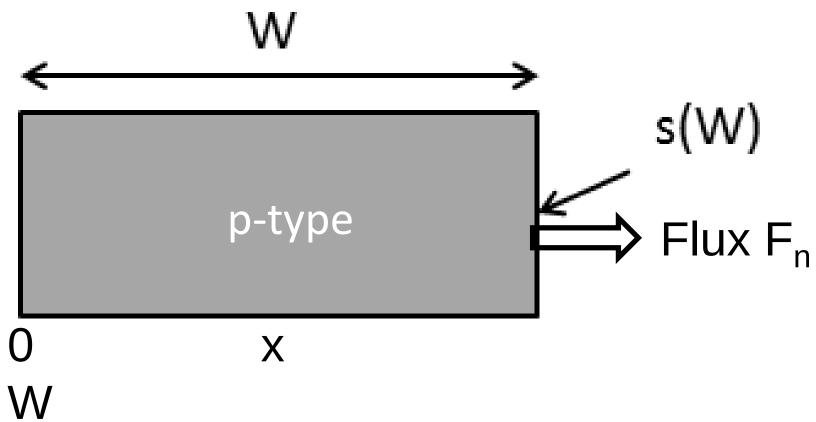
$$\boxed{0 = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau}}$$

$$\Rightarrow \delta n = Aexp\left(-\frac{x}{L_n}\right) + Bexp(\frac{x}{L_n})$$

$$A = (\delta n)_0 \frac{\exp\left(\frac{W}{L_n}\right)}{\exp\left(\frac{W}{L_n}\right) - \exp\left(-\frac{W}{L_n}\right)}$$

$$B = -(\delta n)_0 \frac{\exp\left(-\frac{W}{L_n}\right)}{\exp\left(\frac{W}{L_n}\right) - \exp\left(-\frac{W}{L_n}\right)}$$

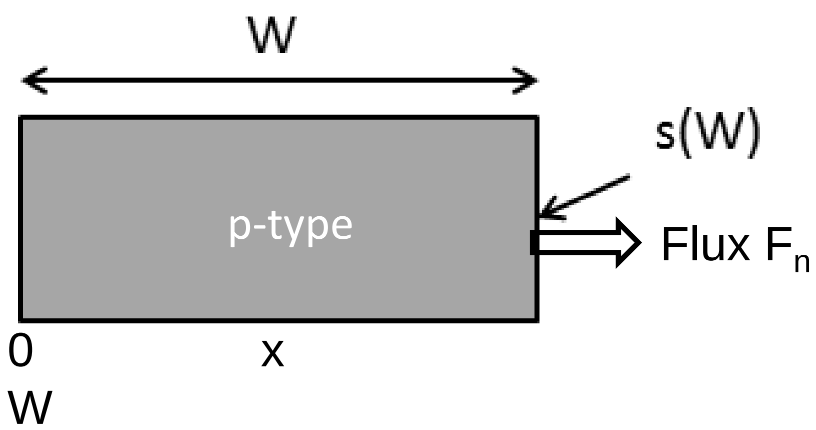
Quantitative analysis of BJT gain



$$\boxed{0 = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau}} \quad \Rightarrow \delta n = Aexp\left(-\frac{x}{L_n}\right) + Bexp(\frac{x}{L_n})$$

$$\delta n(x) = (\delta n)_0 \frac{\sinh\left(\frac{W-x}{L_n}\right)}{\sinh\left(\frac{W}{L_n}\right)}$$

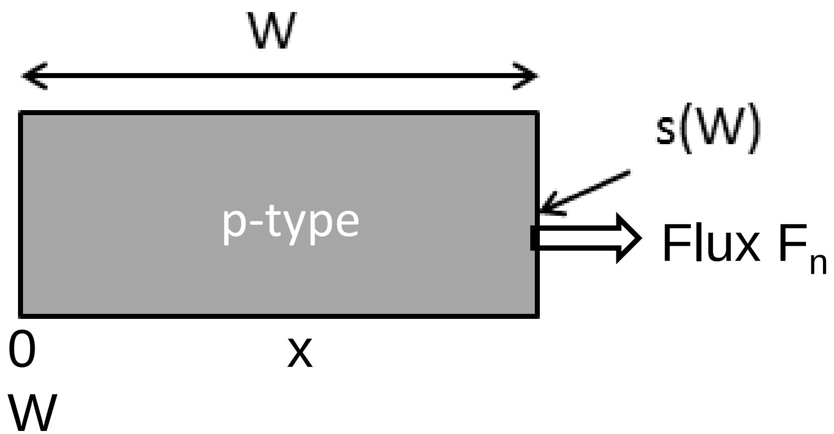
Quantitative analysis of BJT gain



$$\boxed{0 = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau}} \quad \Rightarrow \delta n = Aexp\left(-\frac{x}{L_n}\right) + Bexp(\frac{x}{L_n})$$

$$\delta n(x) = (\delta n)_0 \frac{\sinh\left(\frac{W-x}{L_n}\right)}{\sinh\left(\frac{W}{L_n}\right)} \qquad F_n = -D_n \frac{d\delta n(x)}{dx} = \frac{D_n (\delta n)_0}{L_n} \frac{cosh(\frac{W-x}{L_p})}{sinh(\frac{W}{L_p})}$$

Quantitative analysis of BJT gain



$$F_n = -D_n \frac{d\delta n(x)}{dx} = \frac{D_n (\delta n)_{B0}}{L_n} \frac{cosh(\frac{W-x}{L_p})}{sinh(\frac{W}{L_p})}$$

$$F_n(0) = \frac{D_n (\delta n)_0}{L_n} \frac{cosh(\frac{W}{L_p})}{sinh(\frac{W}{L_p})}$$

$$F_n(W) = \frac{D_n (\delta n)_0}{L_n} \frac{1}{sinh(\frac{W}{L_p})}$$