VE320 – Summer 2021

Introduction to Semiconductor Devices

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Chapter 12 Bipolar Junction Transistor

Outline

12.1 Review and example

12.2 Bipolar Junction transistor

12.3 Early Effect

12.4 Summary

12.5 Quantitative analysis of BJT gain

12.6 BJT symbols and planar device structure

Outline

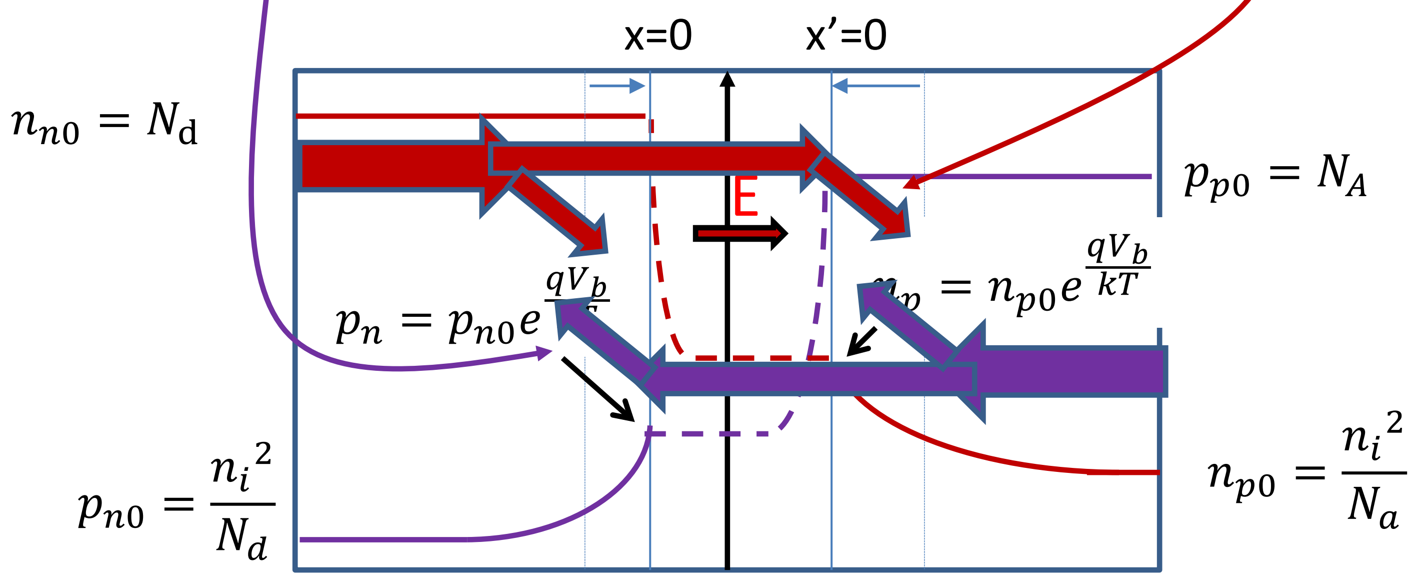
12.1 Previously: pn Junction Current

- charge carrier transport: forward bias: current ratio

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

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

$$\boxed{\frac{J_n}{J_p} = \frac{D_n N_d/L_n}{D_p N_a/L_p}}$$



Assumption: No recombination-generation in depletion region.

12.1 Example: pn Junction Current

Finding L_n, τ_n in **p-type** region because electrons are minority carriers.

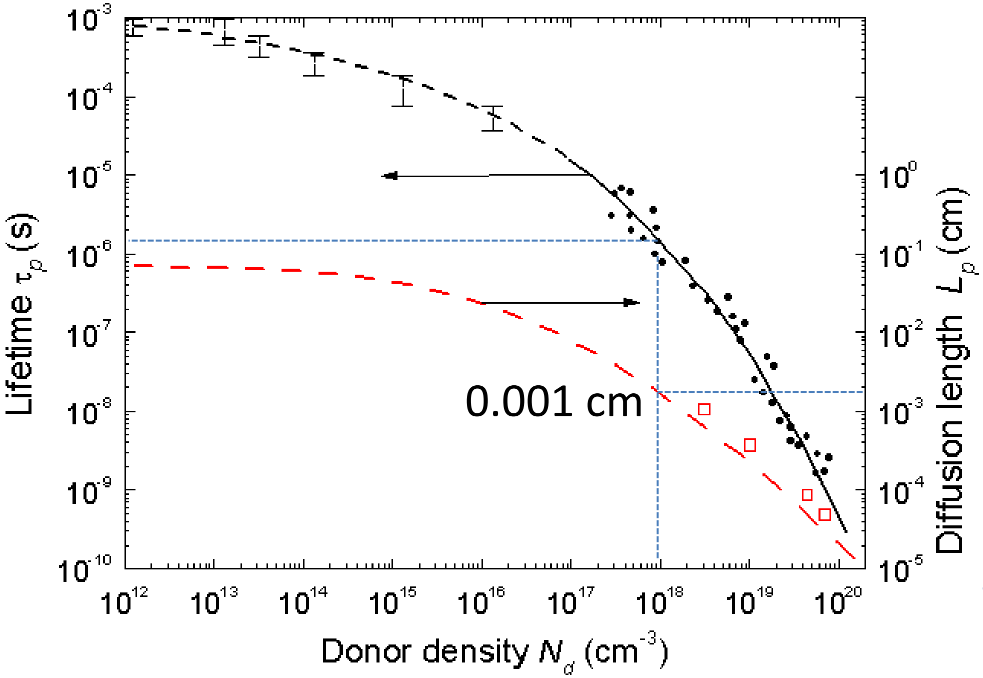
For $N_a = 10^{16}\ cm^{-3}$ $\quad$ $L_n = 0.04cm$ $\quad$ $\tau_n = 5 \times 10^{-5} s$

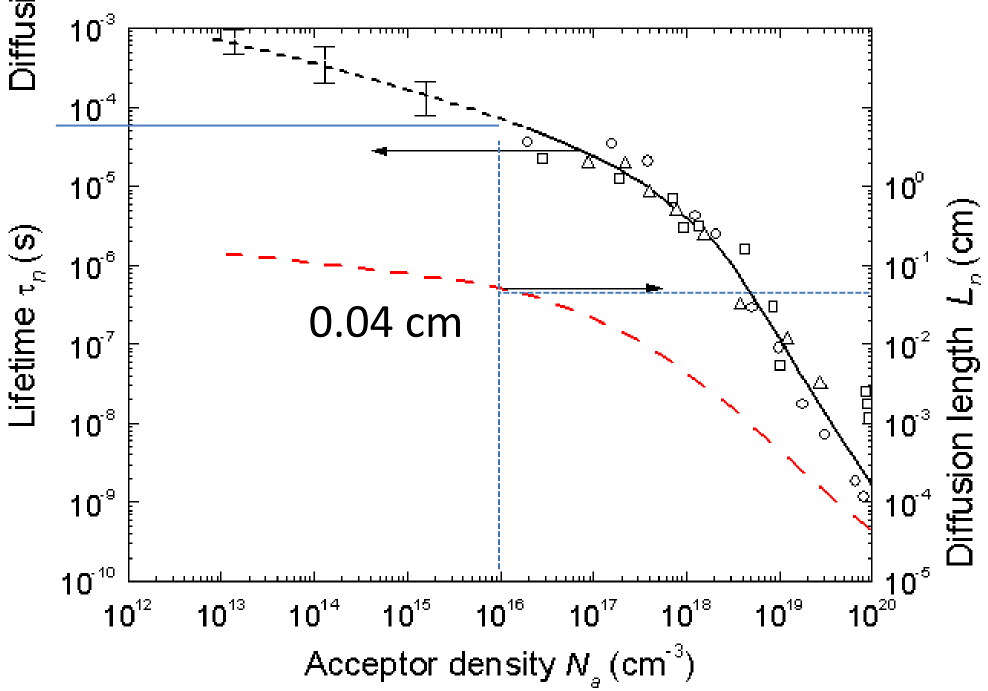
Finding L_p, τ_p in **n-type** region because holes are minority carriers.

For $N_d = 10^{18}\ cm^{-3}$ $\quad$ $L_p = 0.0015cm$ $\quad$ $\tau_p = 1.5 \times 10^{-6} s$

$$\boxed{\frac{J_n}{J_p} = \frac{D_n N_d / L_n}{D_p N_a / L_p} = \frac{L_n/\tau_n}{L_p/\tau_p}\frac{N_d}{N_a} \approx \frac{\dfrac{4 \times 10^{-2}}{5 \times 10^{-5}}}{\dfrac{1.5 \times 10^{-3}}{1.5 \times 10^{-6}}} \times \frac{10^{18}}{10^{16}} = 80}$$

12.1 Example: pn Junction Current





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

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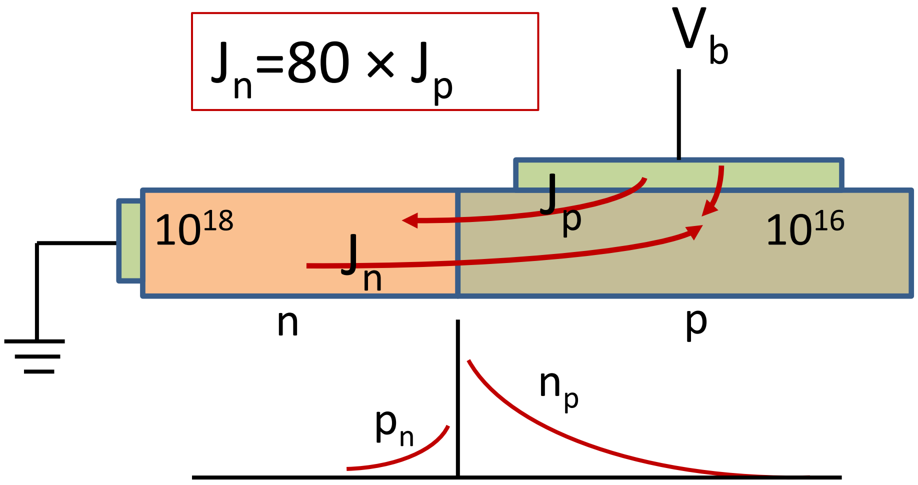
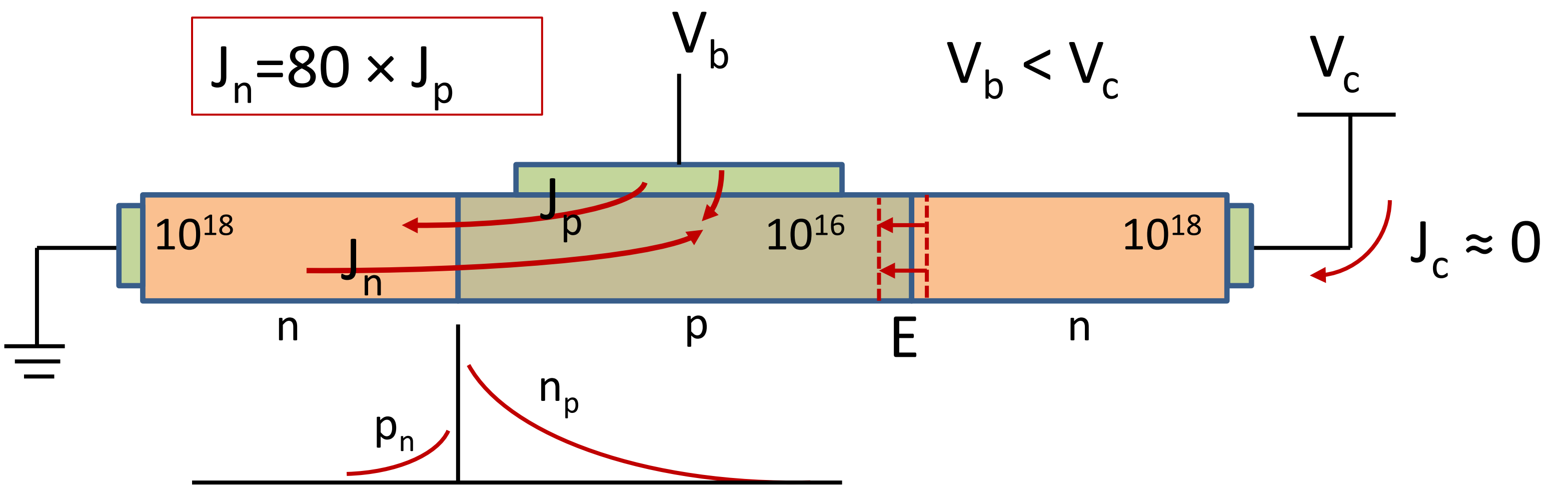
12.2 Bipolar Junction transistor

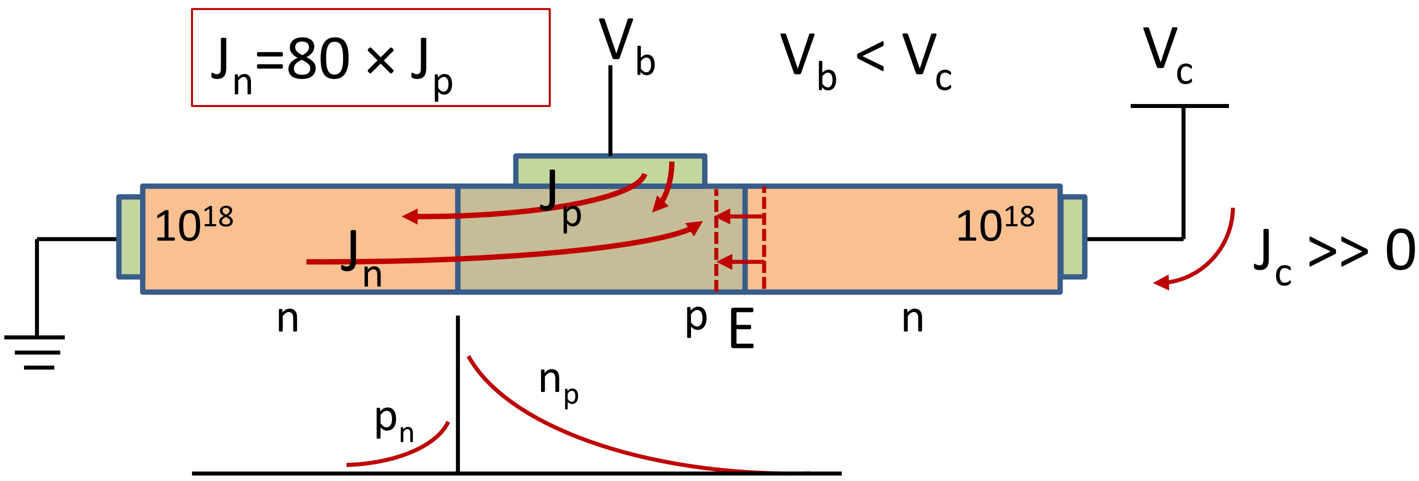
$J_n = 80 \times J_p$



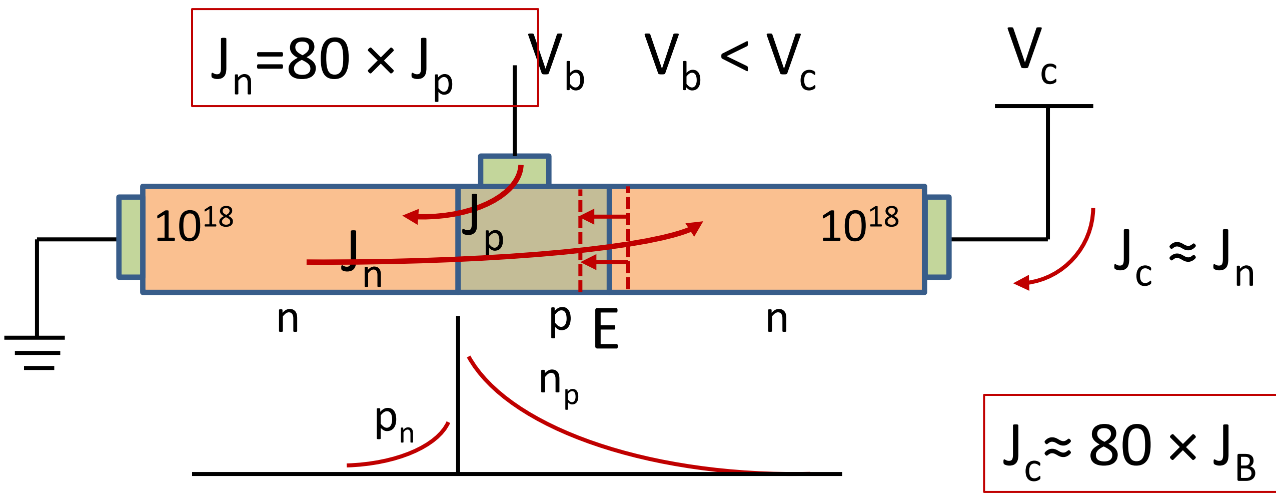
12.2 Bipolar Junction transistor



12.2 Bipolar Junction transistor

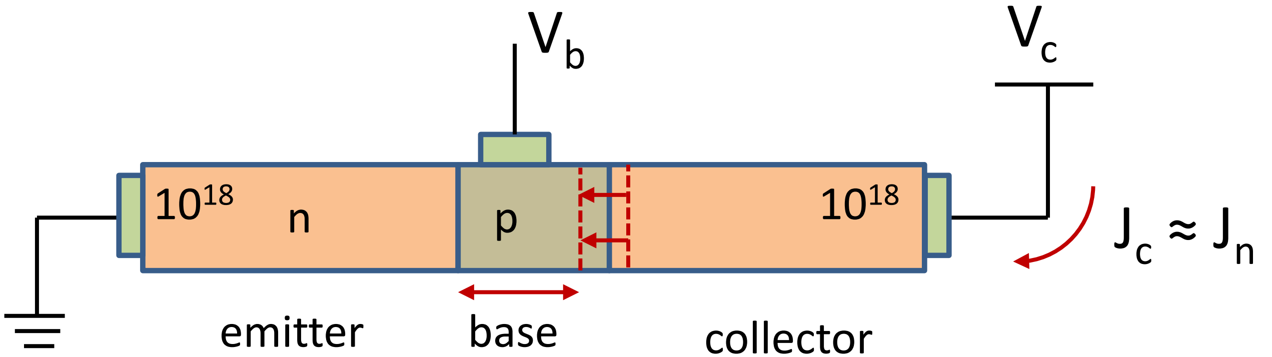


12.2 Bipolar Junction transistor



$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

12.2 Bipolar Junction transistor

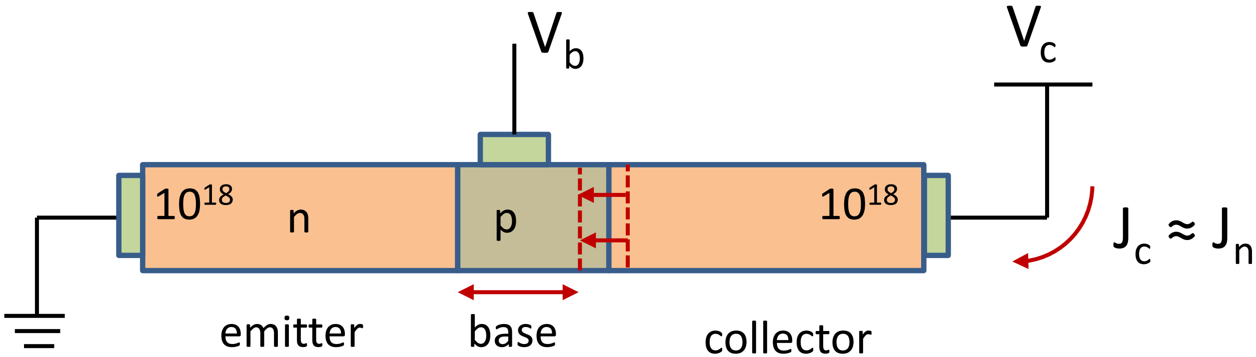


$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

BJT Charateristics:

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

12.2 Bipolar Junction transistor: I-V



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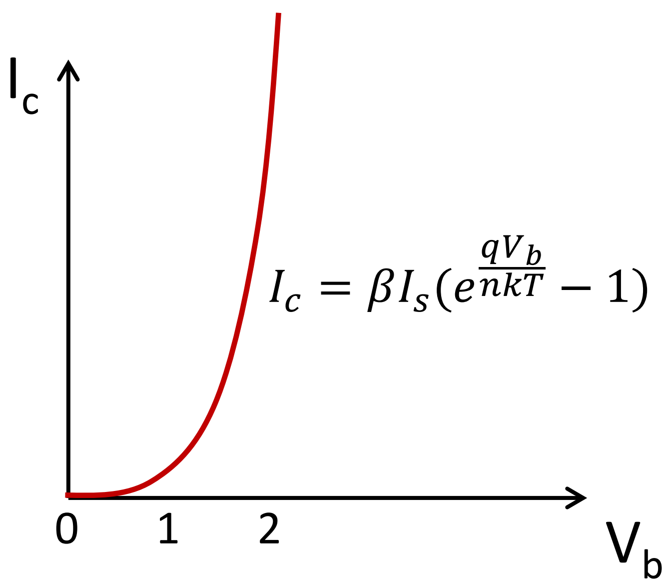
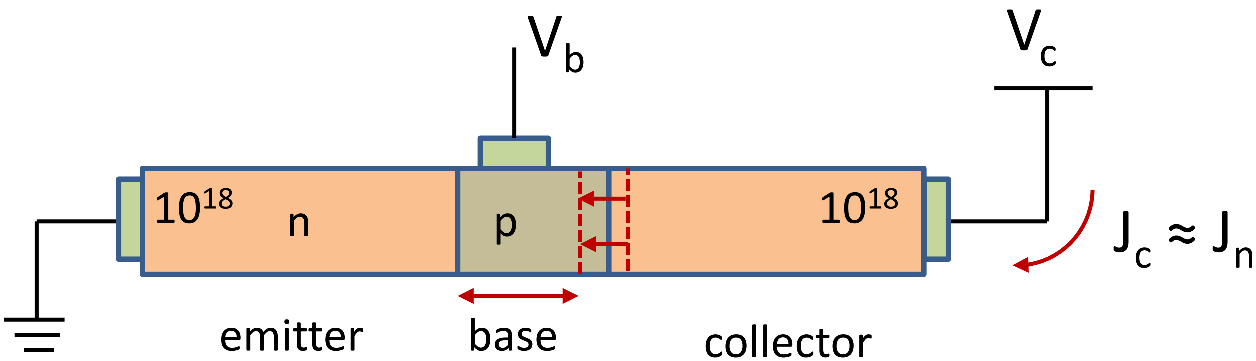


$$I_c = \beta I_s(e^{\frac{qV_b}{nkT}} - 1)$$

12.2 Bipolar Junction transistor: I-V



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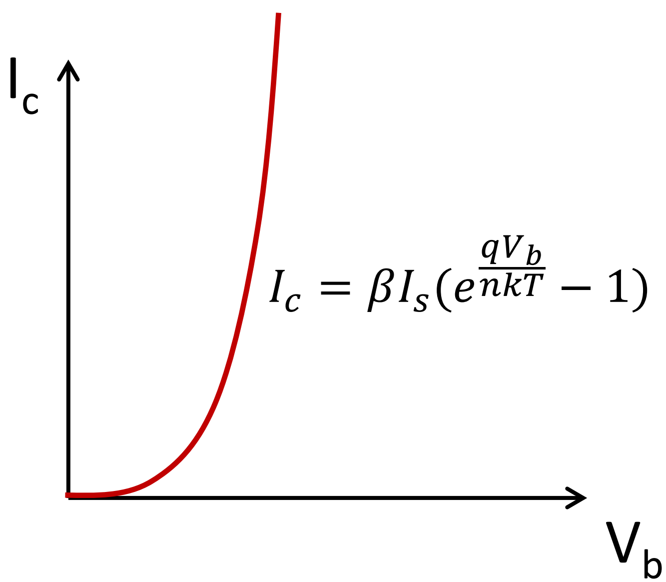
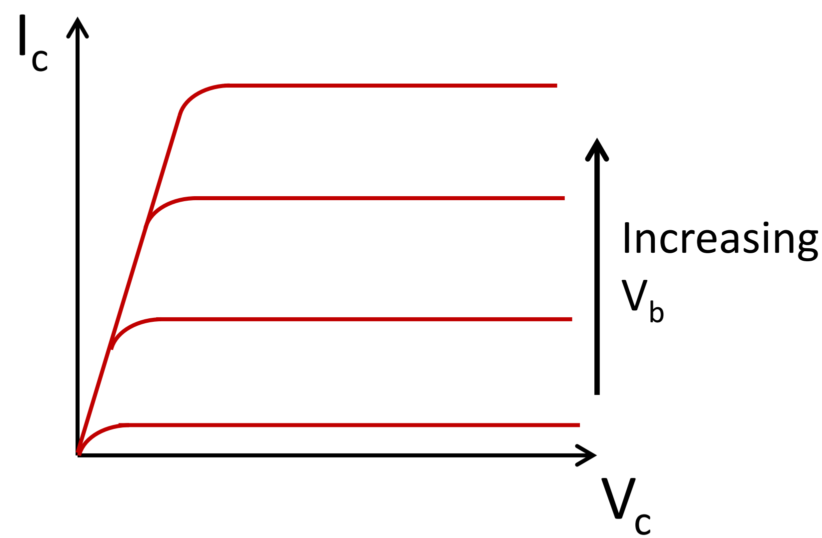
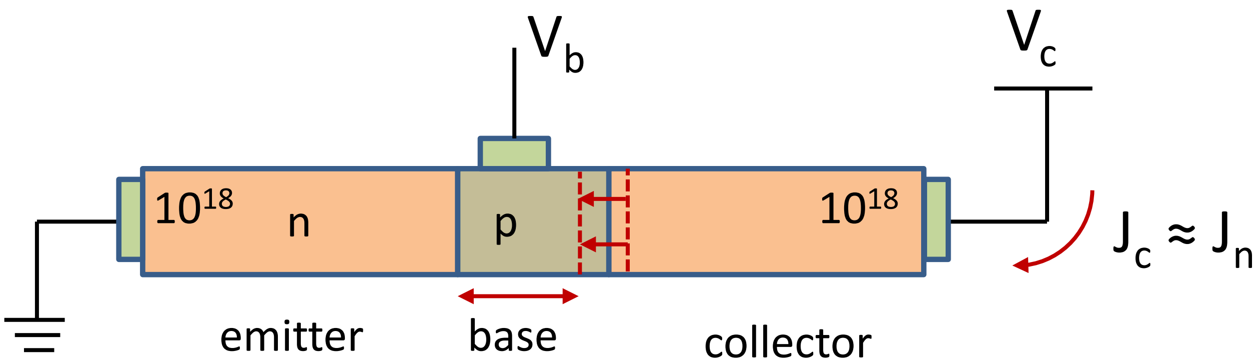
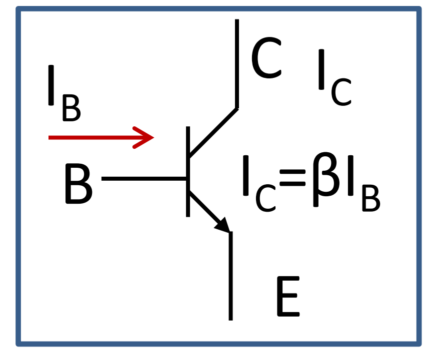




12.2 Bipolar Junction transistor: I-V



$$\boxed{J_c \approx 80 \times J_B \rightarrow \text{Gain } \beta = 80}$$

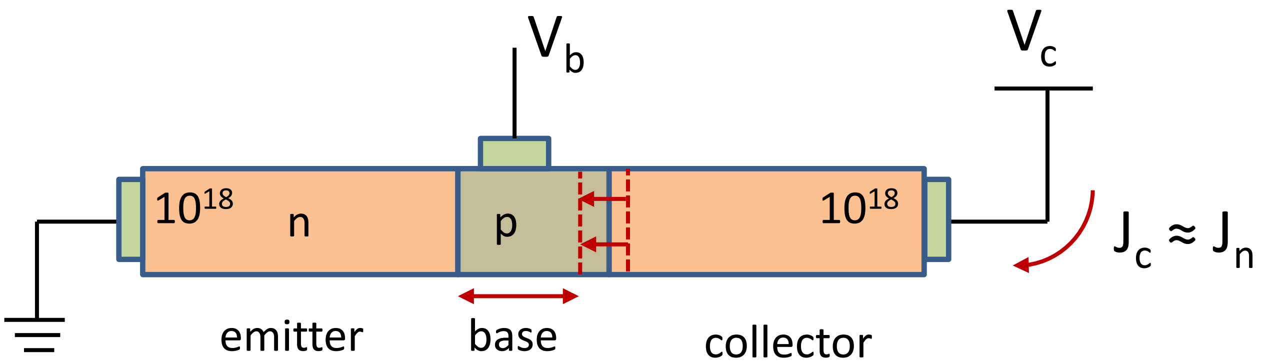


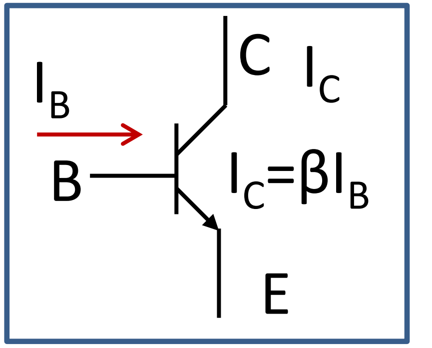
Basic facts:

1. Narrower base → larger gain

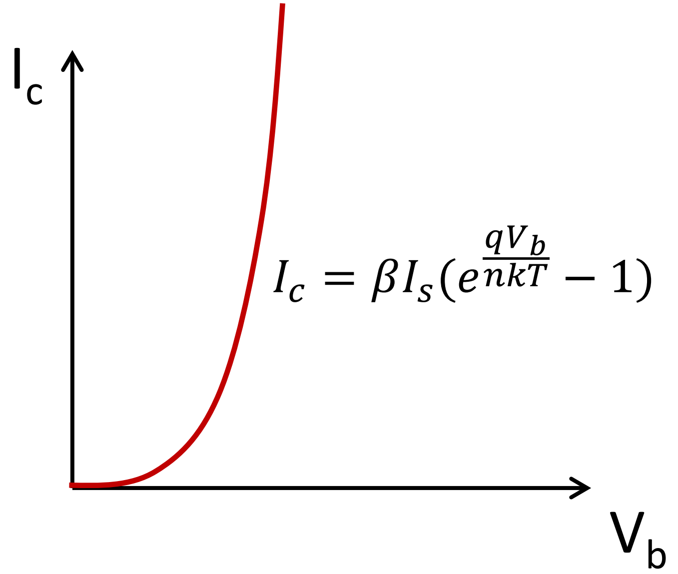
2. $\beta \approx N_D/N_A$, higher emitter-to-base doping ratio → higher gain

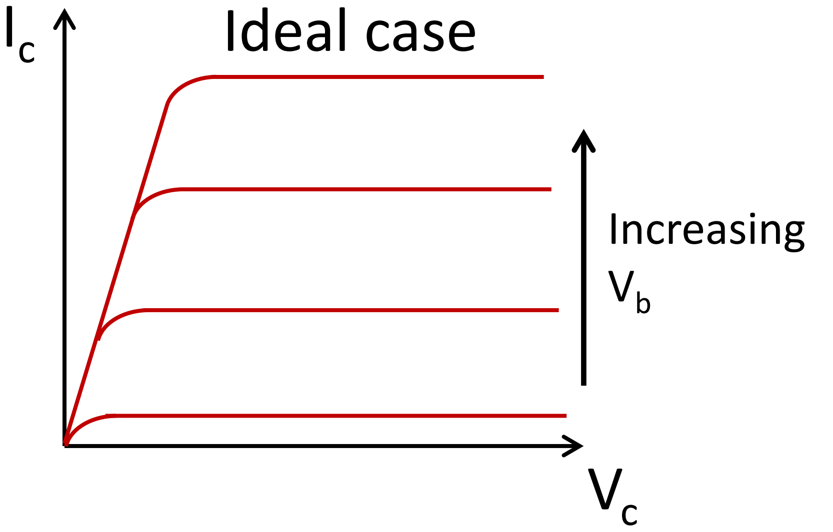
12.2 Bipolar Junction transistor: I-V





$J_c \approx 80 \times J_B \rightarrow$ Gain β=80





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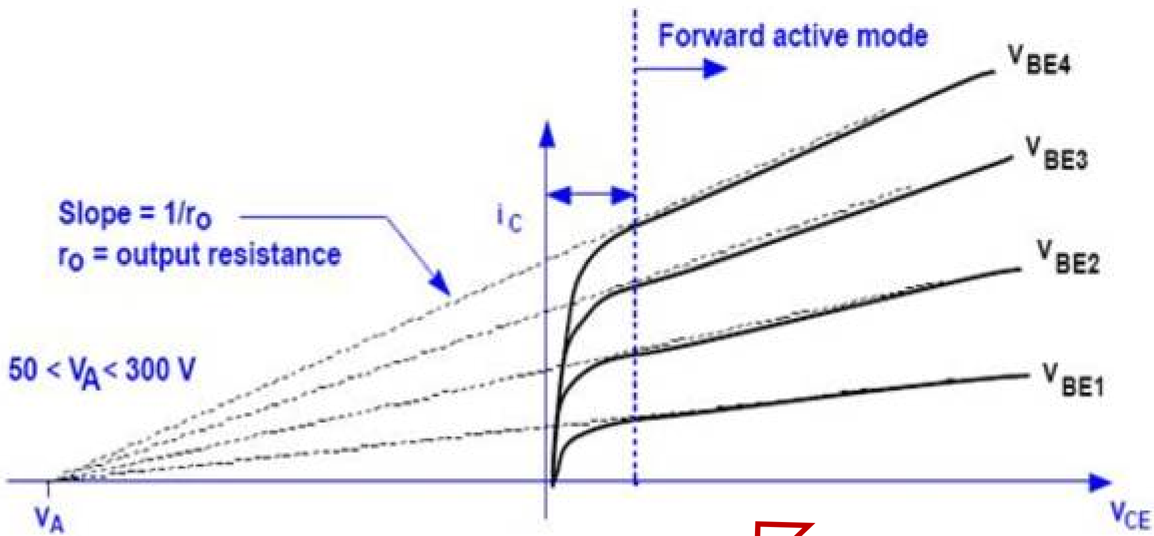
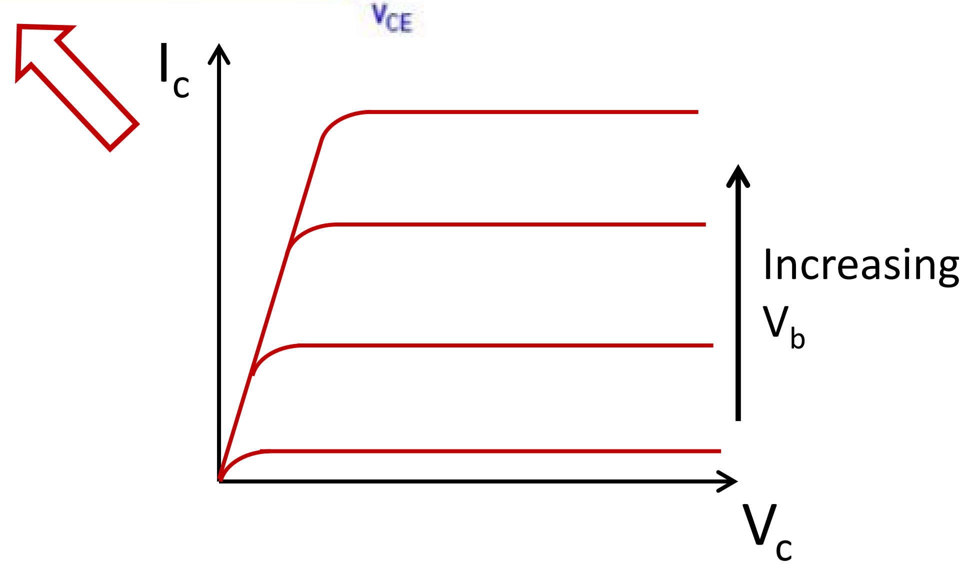
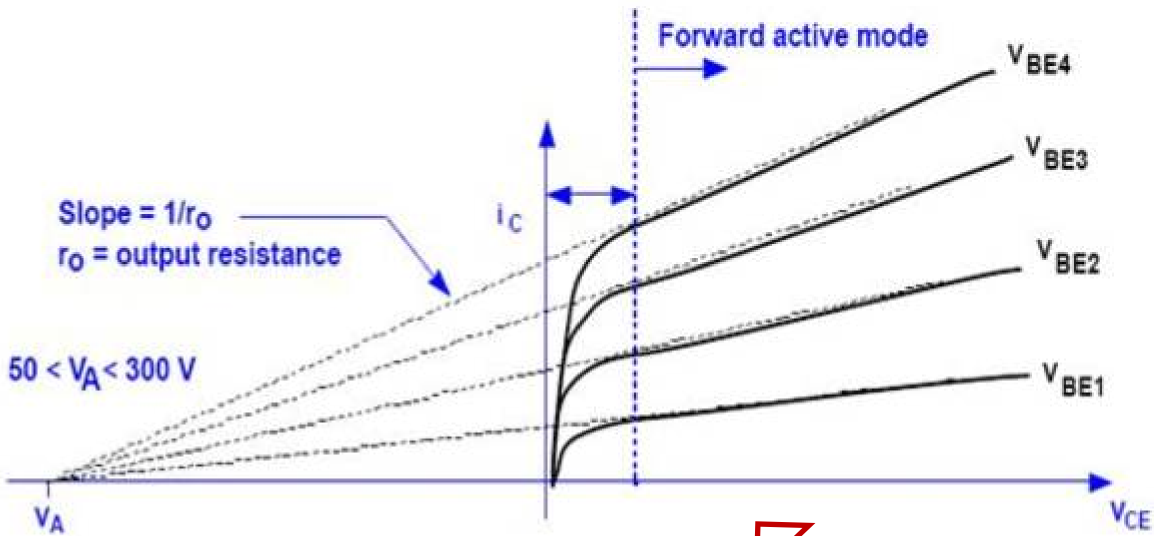
12.3 Early Effect





12.3 Early Effect



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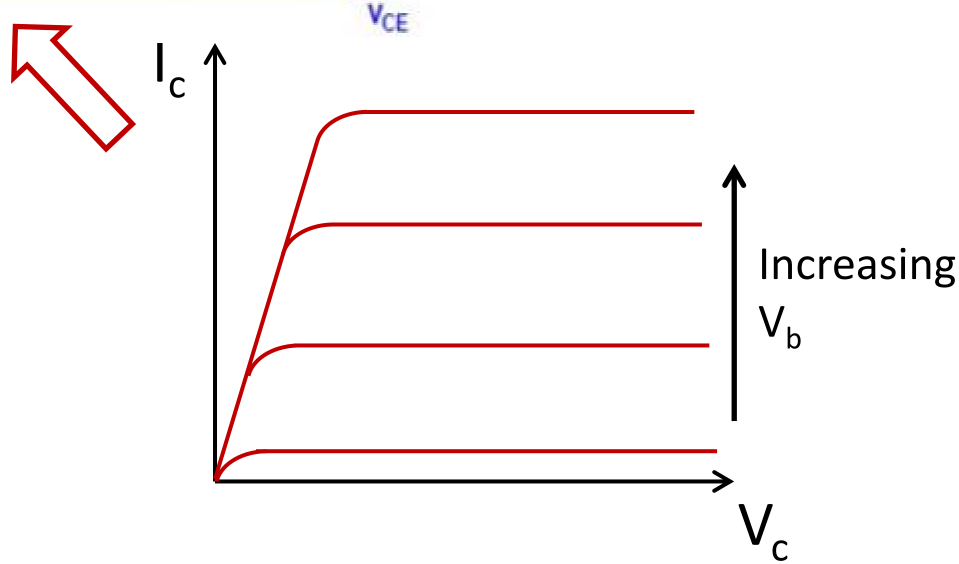

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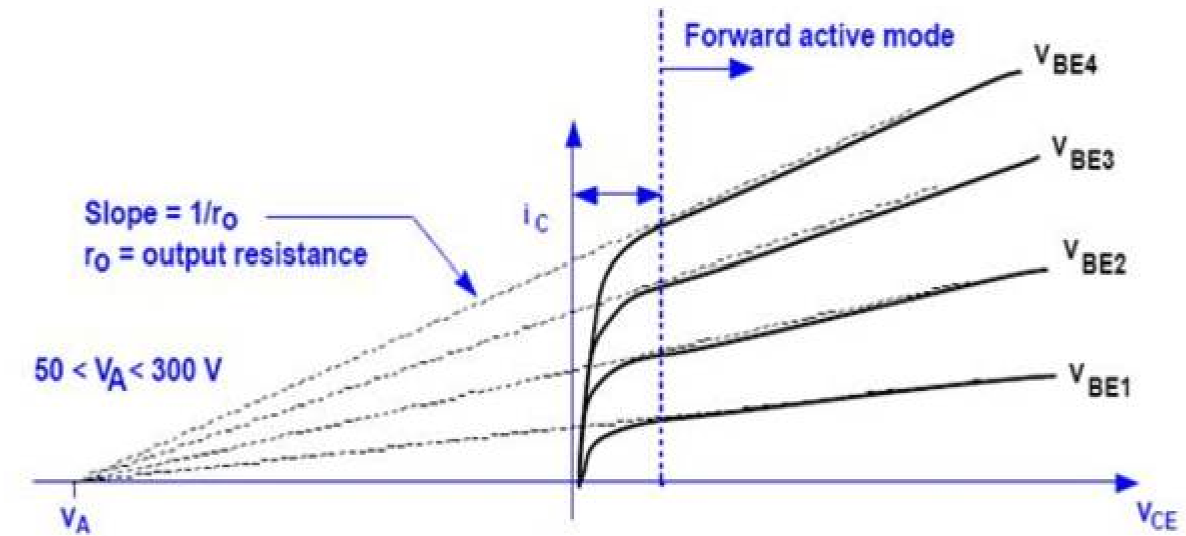

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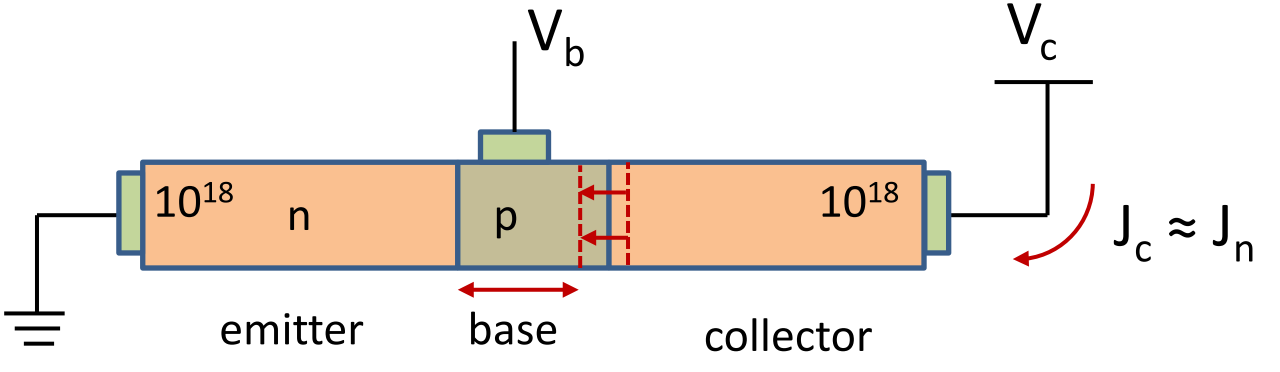

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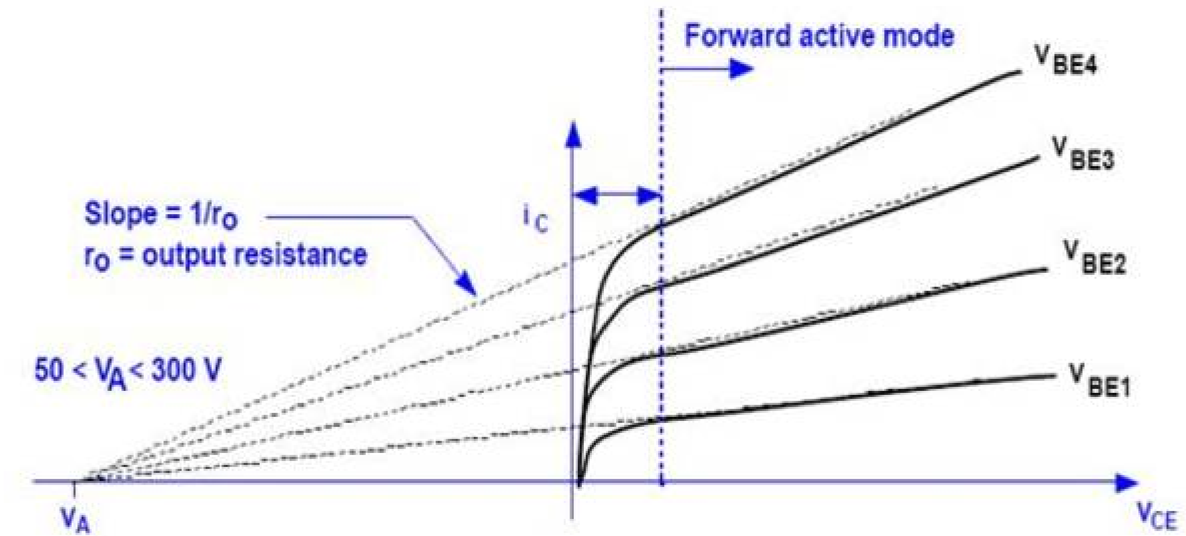

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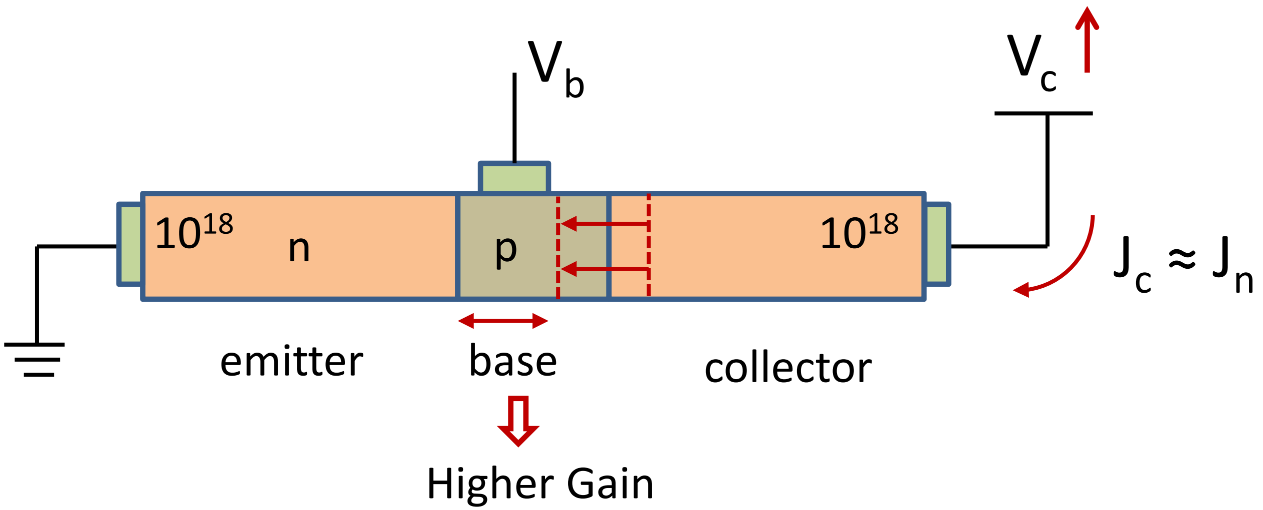
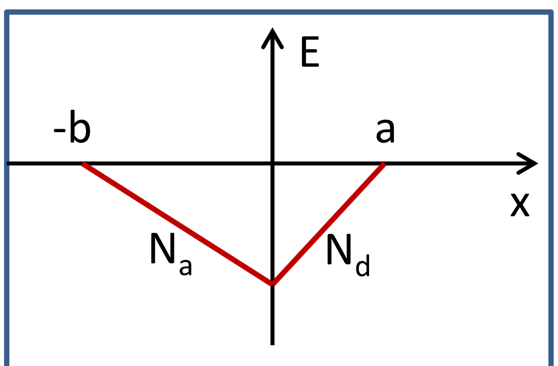
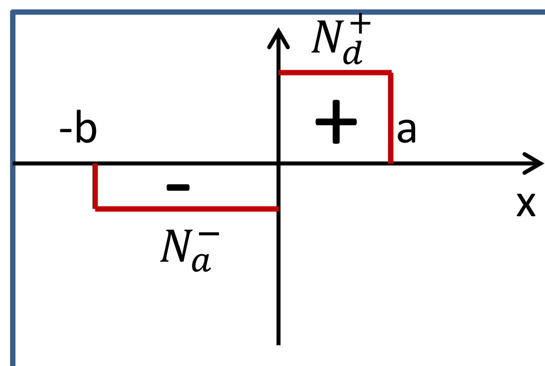


Previously…

$$a = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{N_a}{N_d}\frac{1}{N_a+N_d}}$$

$$N_A^- b = N_D^+ a \Rightarrow b = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{N_d}{N_a}\frac{1}{N_a+N_d}}$$





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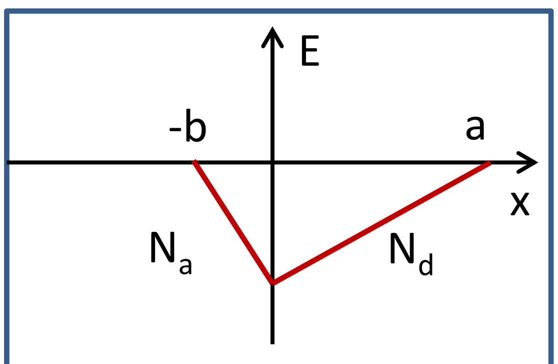
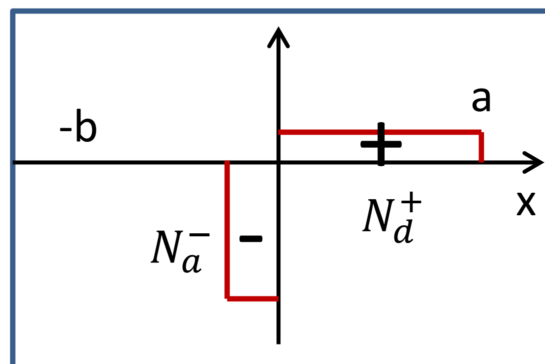
$$N_A^- b = N_D^+ a \Rightarrow b = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{N_d}{N_a}\frac{1}{N_a+N_d}}$$

$N_a = 100\ N_d$

$$a = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{\cancel{100N_d}}{N_d}\frac{1}{\cancel{100N_d}}}$$

$$b = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{\cancel{N_d}}{100\cancel{N_d}}\frac{1}{100N_d}}$$





12.3 Early Effect

=1/10000

$$a = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{10^{16}}{10^{18}}\frac{1}{10^{16}+10^{18}}}$$

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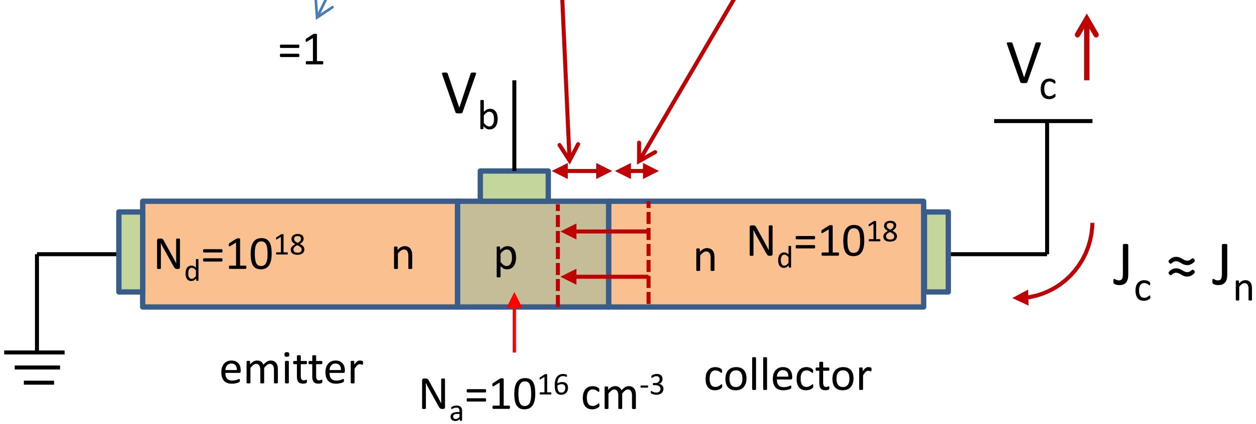
$$b = \sqrt{\frac{2\varepsilon(V_{bi}-V_R)}{q}\frac{10^{18}}{10^{16}}\frac{1}{10^{16}+10^{18}}}$$

=1



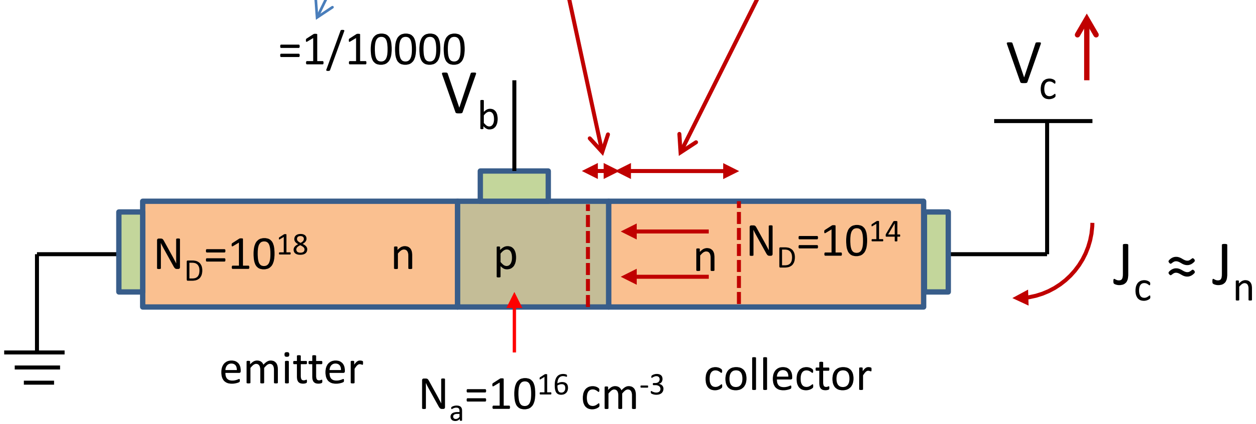
12.3 Early Effect

=1

$$a = \sqrt{\frac{2\varepsilon(V_{bi} - V_R)}{q} \frac{10^{16}}{10^{14}} \frac{1}{10^{16} + 10^{14}}}$$

$$b = \sqrt{\frac{2\varepsilon(V_{bi} - V_R)}{q} \frac{10^{14}}{10^{16}} \frac{1}{10^{16} + 10^{14}}}$$

=1/10000



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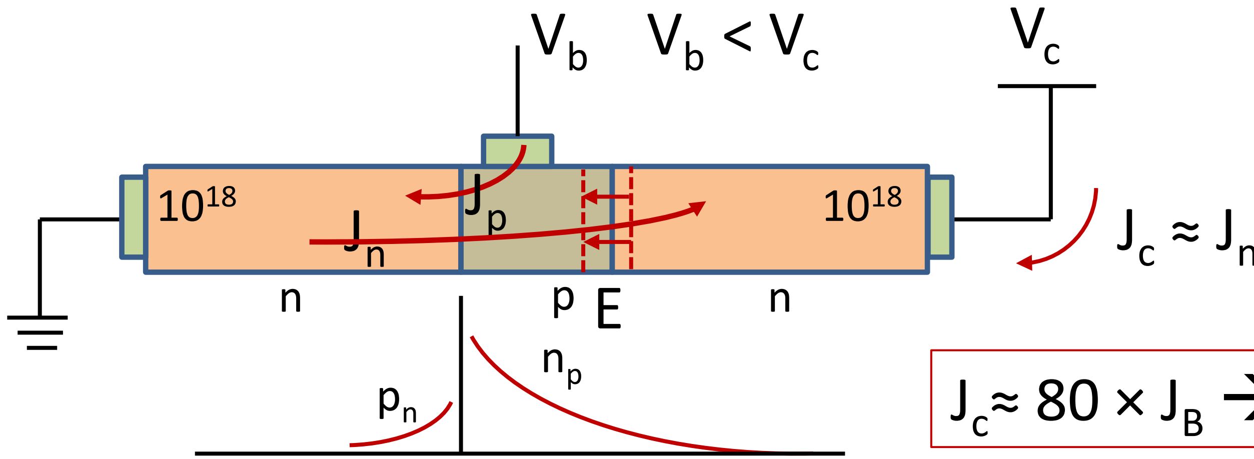
Outline

12.4 Summary



$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

1. highest doping concentration is limited by solubility ($<10^{20}$)
2. Lowest doping concentration is limited by n_i and fabrication process

Basic facts:

1. Narrower base → larger gain
2. $\beta \approx N_D/N_A$, higher emitter-to-base doping ratio → higher gain
3. Trade-off for base doping concentration (gain and Early effect)

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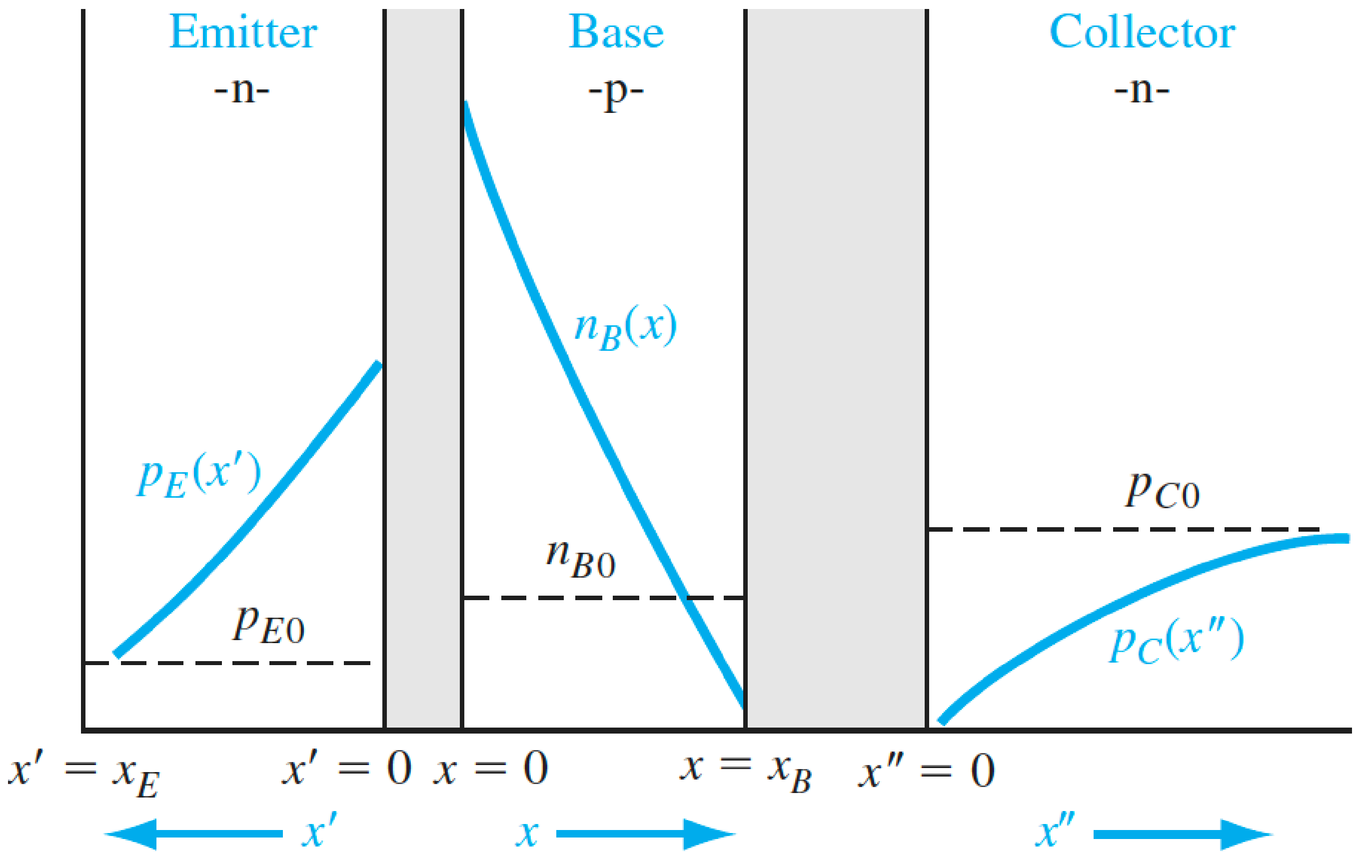
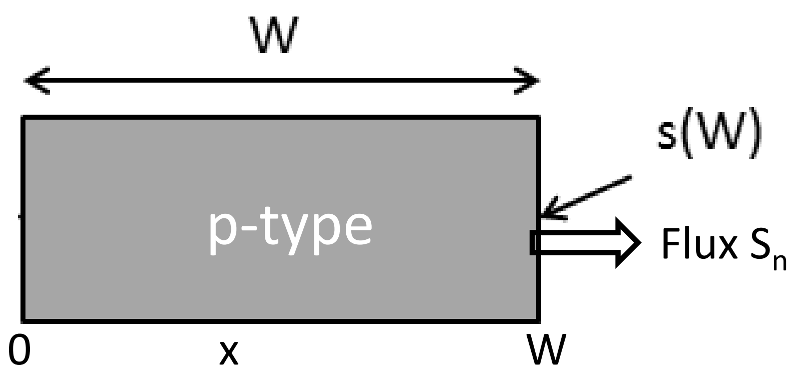
12.5 Quantitative analysis of BJT gain



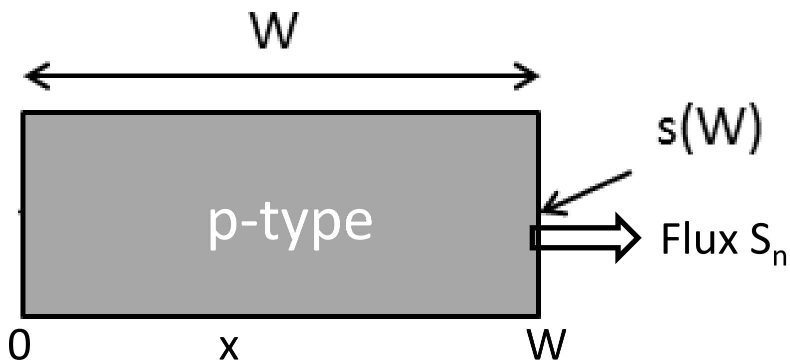
12.5 Quantitative analysis of BJT gain



$N_a = 10^{17}$ 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}

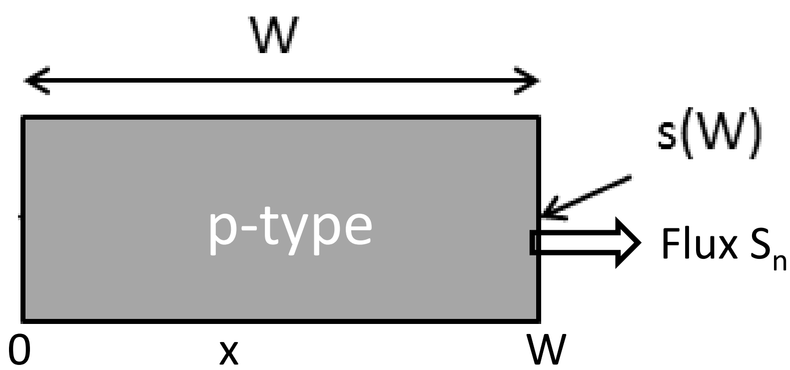
Find the electron flux Sn at x=0 and W, if
1) W=20um
2) W=2um

12.5 Quantitative analysis of BJT gain



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

12.5 Quantitative analysis of BJT gain

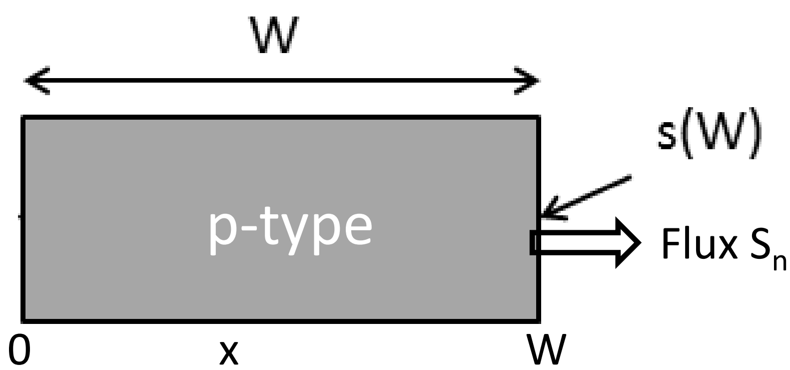


$$\boxed{0 = D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau}}$$

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

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

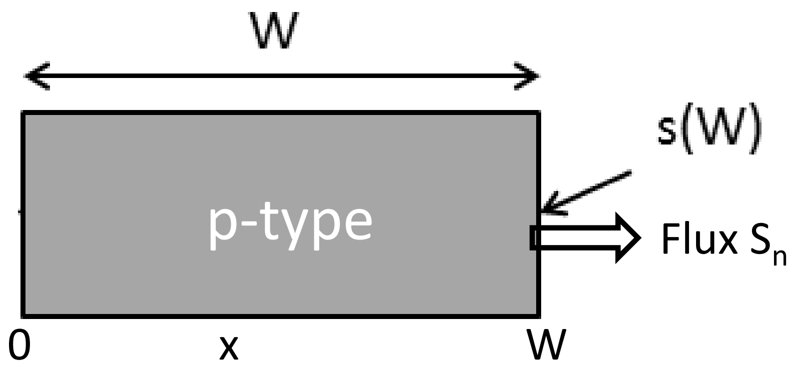
12.5 Quantitative analysis of BJT gain



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

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

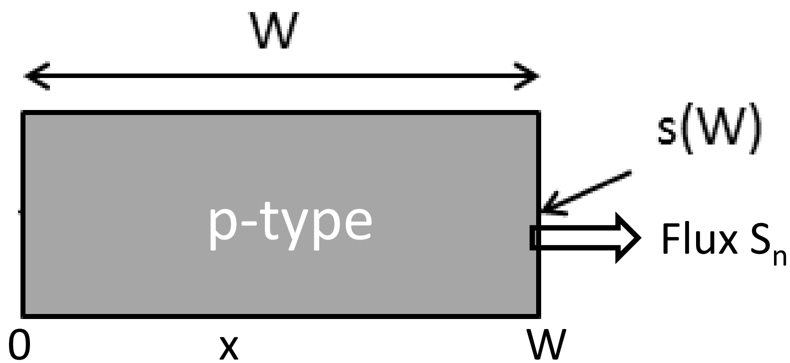
12.5 Quantitative analysis of BJT gain



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

$$\Delta n(x) = (\Delta n)_0 \frac{\mathrm{sh}\left(\frac{W-x}{L_n}\right)}{\mathrm{sh}\left(\frac{W}{L_n}\right)}$$

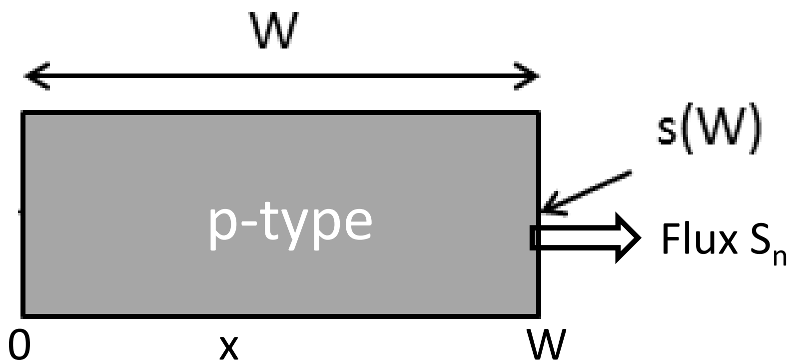
12.5 Quantitative analysis of BJT gain



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

$$\Delta n(x) = (\Delta n)_0 \frac{\mathrm{sh}\left(\frac{W-x}{L_n}\right)}{\mathrm{sh}\left(\frac{W}{L_n}\right)} \qquad S_n = -D_n \frac{d\Delta n(x)}{dx} = \frac{D_n (\Delta n)_0}{L_n} \frac{ch(\frac{W-x}{L_p})}{sh(\frac{W}{L_p})}$$

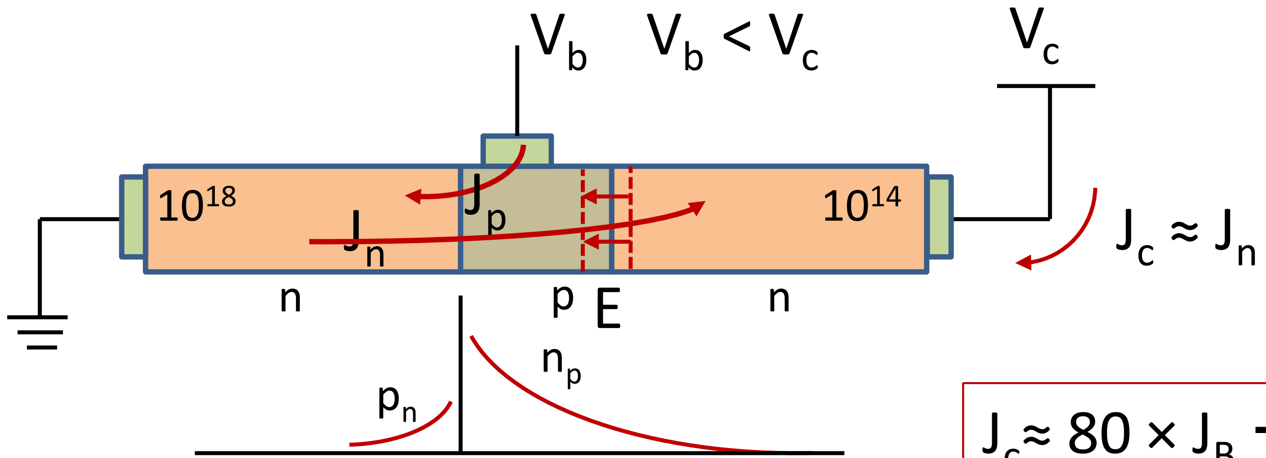
12.5 Quantitative analysis of BJT gain



$$S_n = -D_n \frac{d\Delta n(x)}{dx} = \frac{D_n (\Delta n)_{B0}}{L_n} \frac{ch(\frac{W-x}{L_p})}{sh(\frac{W}{L_p})}$$

$$S_n(0) = \frac{D_n (\Delta n)_0}{L_n} \frac{ch(\frac{W}{L_p})}{sh(\frac{W}{L_p})} \qquad S_n(W) = \frac{D_n (\Delta n)_0}{L_n} \frac{1}{sh(\frac{W}{L_p})}$$

12.5 Quantitative analysis of BJT gain

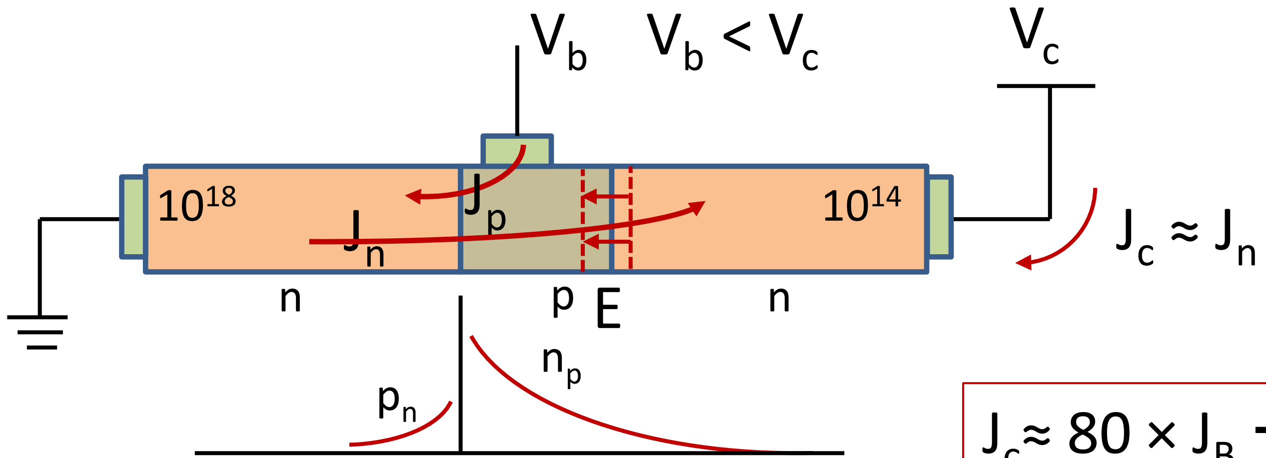


$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

$$S_n(0) = \frac{D_B \cdot (\Delta n)_{B0}}{L_B} \frac{ch(\frac{W}{L_B})}{sh(\frac{W}{L_B})} \qquad S_n(W_b) = \frac{D_B \cdot (\Delta n)_{B0}}{L_B} \frac{1}{sh(\frac{W}{L_B})}$$

Electron flux from emitter to base: $S_n(0)$
Electron flux from base to collector: $S_n(W_b)$

12.5 Quantitative analysis of BJT gain



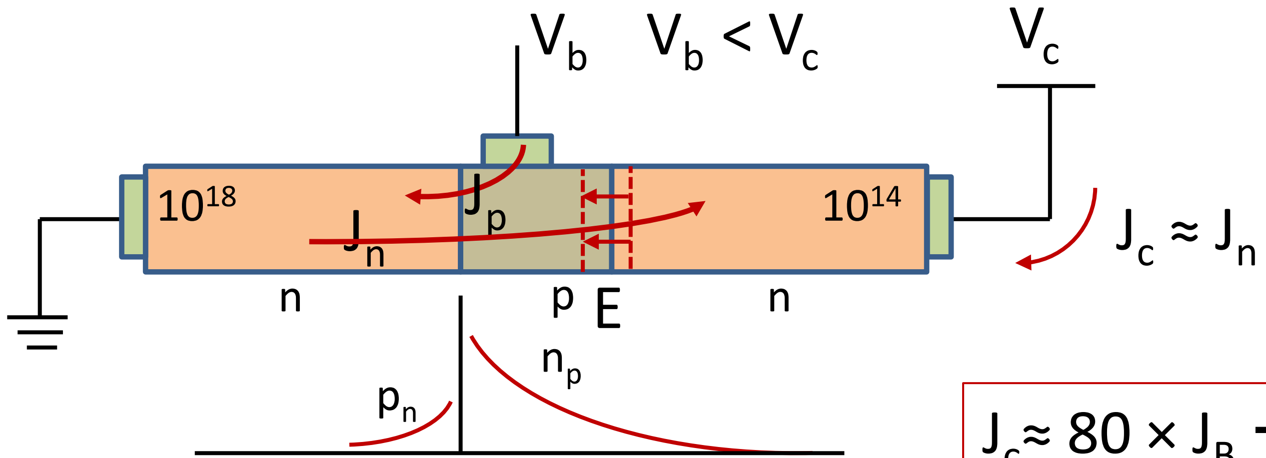
$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

$$S_n(0) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{ch(\frac{W}{L_B})}{sh(\frac{W}{L_B})} \qquad S_n(W_b) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{1}{sh(\frac{W}{L_B})}$$

Electron flux from emitter to base: $S_n(0)$
Electron flux from base to collector: $S_n(W_b)$
Hole flux from base to emitter: S_p

$$S_p = D_E\frac{dp_E}{dx} = \frac{D_E p_{E0}}{L_E}$$

12.5 Quantitative analysis of BJT gain



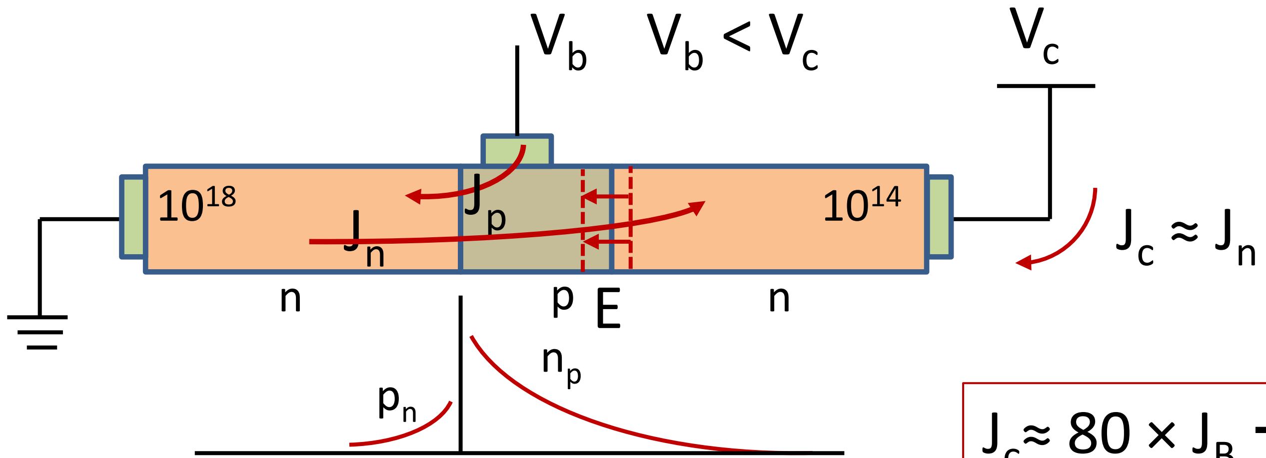
$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

$$S_n(0) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{ch(\frac{W}{L_B})}{sh(\frac{W}{L_B})} \qquad S_n(W_b) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{1}{sh(\frac{W}{L_B})}$$

Electron flux from emitter to base: $S_n(0)$
Electron flux from base to collector: $S_n(W_b)$
Hole flux from base to emitter: S_p
Base electrode flux: $S_p + S_n(0) - S_n(W_b)$

$$S_p = D_E\frac{dp_E}{dx} = \frac{D_E p_{E0}}{L_E}$$

12.5 Quantitative analysis of BJT gain



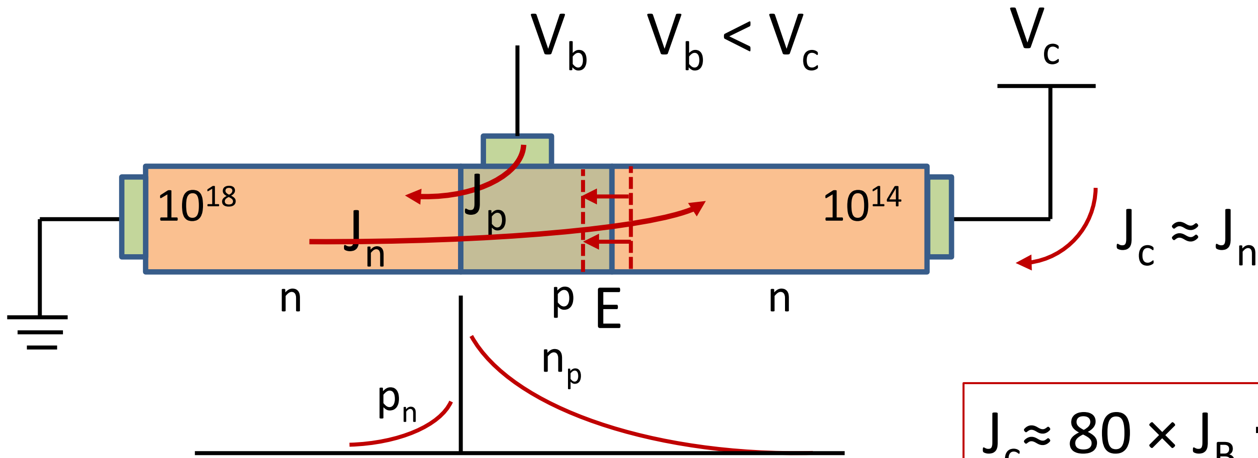
$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

$$S_n(0) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{ch(\frac{W}{L_B})}{sh(\frac{W}{L_B})} \qquad S_n(W_b) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{1}{sh(\frac{W}{L_B})}$$

Electron flux from emitter to base: $S_n(0)$
Electron flux from base to collector: $S_n(W_b)$
Hole flux from base to emitter: S_p
Base electrode flux: $S_p + S_n(0) - S_n(W_b)$
Gain β = collector flux /base electrode flux = $S_n(W_b)/(S_p+S_n(0)-S_n(W_b))$

$$S_p = D_E\frac{dp_E}{dx} = \frac{D_E p_{E0}}{L_E}$$

12.5 Quantitative analysis of BJT gain

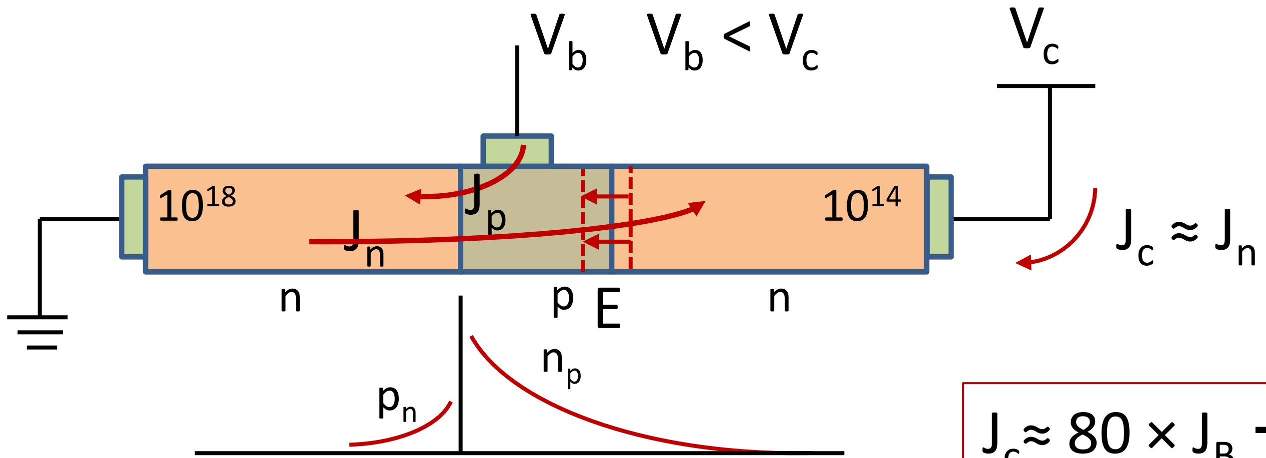


$J_c \approx 80 \times J_B \rightarrow$ Gain $\beta=80$

$$S_n(0) = \frac{D_B(\Delta n)_{B0}}{L_B} \frac{ch(\frac{W}{L_B})}{sh(\frac{W}{L_B})} \qquad S_n(W_b) = \frac{D_B(\Delta n)_{B0}}{L_B} \frac{1}{sh(\frac{W}{L_B})}$$

$$\beta = \frac{\frac{D_B(\Delta n)_{B0}}{L_B} \frac{1}{sh(\frac{W}{L_B})}}{\frac{D_E(\Delta p)_{E0}}{L_E} + \frac{D_B(\Delta n)_{B0}}{L_B} \frac{ch(\frac{W}{L_B})}{sh(\frac{W}{L_B})} - \frac{D_B(\Delta n)_{B0}}{L_B} \frac{1}{sh(\frac{W}{L_B})}}$$

12.5 Quantitative analysis of BJT gain



$J_c \approx 80 \times J_B \rightarrow$ Gain β=80

$$S_n(0) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{ch(\frac{W}{L_p})}{sh(\frac{W}{L_p})} \qquad S_n(W_b) = \frac{D_B(\Delta n)_{B0}}{L_B}\frac{1}{sh(\frac{W}{L_p})}$$

$$\beta = \frac{\frac{D_B(\Delta n)_{B0}}{L_B}}{\frac{D_E(\Delta p)_{E0}}{L_E}sh(\frac{W}{L_B}) + \frac{D_B(\Delta n)_{B0}}{L_B}[ch\left(\frac{W}{L_p}\right) - 1]}$$

12.5 Quantitative analysis of BJT gain

$$sh\left(\frac{W}{L_B}\right) = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) - exp\left(-\frac{W}{L_B}\right)\right]$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$\beta = \frac{\frac{D_B(\Delta n)_{B0}}{L_B}}{\frac{D_E(\Delta p)_{E0}}{L_E} sh\left(\frac{W}{L_B}\right) + \frac{D_B(\Delta n)_{B0}}{L_B}\left[ch\left(\frac{W}{L_p}\right) - 1\right]}$$

12.5 Quantitative analysis of BJT gain

$$sh\left(\frac{W}{L_B}\right) = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) - exp\left(-\frac{W}{L_B}\right)\right] = \frac{W}{L_B}$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$if\ \frac{W}{L_p} < 1$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$\beta = \frac{\frac{D_B(\Delta n)_{B0}}{L_B}}{\frac{D_E(\Delta p)_{E0}}{L_E} sh\left(\frac{W}{L_B}\right) + \frac{D_B(\Delta n)_{B0}}{L_B}\left[ch\left(\frac{W}{L_p}\right) - 1\right]}$$

12.5 Quantitative analysis of BJT gain

$$ch\left(\frac{W}{L_B}\right) - 1 = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) + \exp\left(-\frac{W}{L_B}\right)\right] - 1$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$\beta = \frac{\frac{D_B(\Delta n)_{B0}}{L_B}}{\frac{D_E(\Delta p)_{E0}}{L_E}\frac{W}{L_B} + \frac{D_B(\Delta n)_{B0}}{L_B}\left[ch\left(\frac{W}{L_p}\right) - 1\right]}$$

12.5 Quantitative analysis of BJT gain

$$ch\left(\frac{W}{L_B}\right) - 1 = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) + \exp\left(-\frac{W}{L_B}\right)\right] - 1 = \frac{1}{2}\left(\frac{W}{L_B}\right)^2$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$if\ \frac{W}{L_B} < 1$$

$$\beta = \frac{\dfrac{D_B(\Delta n)_{B0}}{L_B}}{\dfrac{D_E(\Delta p)_{E0}}{L_E}\dfrac{W}{L_B} + \dfrac{D_B(\Delta n)_{B0}}{L_B}\left[\dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2\right]}$$

12.5 Quantitative analysis of BJT gain

$$ch\left(\frac{W}{L_B}\right) - 1 = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) + \exp\left(-\frac{W}{L_B}\right)\right] - 1 = \frac{1}{2}\left(\frac{W}{L_B}\right)^2$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$if\ \frac{W}{L_B} < 1$$

$$\beta = \frac{\frac{D_B(\Delta n)_{B0}}{L_B}}{\frac{D_E(\Delta p)_{E0}}{L_E}\frac{W}{L_B} + \frac{D_B(\Delta n)_{B0}}{L_B}\left[\frac{1}{2}\left(\frac{W}{L_B}\right)^2\right]} = \frac{1}{\frac{D_E(\Delta p)_{E0}W}{D_B(\Delta n)_{B0}L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

12.5 Quantitative analysis of BJT gain

$$ch\left(\frac{W}{L_B}\right) - 1 = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) + \exp\left(-\frac{W}{L_B}\right)\right] - 1 = \frac{1}{2}\left(\frac{W}{L_B}\right)^2$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$if\ \frac{W}{L_B} < 1$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$\boxed{\beta = \frac{1}{\frac{N_B D_E W}{N_E D_B L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}}$$

12.5 Quantitative analysis of BJT gain

$$ch\left(\frac{W}{L_B}\right) - 1 = \frac{1}{2}\left[\exp\left(\frac{W}{L_B}\right) + \exp\left(-\frac{W}{L_B}\right)\right] - 1 = \frac{1}{2}\left(\frac{W}{L_B}\right)^2$$

$$\exp\left(\frac{W}{L_B}\right) = 1 + \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 + \cdots$$

$$if\ \frac{W}{L_B} < 1$$

$$\exp\left(-\frac{W}{L_B}\right) = 1 - \frac{W}{L_B} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2 - \cdots$$

$$\beta = \frac{1}{\frac{N_B D_E W}{N_E D_B L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$\beta = S_n(W_b)/(S_p + \underbrace{S_n(0) - S_n(W_b)}))$

Outline

12.1 Review and example

12.2 Bipolar Junction transistor

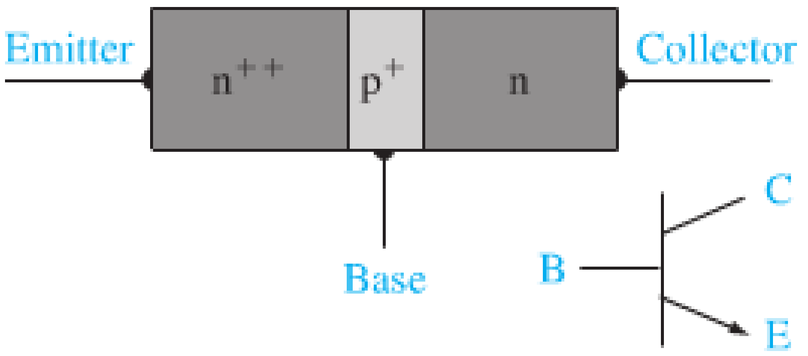
12.3 Early Effect

12.4 Summary

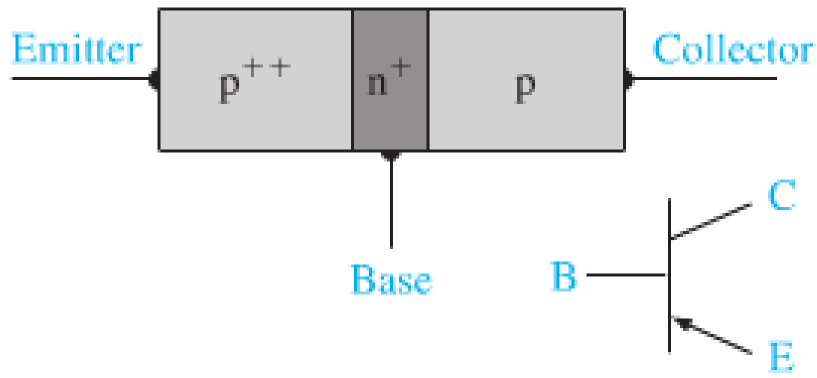
12.5 Quantitative analysis of BJT gain

12.6 BJT symbols and planar device structure

12.6 BJT symbols and planar device structure

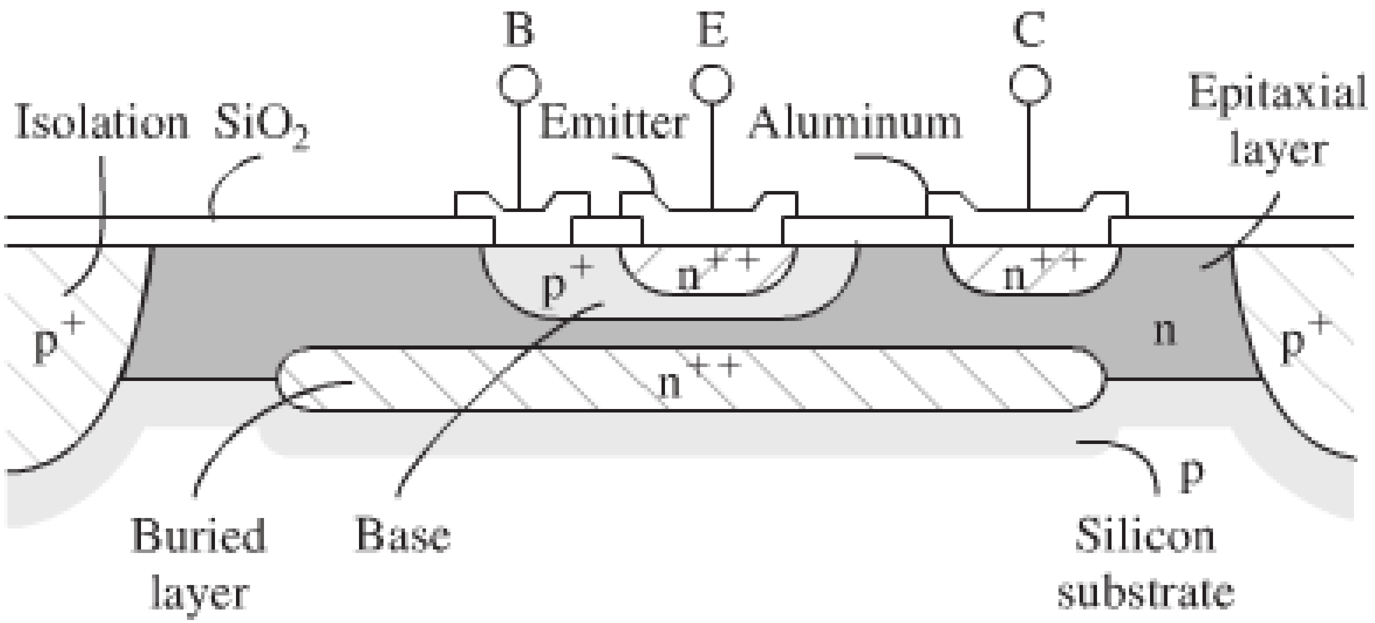


(a)



(b)

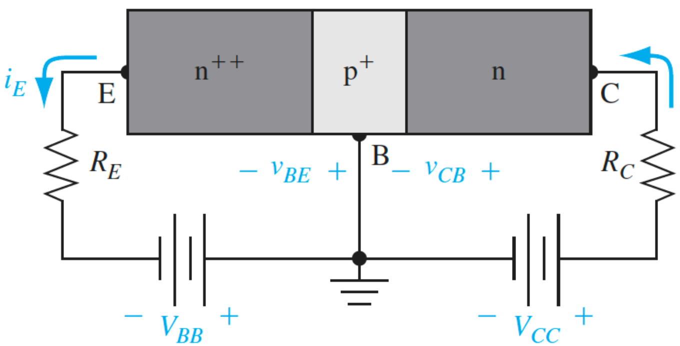
12.6 BJT symbols and planar device structure



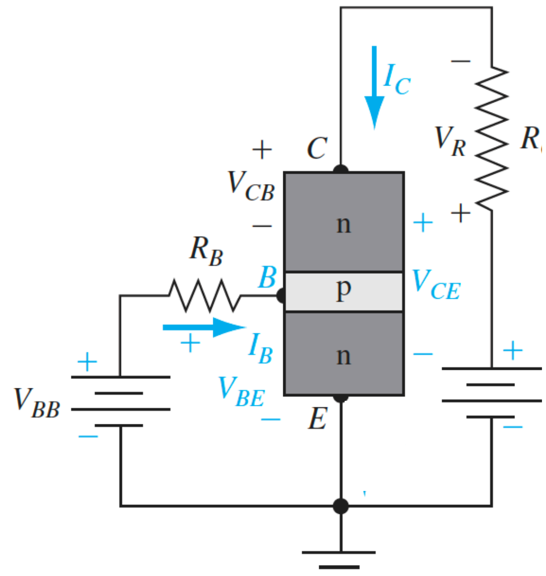
Conventional npn transistor

12.7 BJT symbols and planar device structure

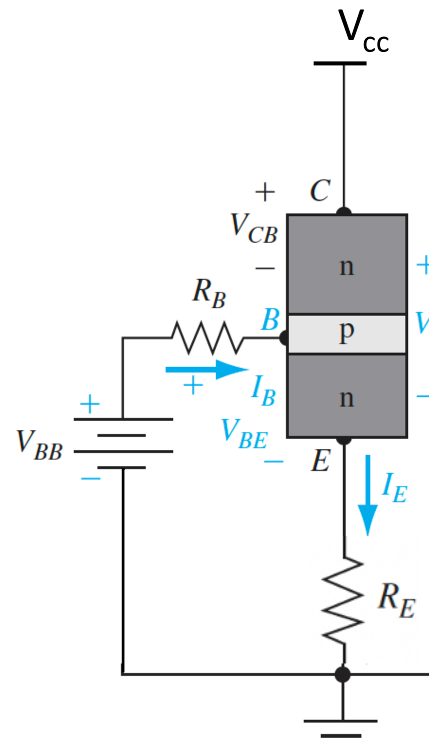
The basic principle of operation



Common base



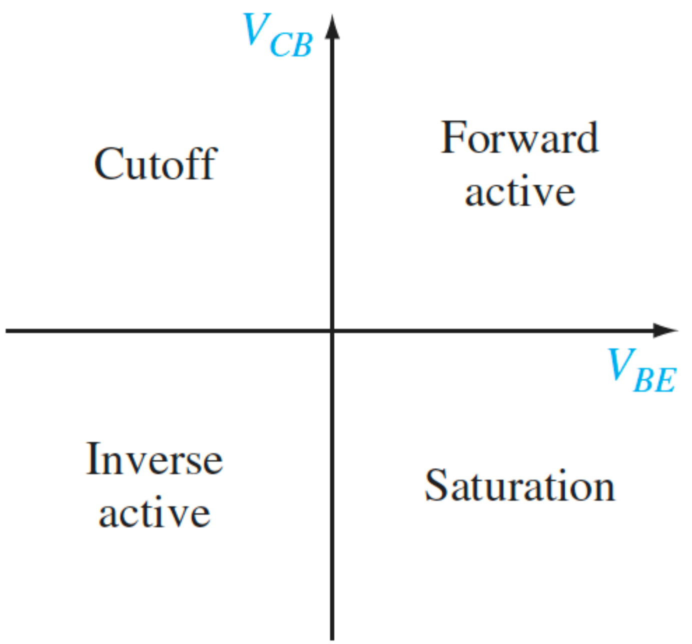
Common emitter

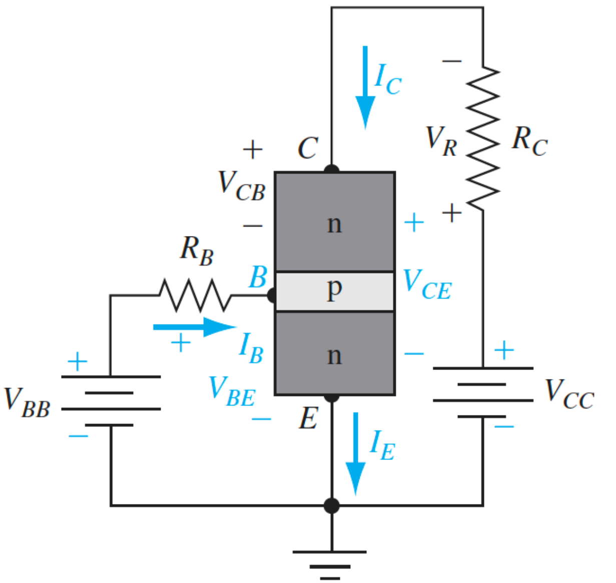


Common collector

12.7 BJT symbols and planar device structure

The basic principle of operation

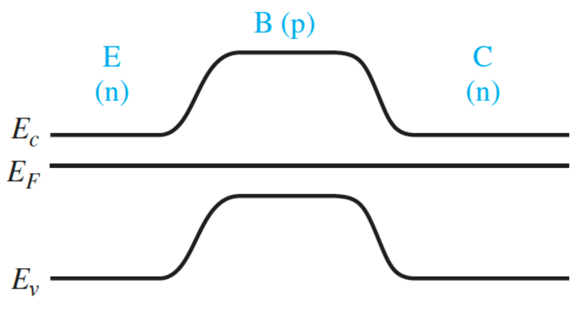




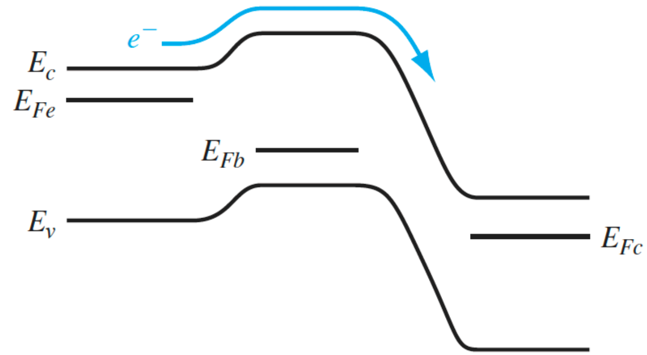
Common emitter

12.7 BJT symbols and planar device structure

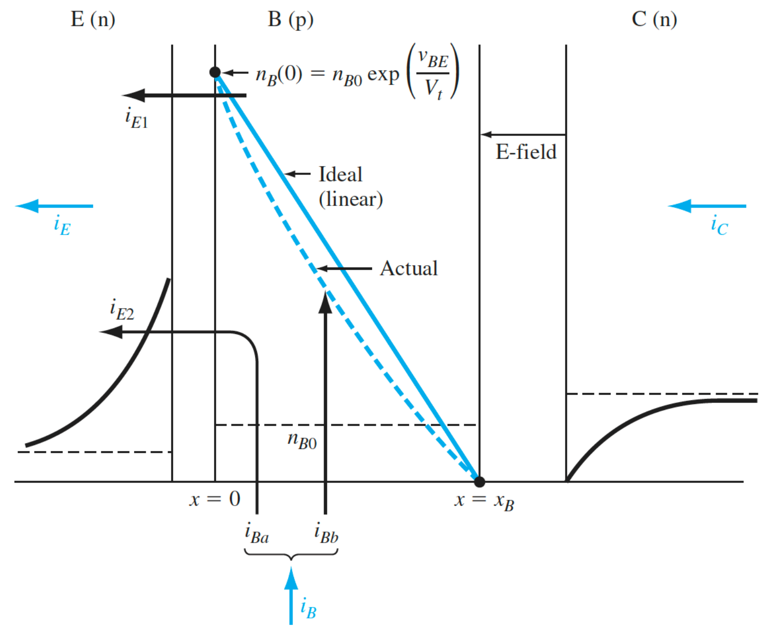
The basic principle of operation



Zero bias

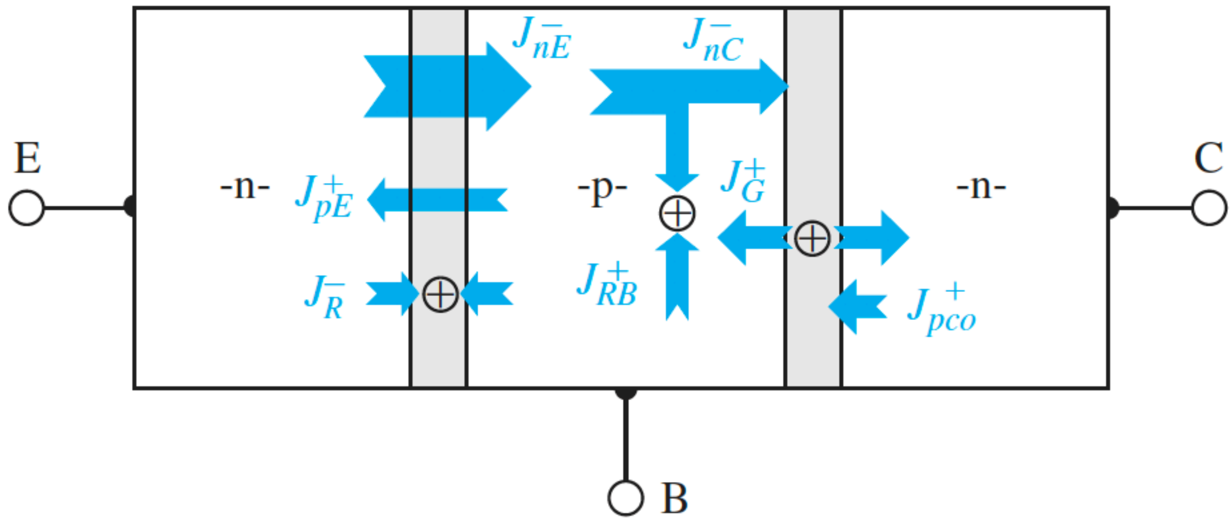


Forward active



12.7 BJT symbols and planar device structure

The basic principle of operation

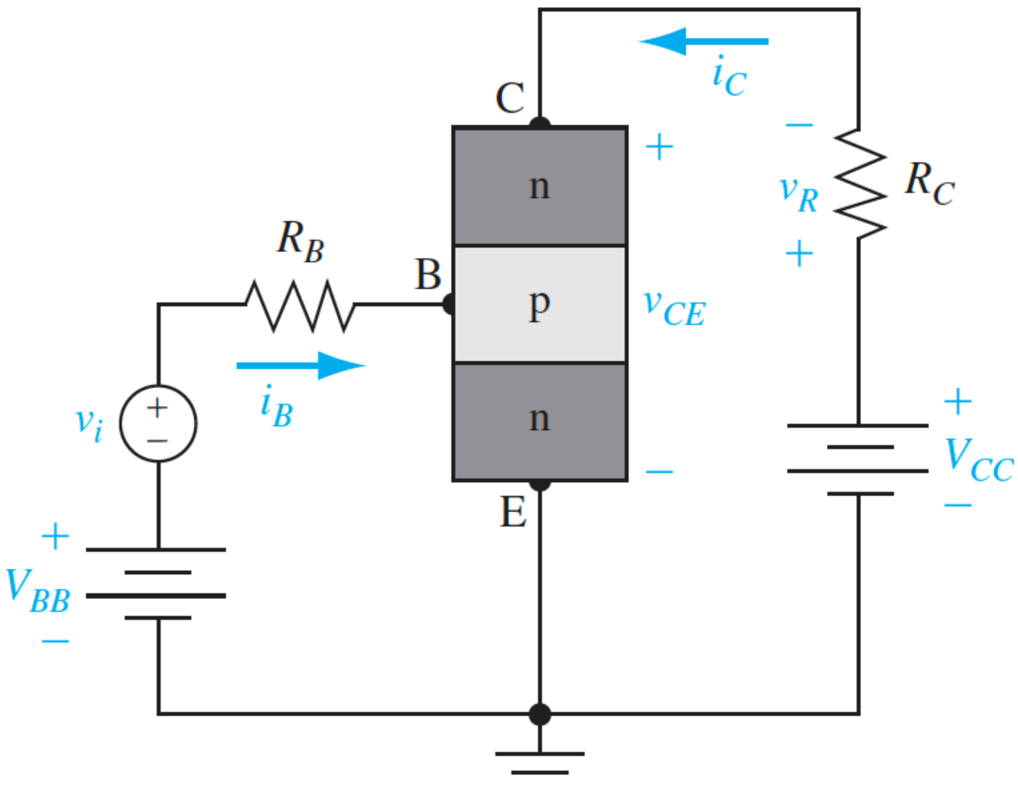


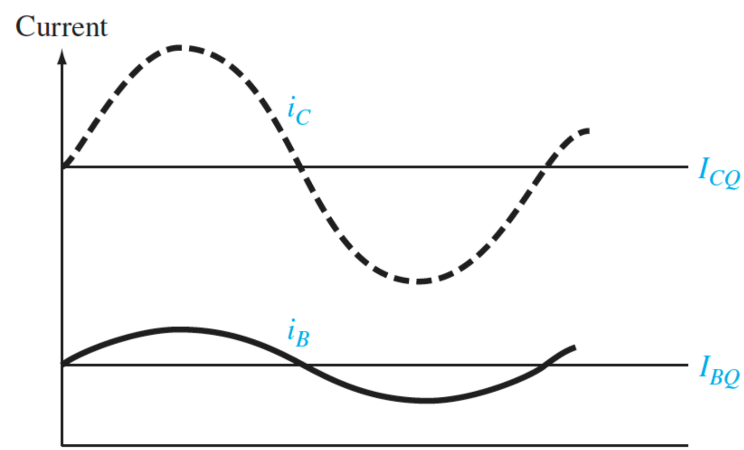
$$\alpha_0 = \frac{I_C}{I_E}$$

$$\alpha_0 = \frac{J_C}{J_E} = \frac{J_{nC} + J_G + J_{pc0}}{J_{nE} + J_R + J_{pE}}$$

12.7 BJT symbols and planar device structure

The basic principle of operation

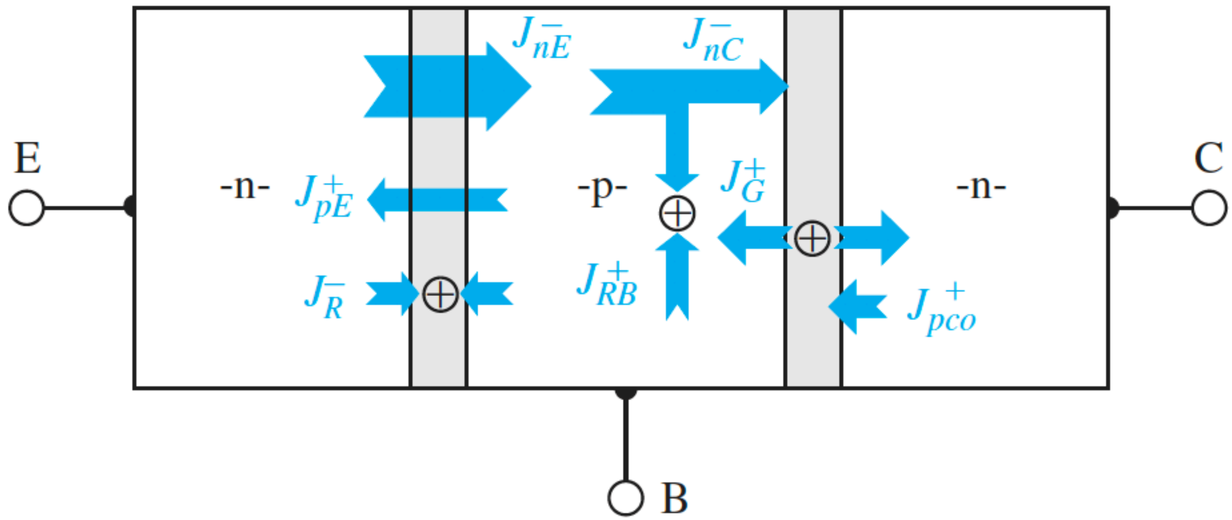




(b)

12.7 BJT symbols and planar device structure

The basic principle of operation



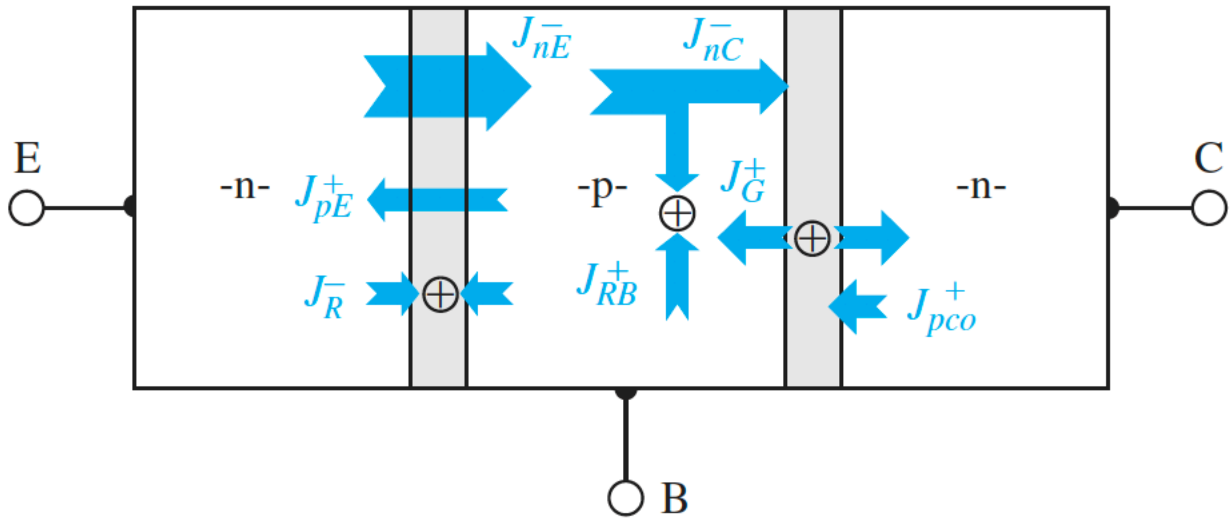
$$\alpha_0 = \frac{I_C}{I_E}$$

$$\alpha_0 = \frac{J_C}{J_E} = \frac{J_{nC} + J_G + J_{pc0}}{J_{nE} + J_R + J_{pE}}$$

$$\boxed{\alpha = \frac{\partial J_C}{\partial J_E} = \frac{J_{nC}}{J_{nE} + J_R + J_{pE}}}$$

12.7 BJT symbols and planar device structure

The basic principle of operation

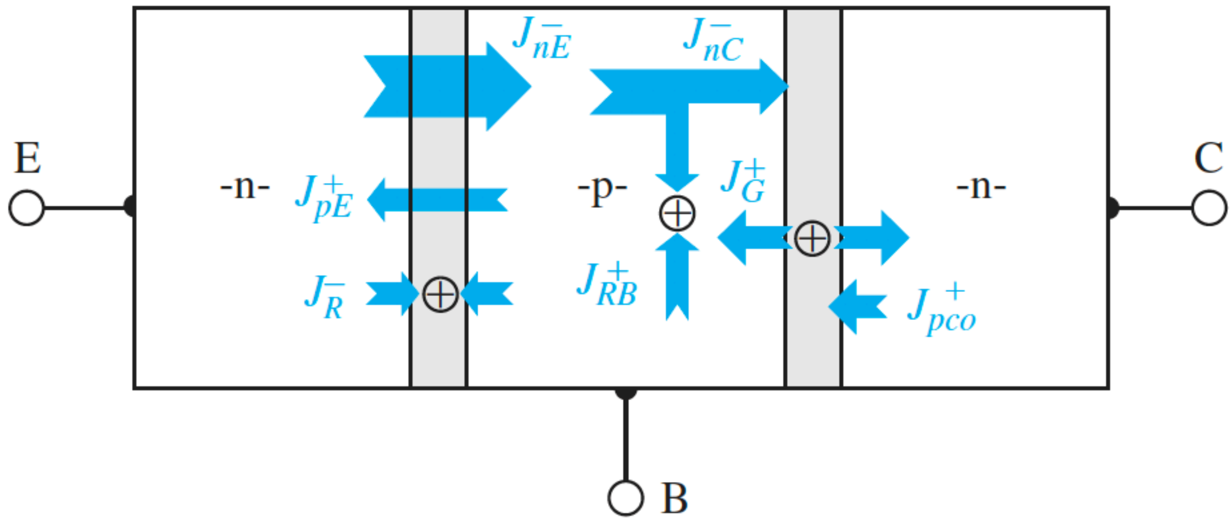


$$\boxed{\alpha = \frac{\partial J_C}{\partial J_E} = \frac{J_{nC}}{J_{nE} + J_R + J_{pE}}}$$

$$\alpha = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right)\left(\frac{J_{nC}}{J_{nE}}\right)\left(\frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}}\right)$$

12.7 BJT symbols and planar device structure

The basic principle of operation



$$\gamma = \left(\frac{J_{nE}}{J_{nE} + J_{pE}}\right) \equiv \text{emitter injection efficiency factor}$$

$$\alpha_T = \left(\frac{J_{nC}}{J_{nE}}\right) \equiv \text{base transport factor}$$

$$\delta = \frac{J_{nE} + J_{pE}}{J_{nE} + J_R + J_{pE}} \equiv \text{recombination factor}$$