
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

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12.1 Review and example

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12.5 Quantitative analysis of BJT gain

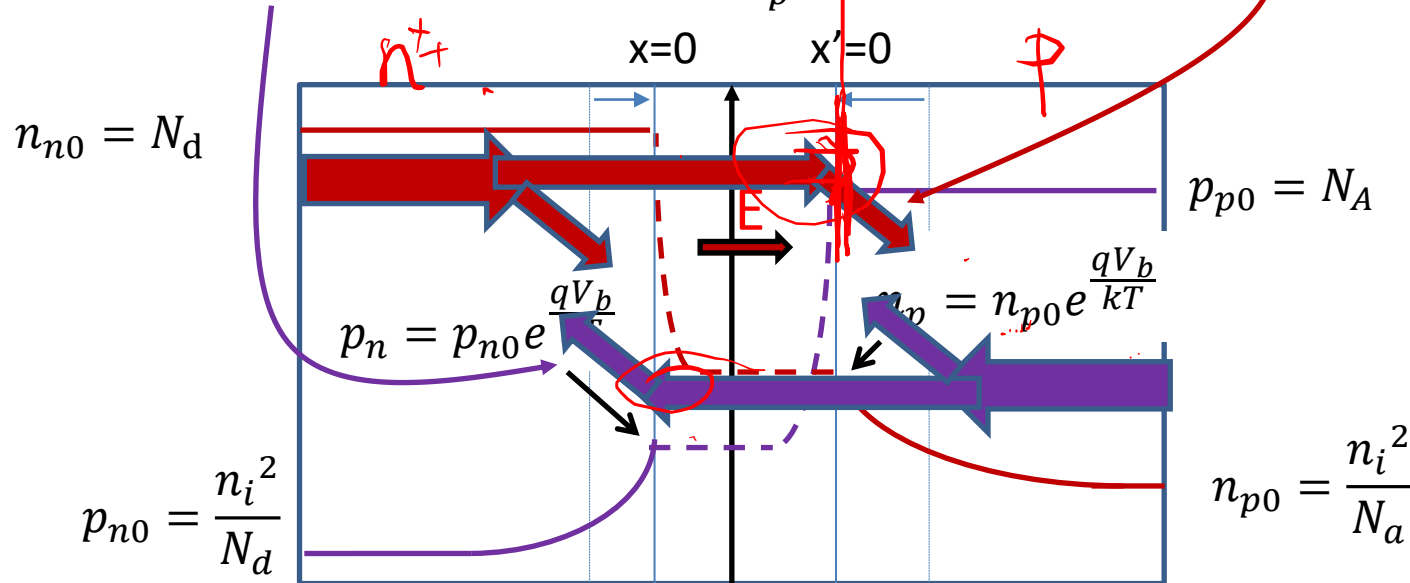
12.1 Previously: pn Junction Current

- charge carrier transport: forward bias: current ratio

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

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

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



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.

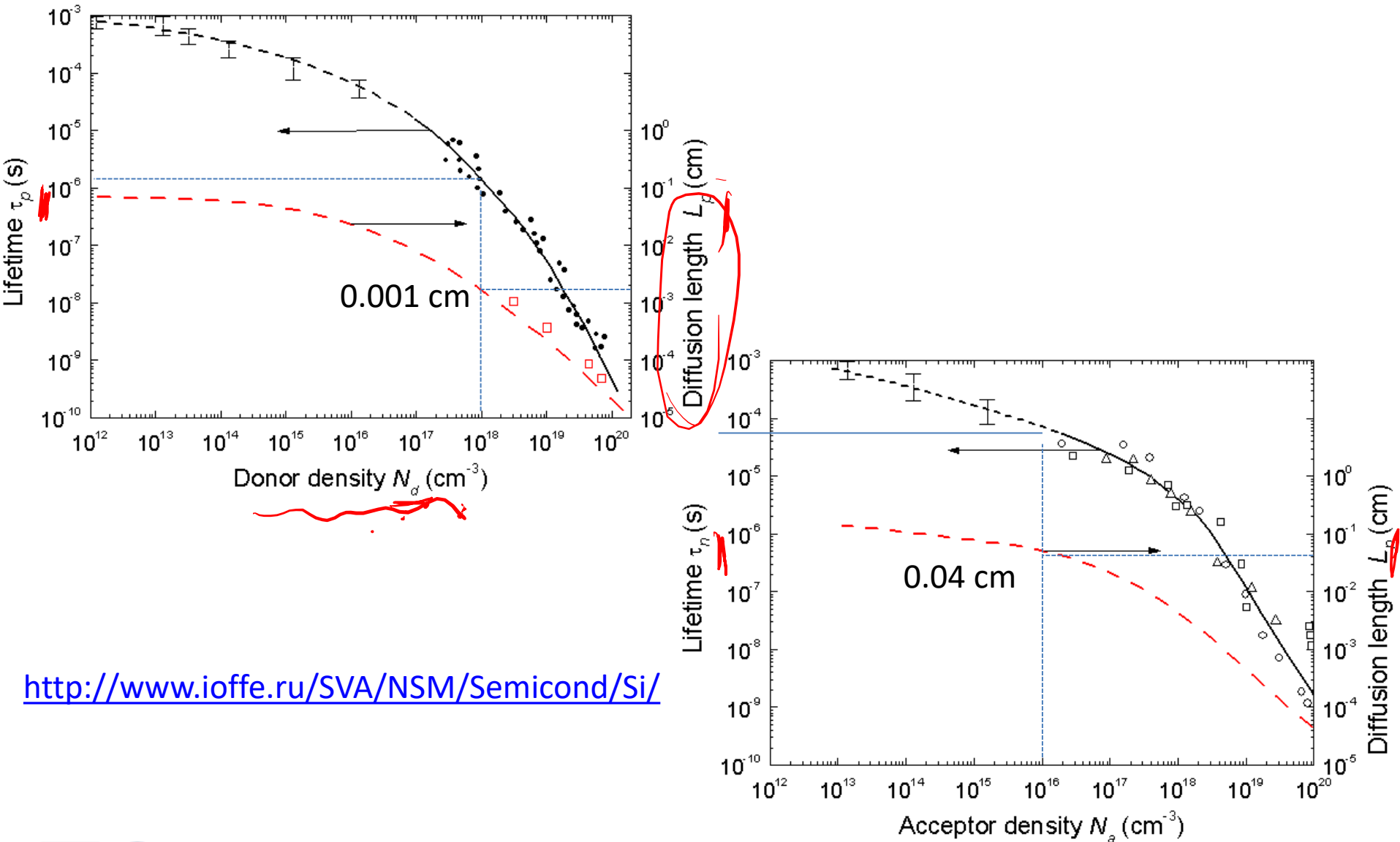
$$\text{For } N_a = 10^{16} \text{ cm}^{-3} \quad L_n = 0.04 \text{ cm} \quad \tau_n = 5 \times 10^{-5} \text{ s}$$

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

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

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

12.1 Example: pn Junction Current



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

Outline

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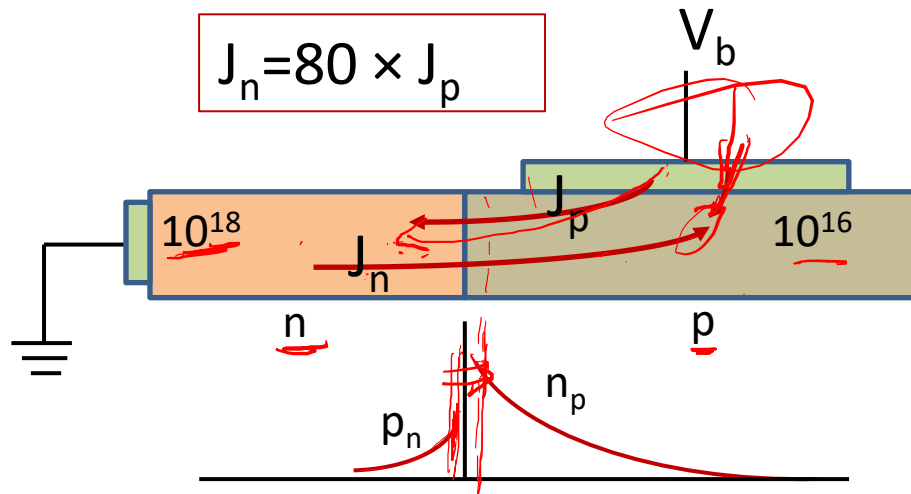
12.2 Bipolar Junction transistor

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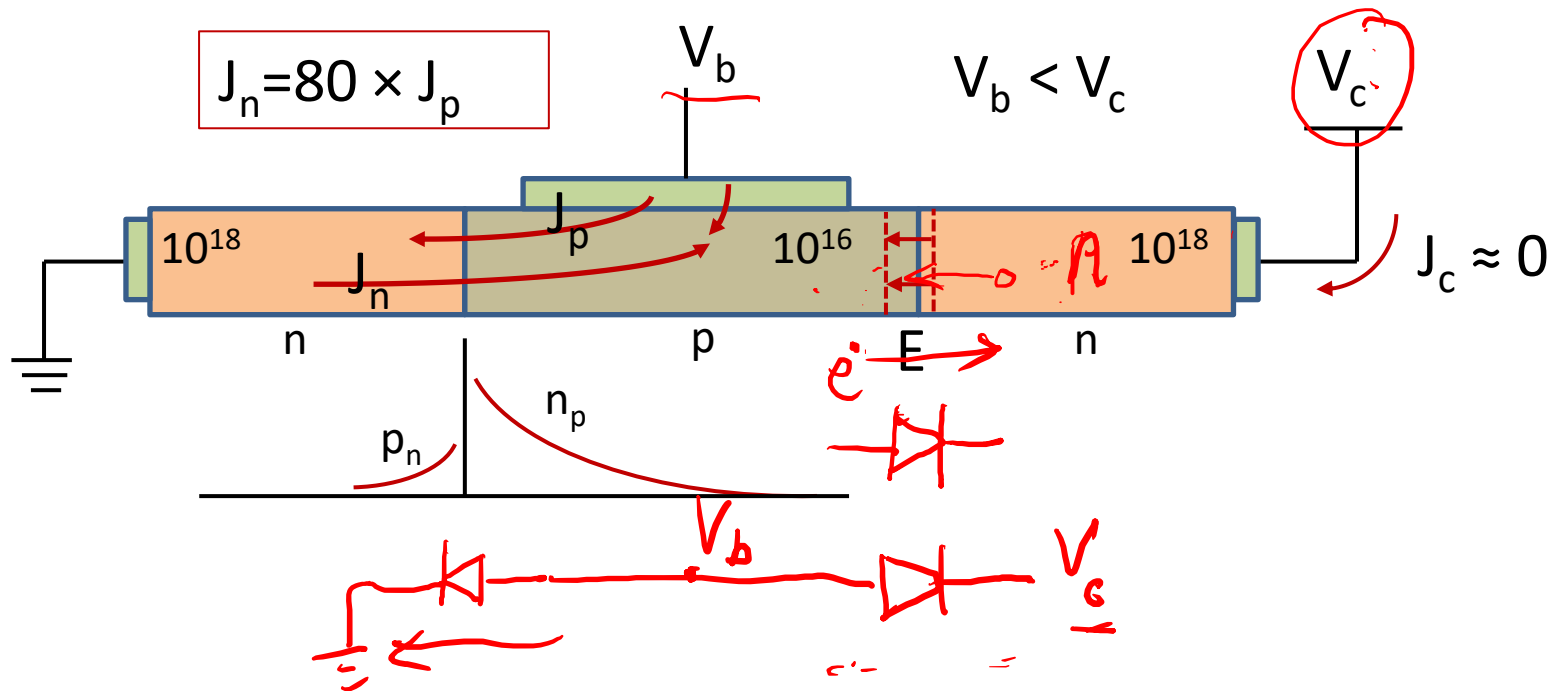
12.4 Summary

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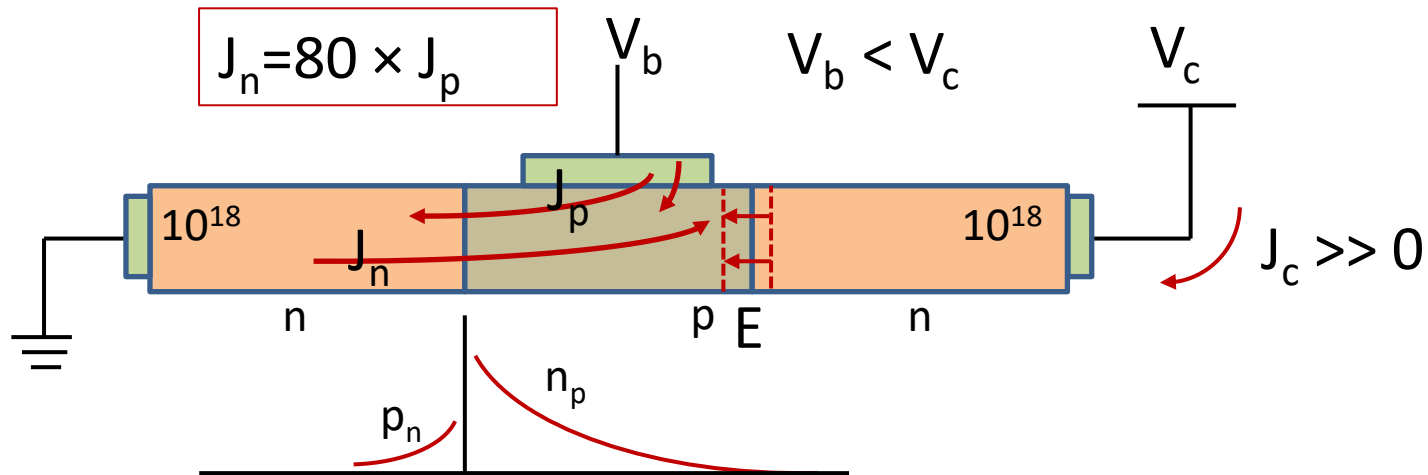
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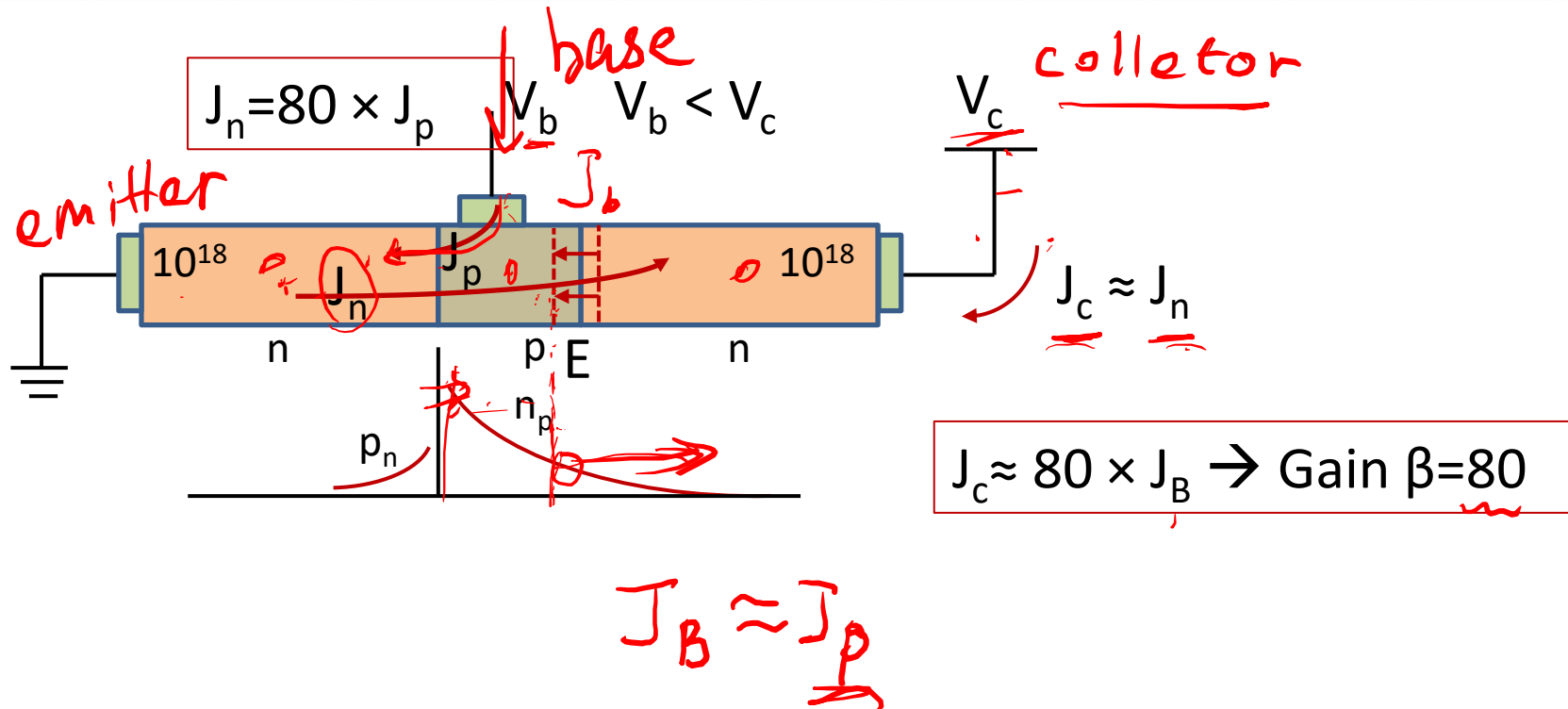
12.2 Bipolar Junction transistor



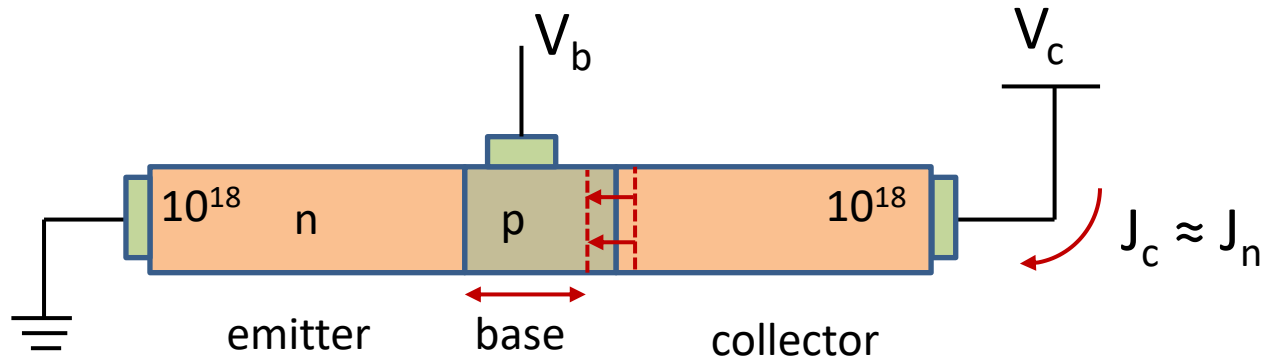
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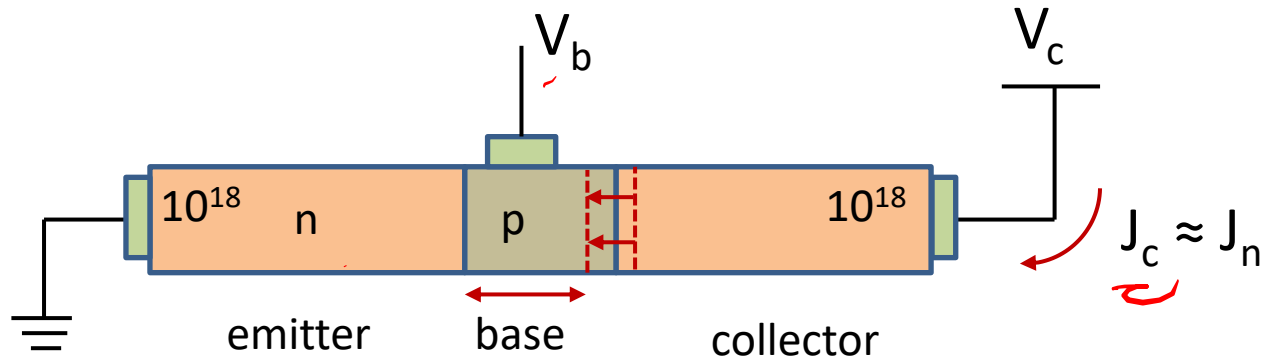


$$J_c \approx 80 \times J_B \rightarrow \text{Gain } \beta = 80$$

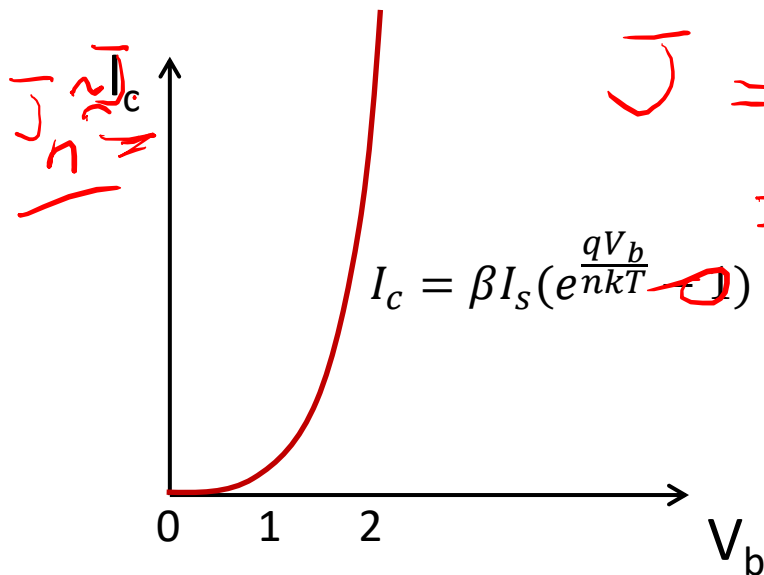
BJT Characteristics:

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

12.2 Bipolar Junction transistor: I-V

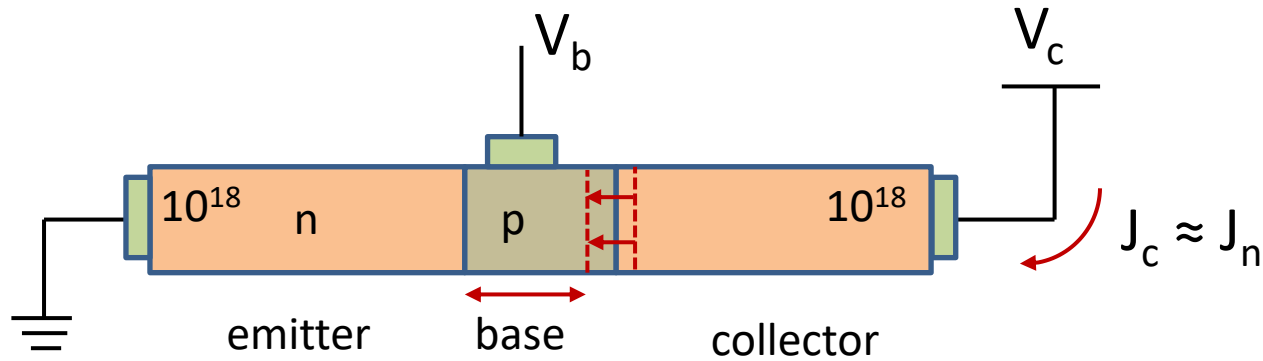


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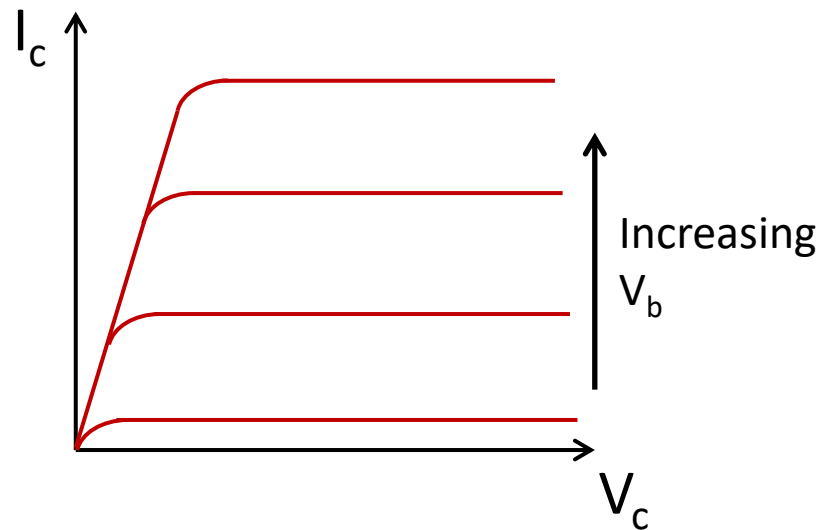
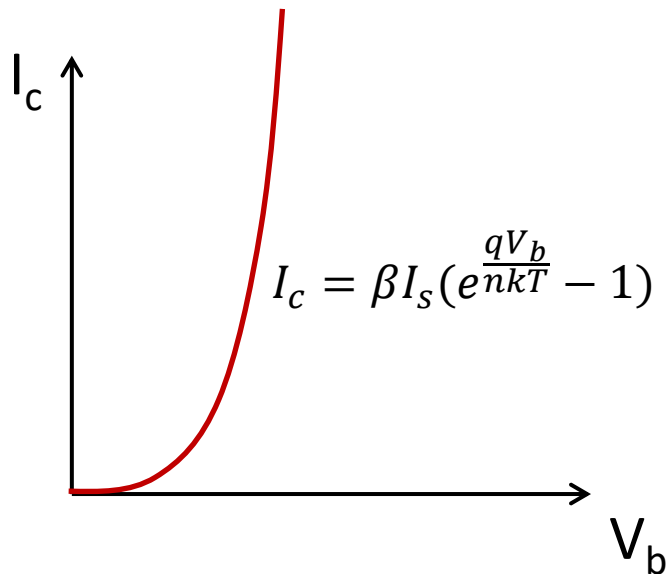


$$\begin{aligned}
 J &= J_s \left(e^{\frac{qV_b}{kT}} + 1 \right) \\
 &= \left(\frac{D_n n_{p0}}{L_n} + \frac{D_p p_{n0}}{L_p} \right) e^{\frac{qV_b}{kT}} \\
 &\approx \underbrace{\frac{D_n n_{p0}}{L_n}}_{J_n} e^{\frac{qV_b}{kT}} + \underbrace{\frac{D_p p_{n0}}{L_p}}_{J_p} e^{\frac{qV_b}{kT}}
 \end{aligned}$$

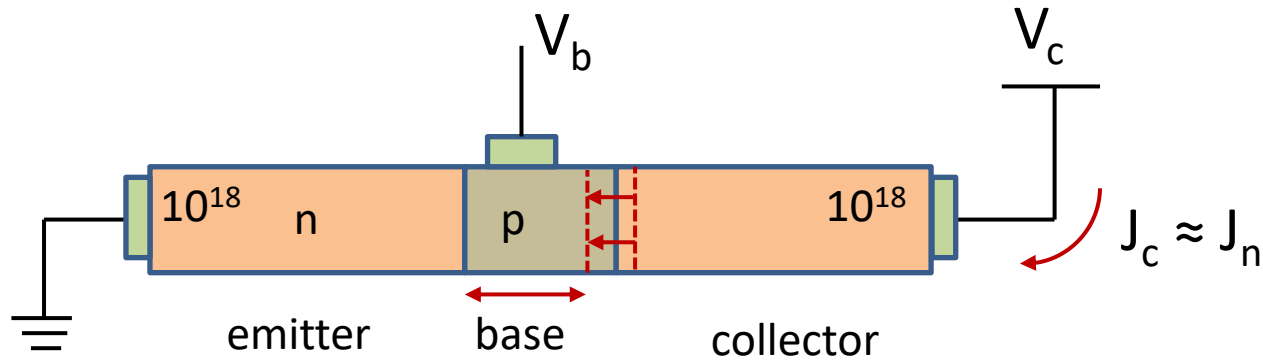
12.2 Bipolar Junction transistor: I-V



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

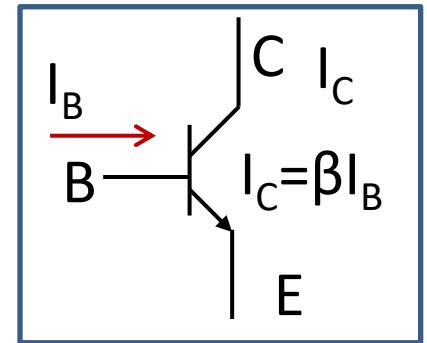


12.2 Bipolar Junction transistor: I-V

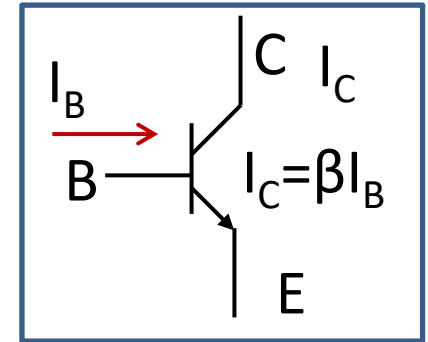
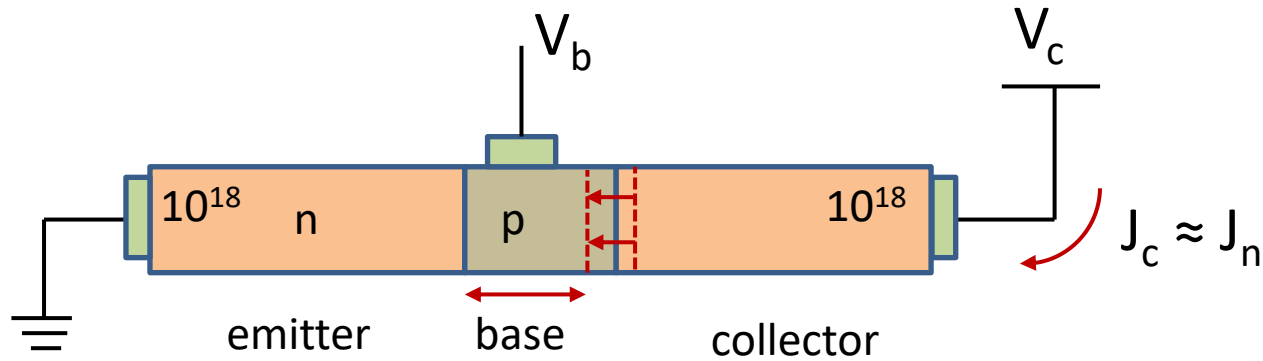


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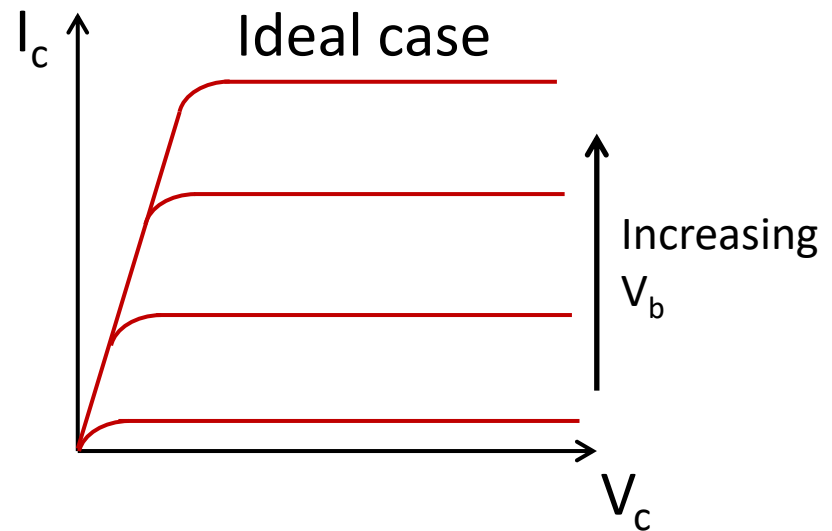
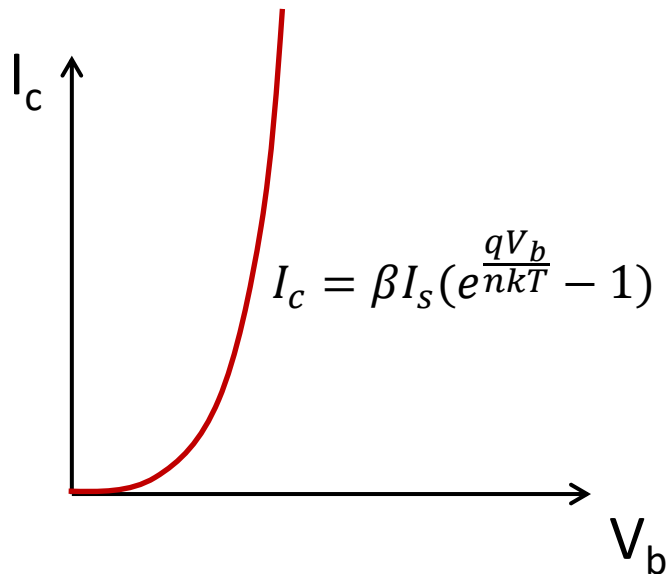
Basic facts:



12.2 Bipolar Junction transistor: I-V



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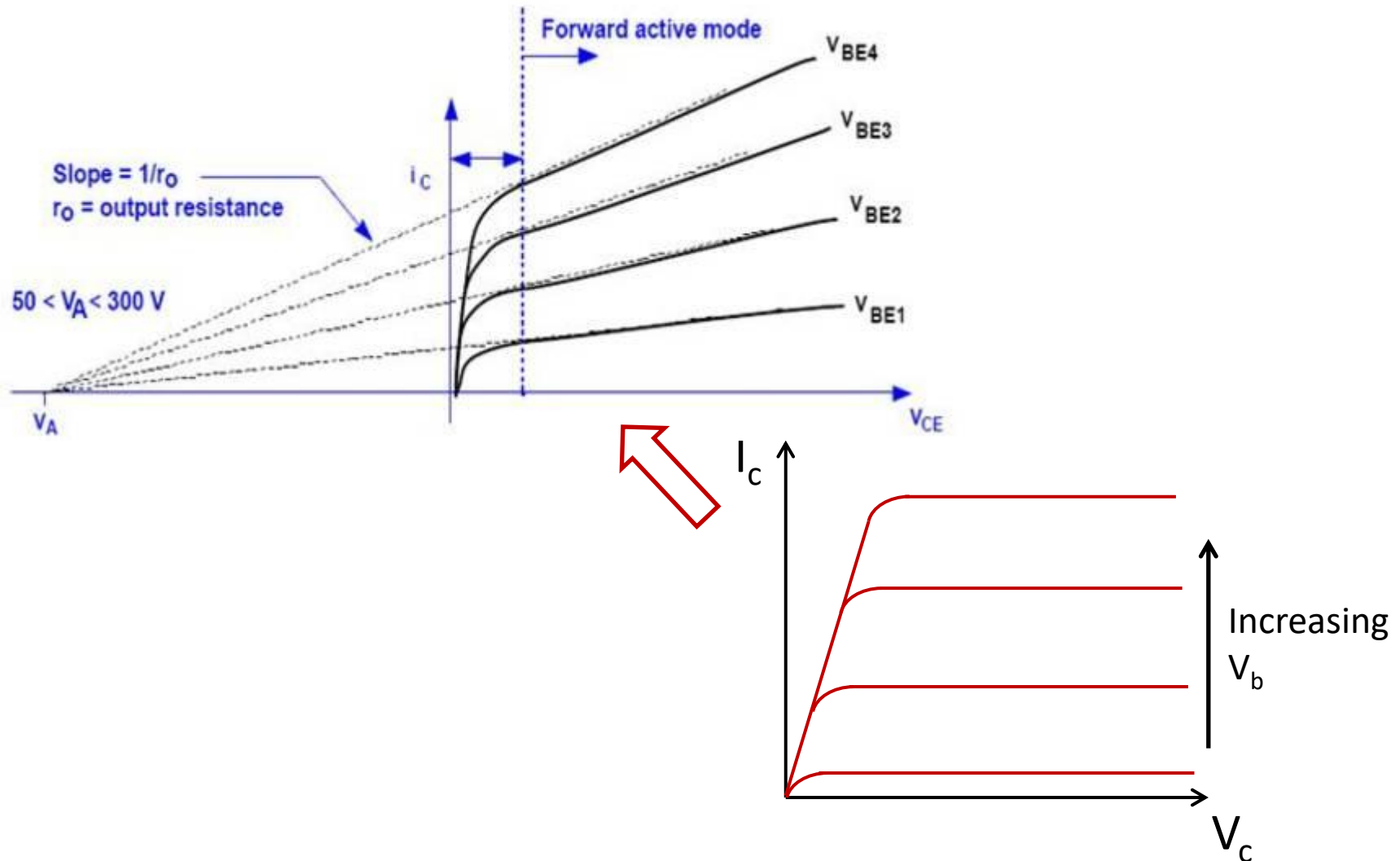
12.2 Bipolar Junction transistor

12.3 Early Effect

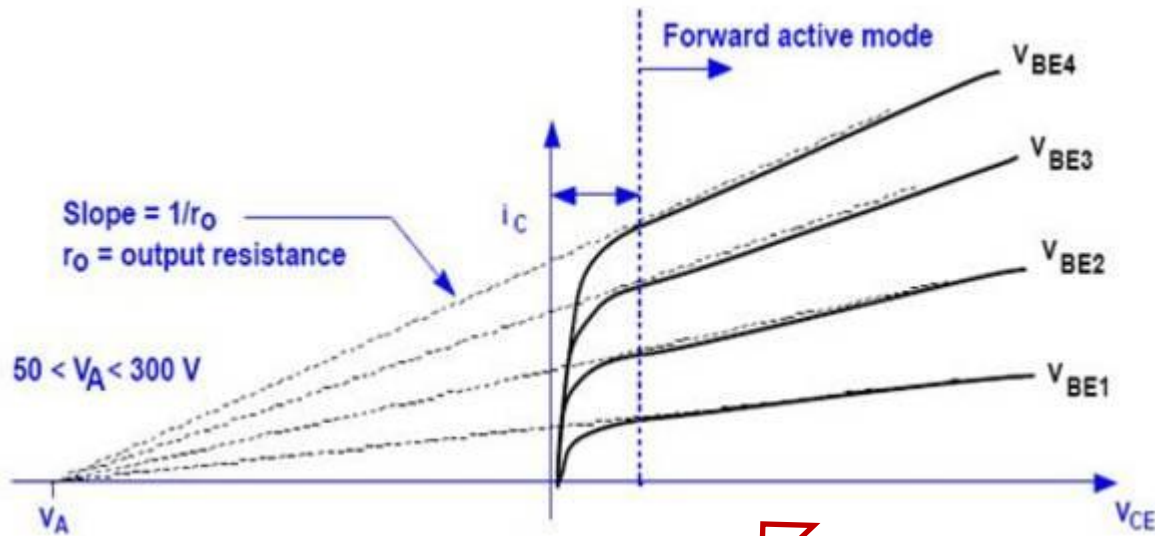
12.4 Summary

12.5 Quantitative analysis of BJT gain

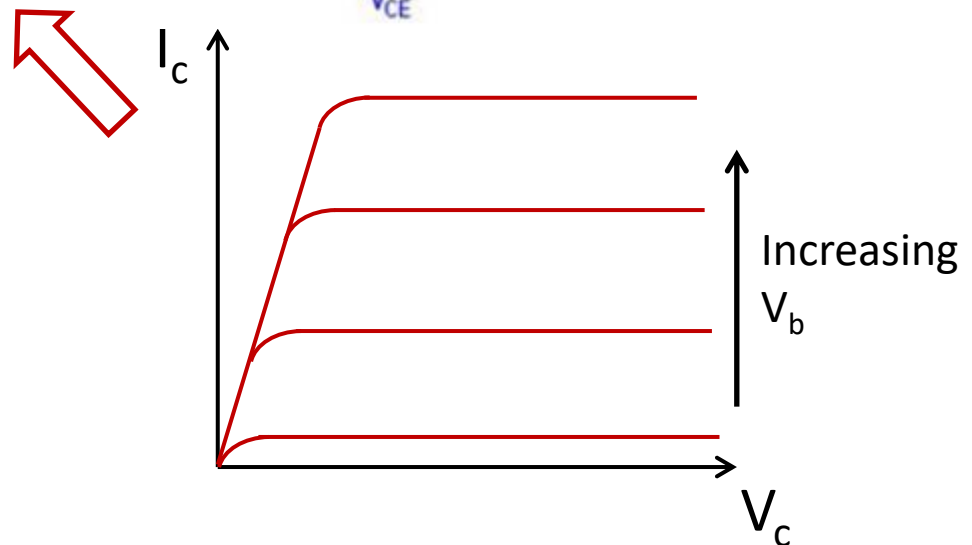
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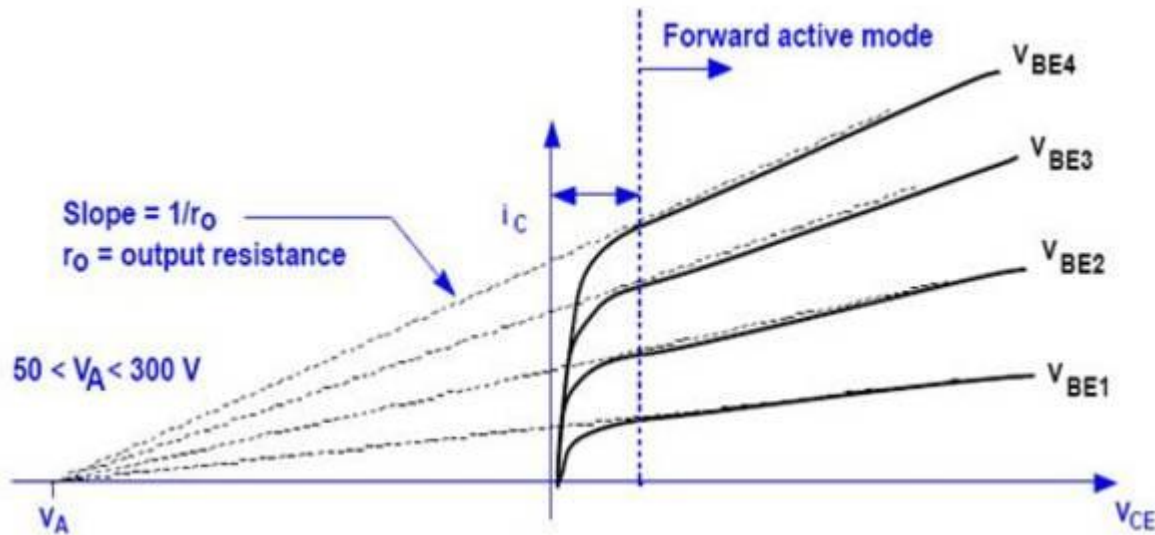
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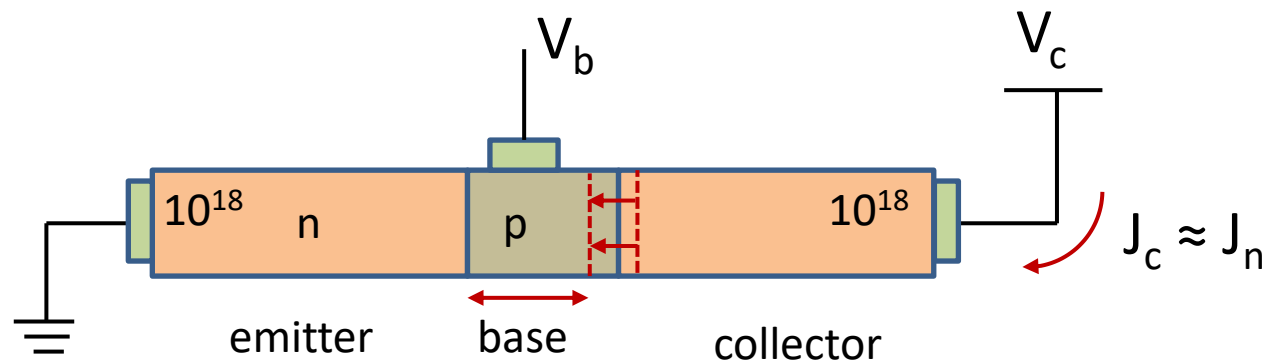
James M. Early



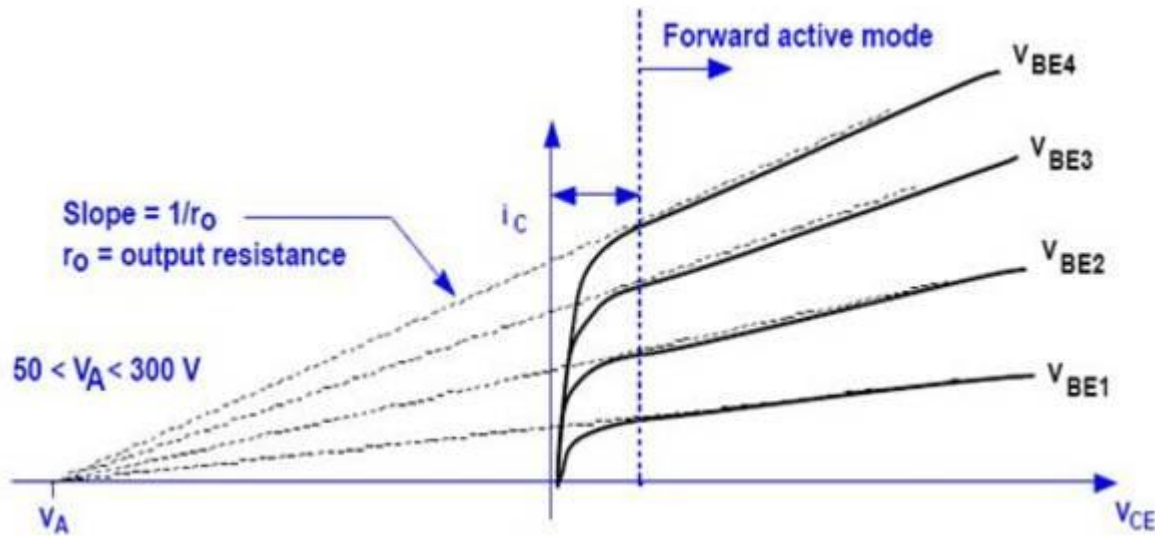
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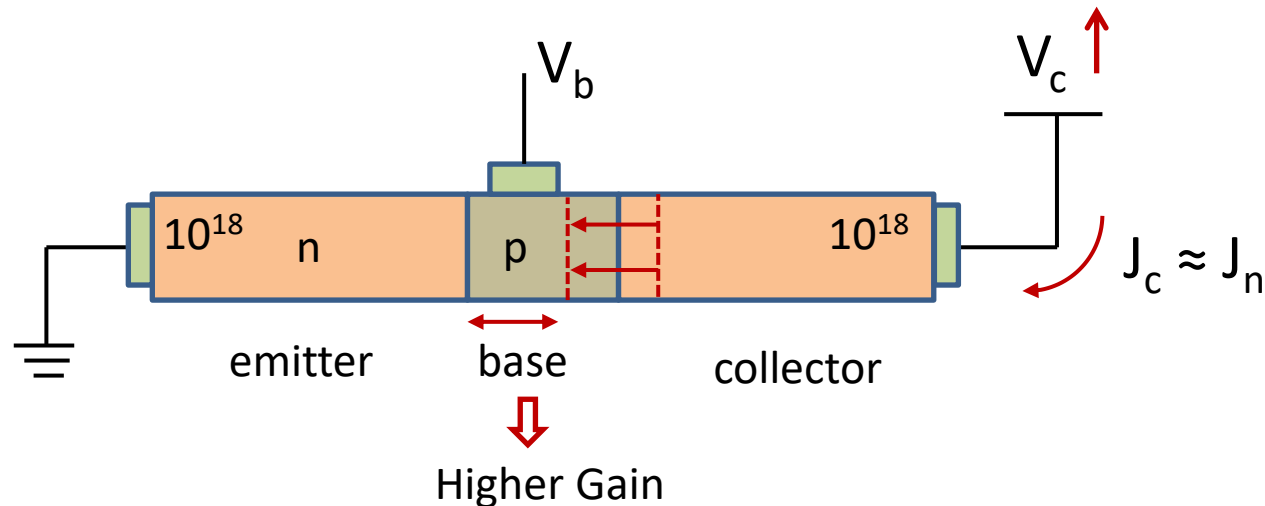
[James M. Early](#)



12.3 Early Effect



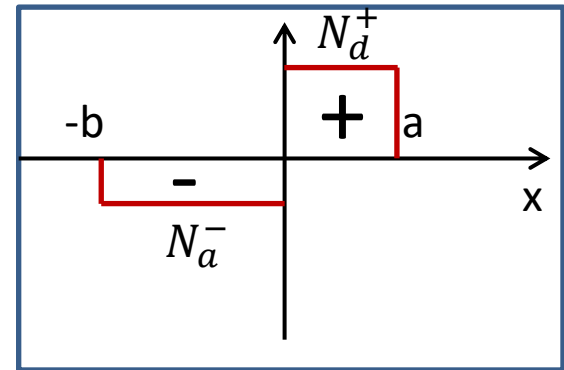
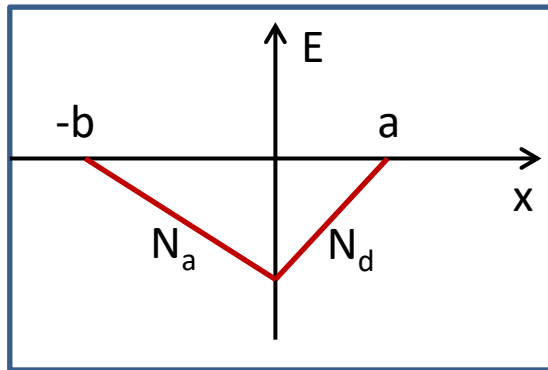
James M. Early



Previously...

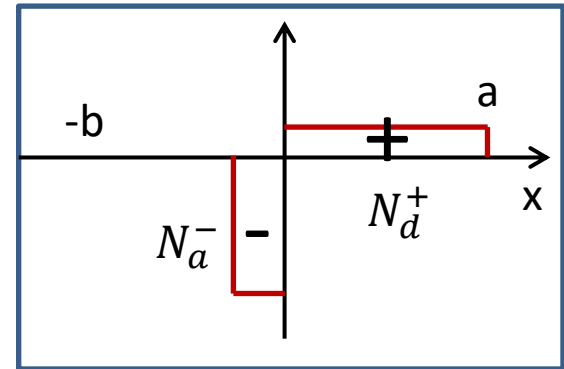
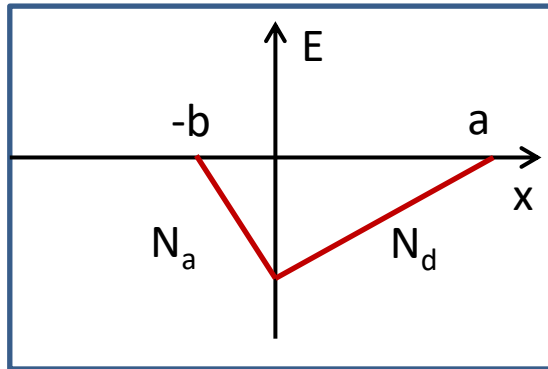
$$a = \sqrt{\frac{2\epsilon(V_{bi} - V_R)}{q} \frac{N_a}{N_d} \frac{1}{N_a + N_d}}$$

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



Previously...

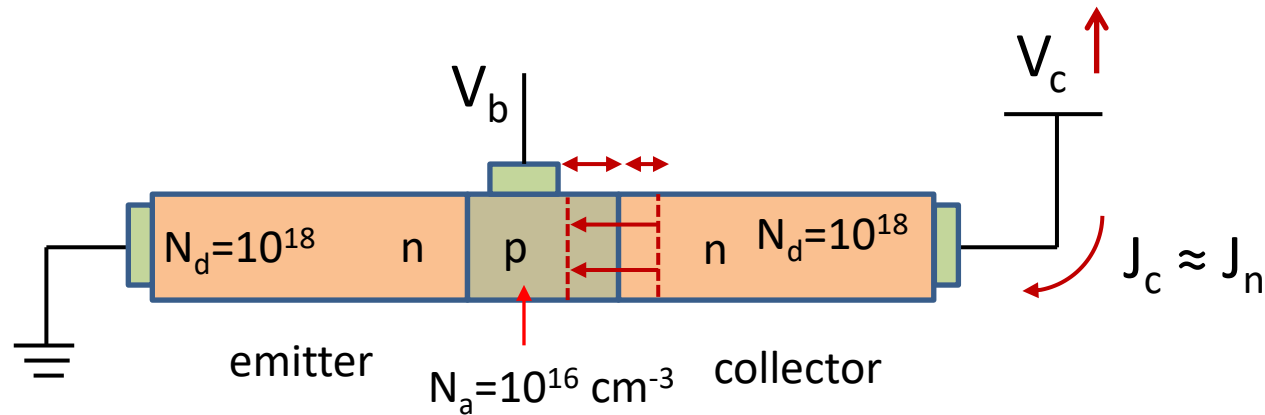
Depletion region width $W = a + b$



12.3 Early Effect



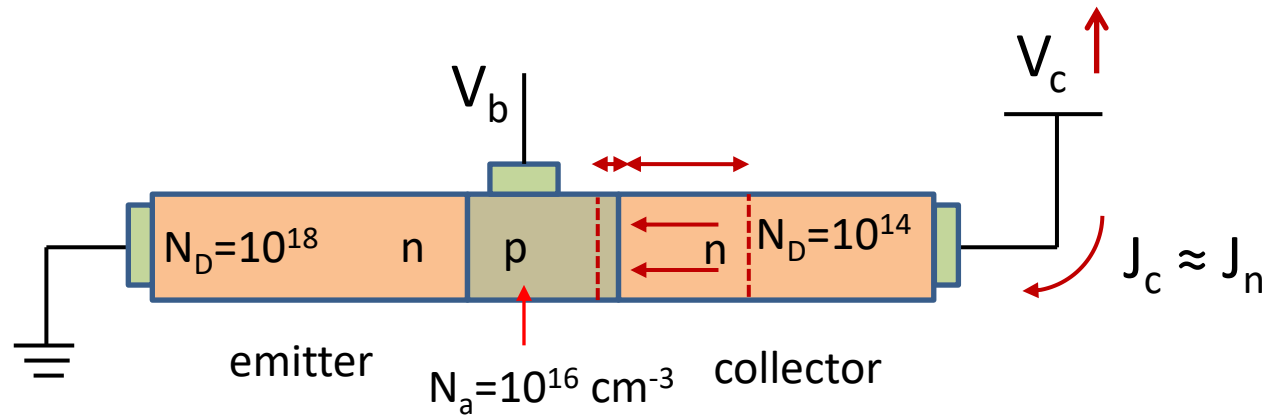
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12.3 Early Effect



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12.3 Early Effect

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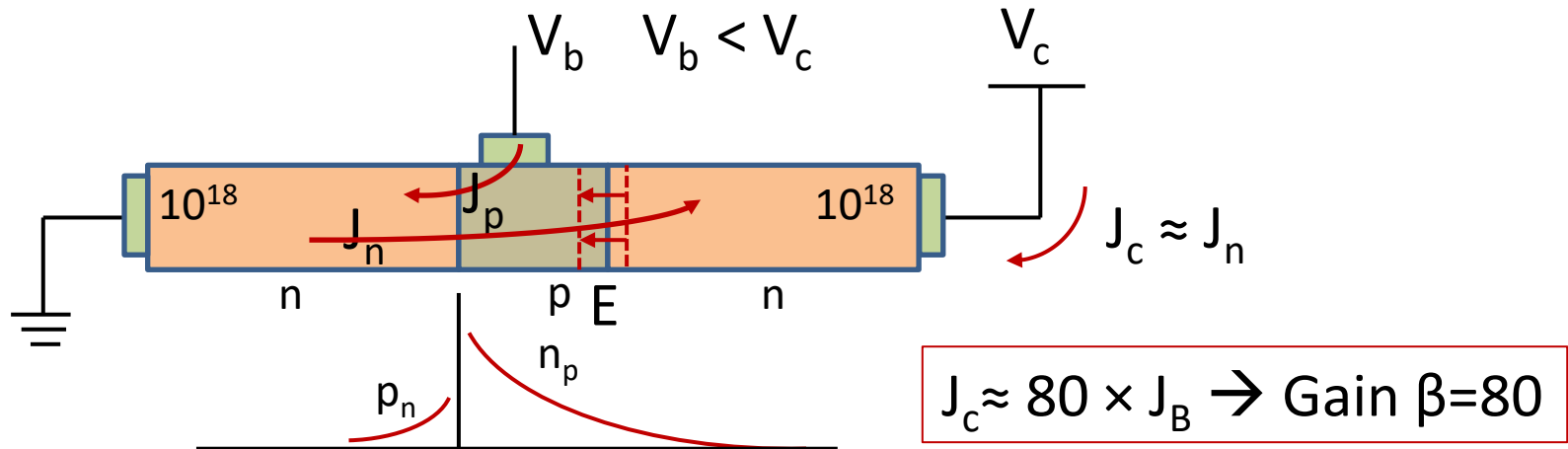
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12.4 Summary



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

Basic facts:

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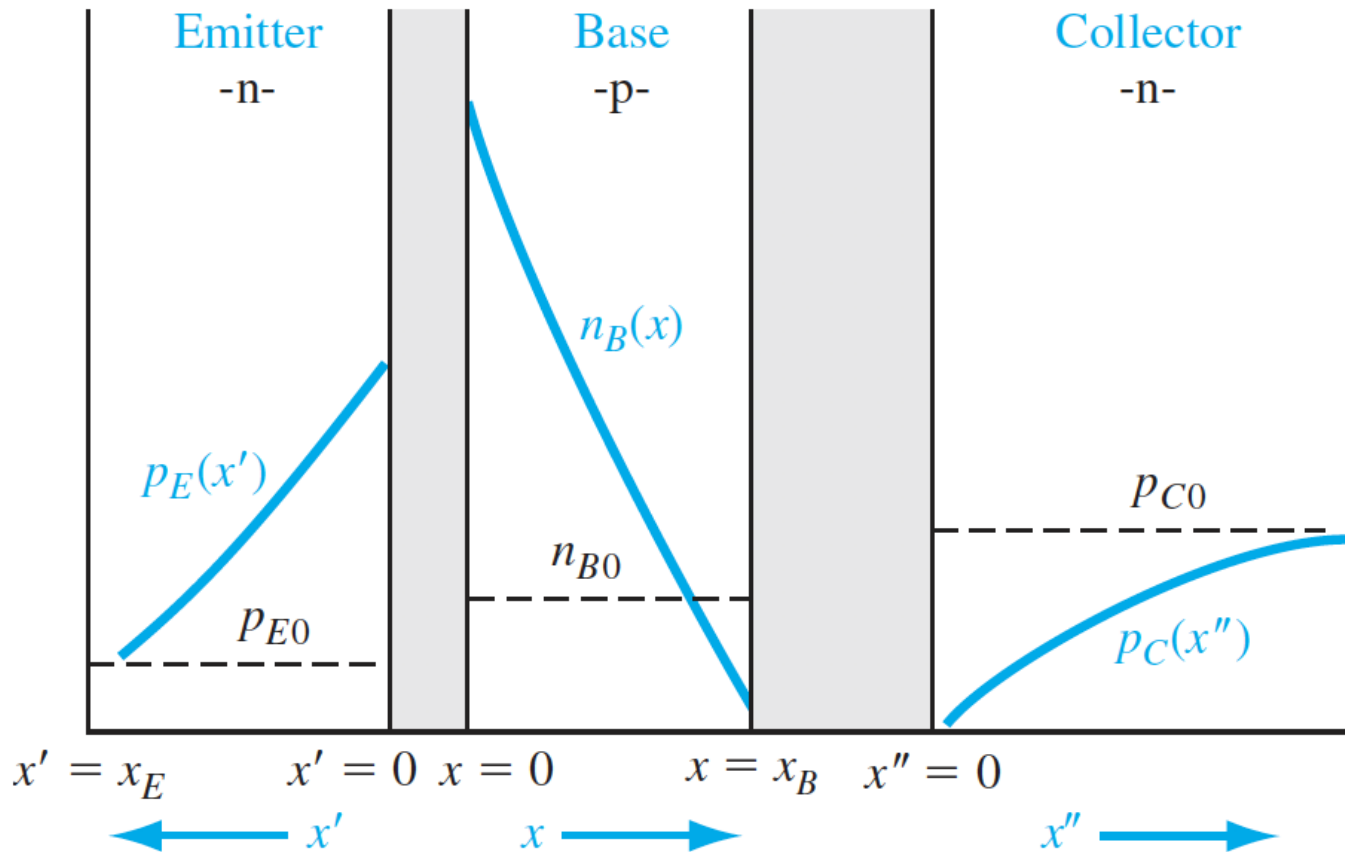
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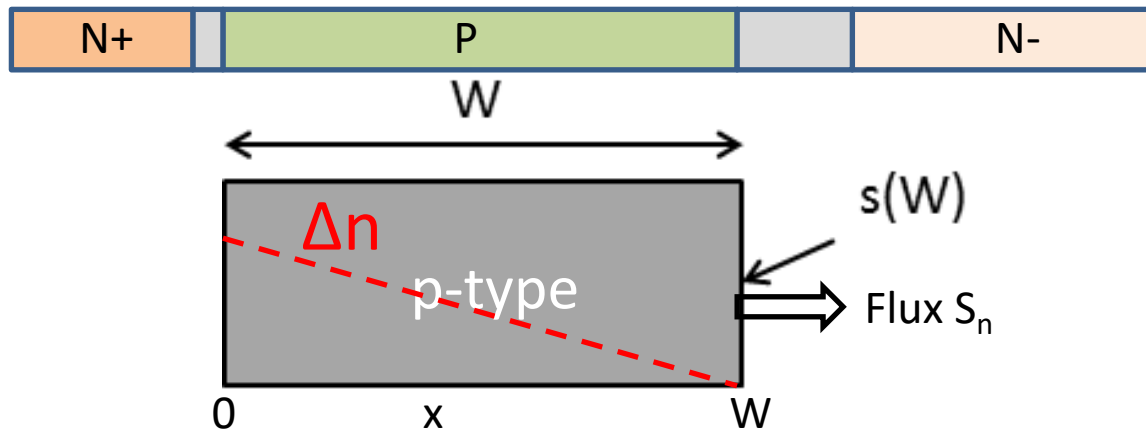
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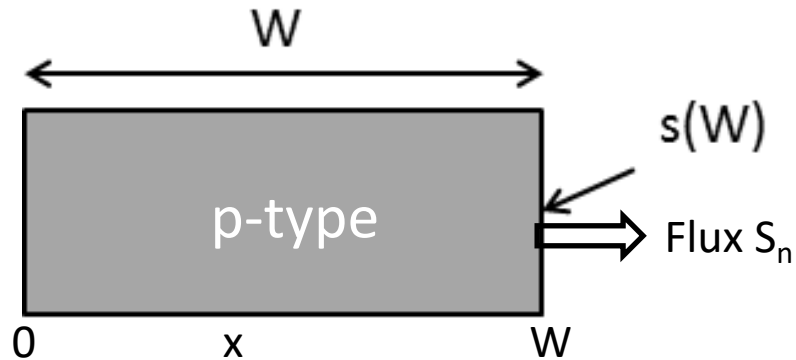


$$N_a = 10^{17} \text{ cm}^{-3}, D_n = 10 \text{ cm}^2/\text{s}, \tau_n = 10^{-7} \text{ s}, \text{SRV } s(x=W) = \infty$$
$$\Delta n(x=0) = 10^{14} \text{ cm}^{-3}$$

Find the electron flux S_n at $x=0$ and W , if

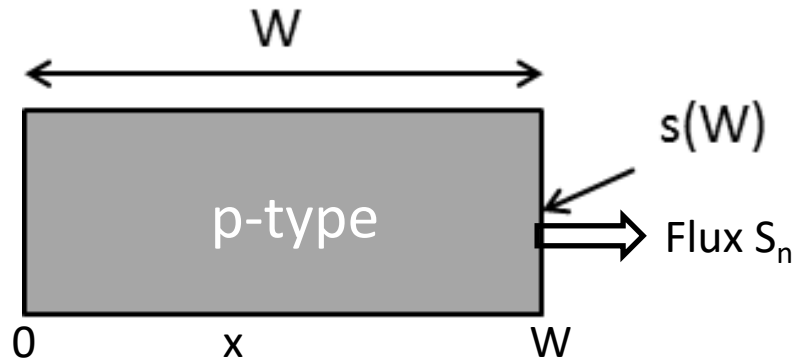
- 1) $W=20\mu\text{m}$
- 2) $W=2\mu\text{m}$

12.5 Quantitative analysis of BJT gain



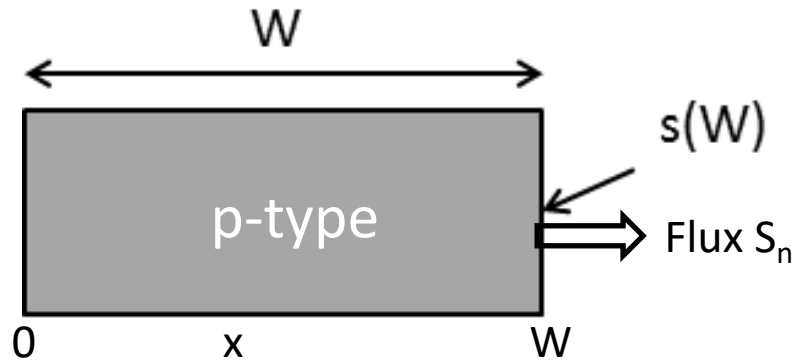
$$0 = D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau}$$

12.5 Quantitative analysis of BJT gain



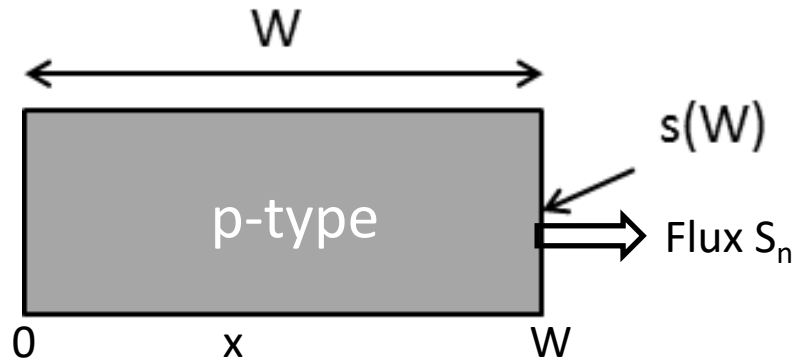
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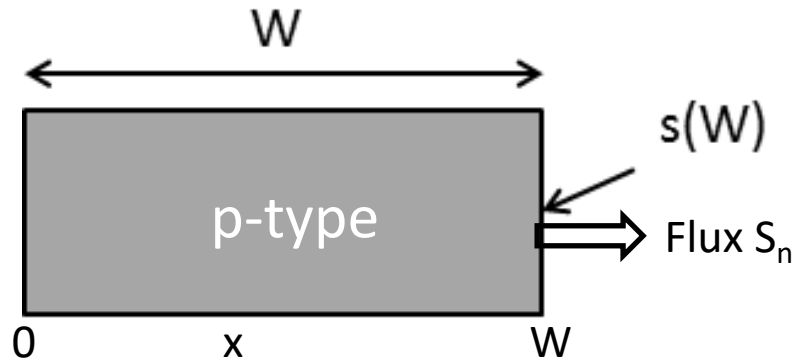
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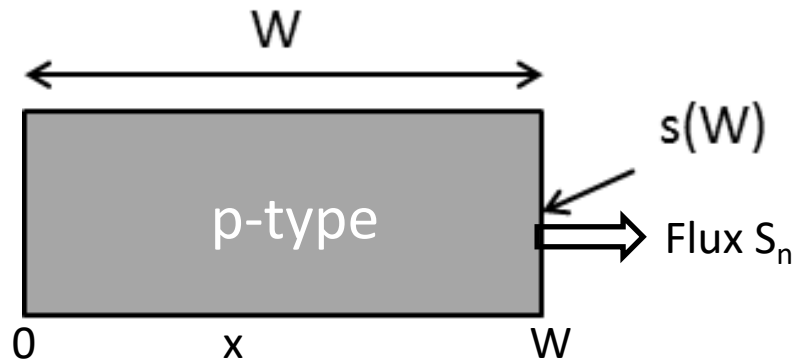
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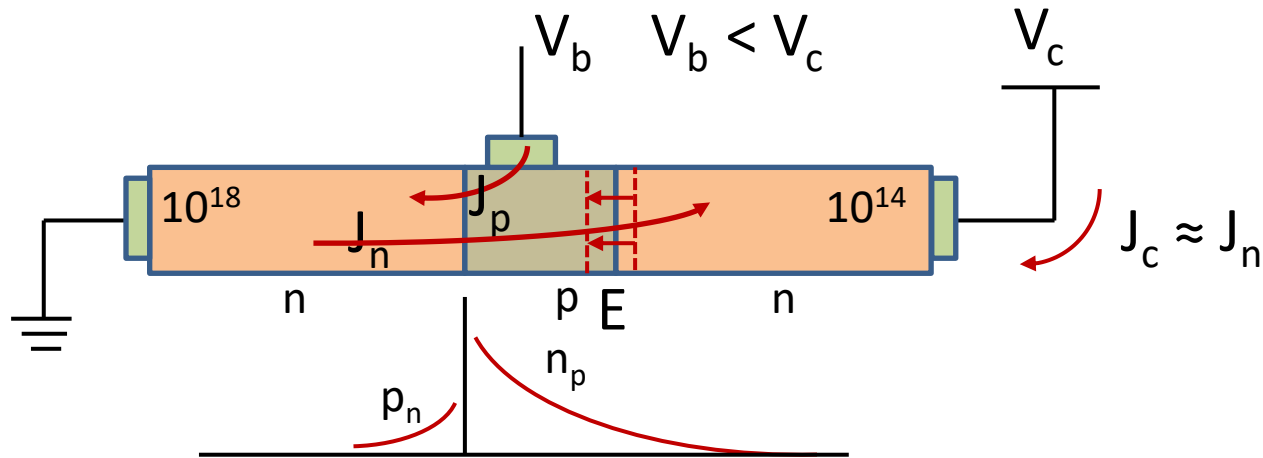


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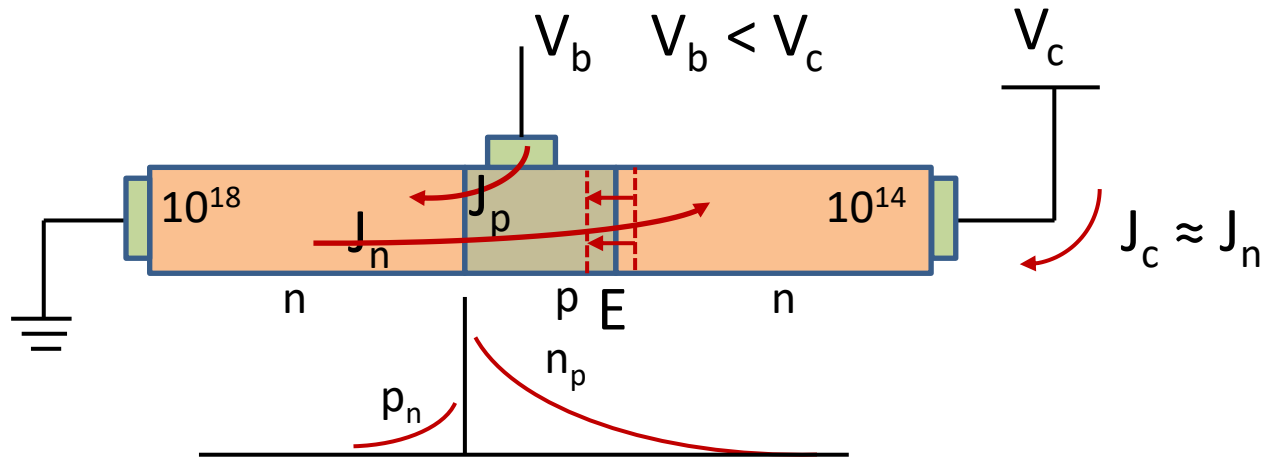
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Electron flux from emitter to base: $S_n(0)$

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

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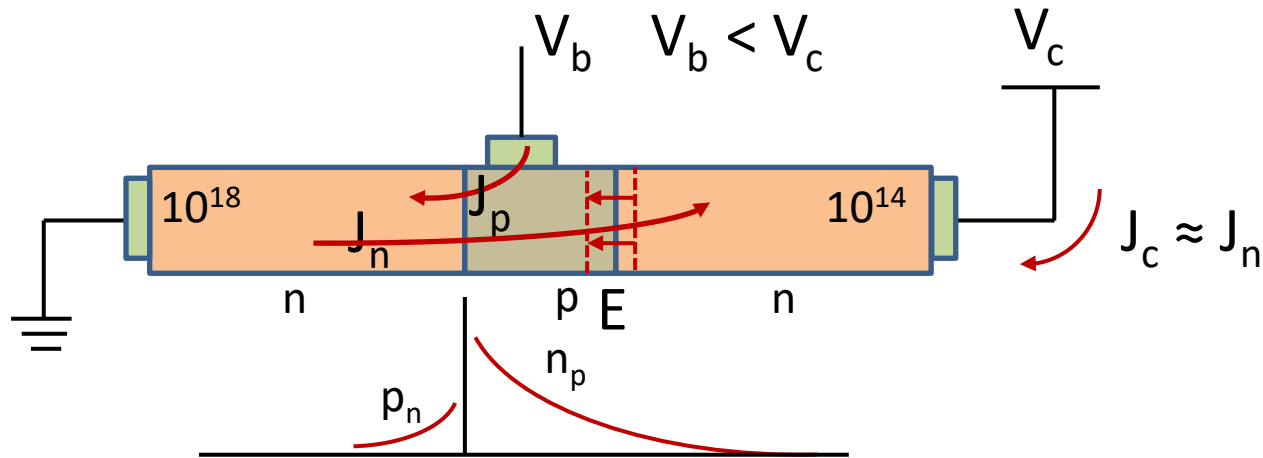


Electron flux from emitter to base: $S_n(0)$

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

Hole flux from base to emitter: S_p

12.5 Quantitative analysis of BJT gain



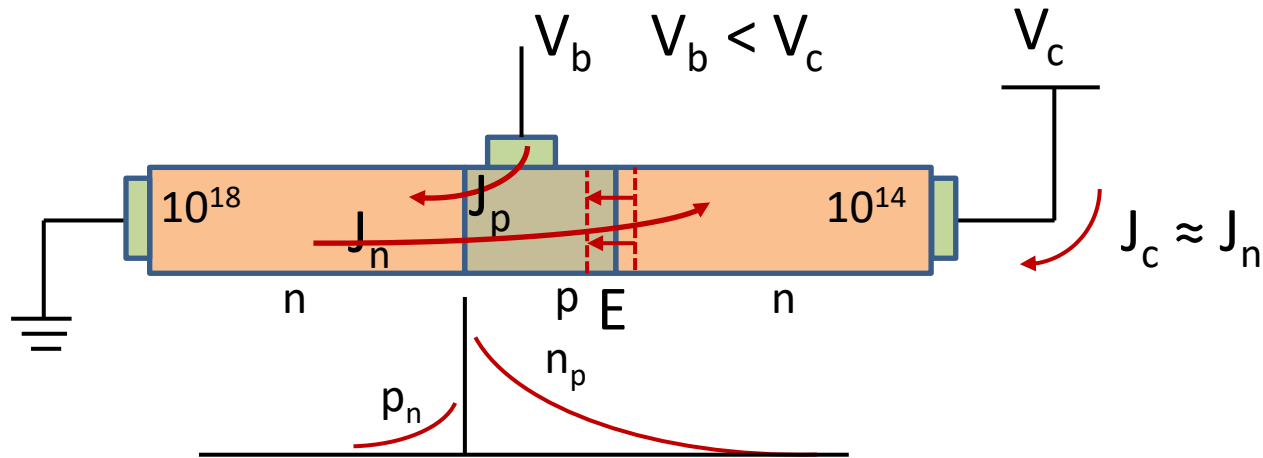
Electron flux from emitter to base: $S_n(0)$

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

Hole flux from base to emitter: S_p

Base electrode flux: $S_p + S_n(0) - S_n(W_b)$

12.5 Quantitative analysis of BJT gain



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

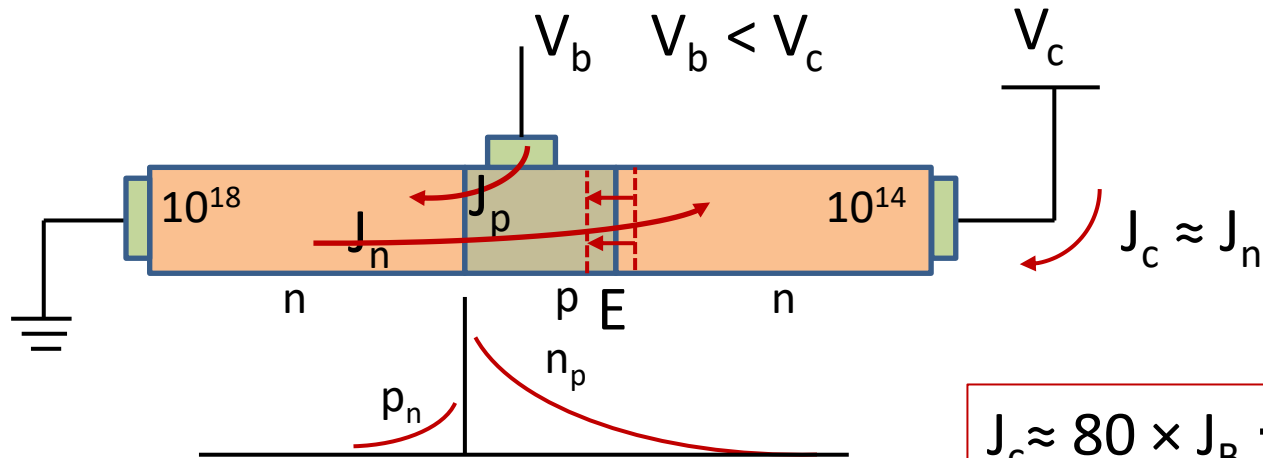
Electron flux from base to collector: $S_n(W_b)$

Hole flux from base to emitter: S_p

Base electrode flux: $S_p + S_n(0) - S_n(W_b)$

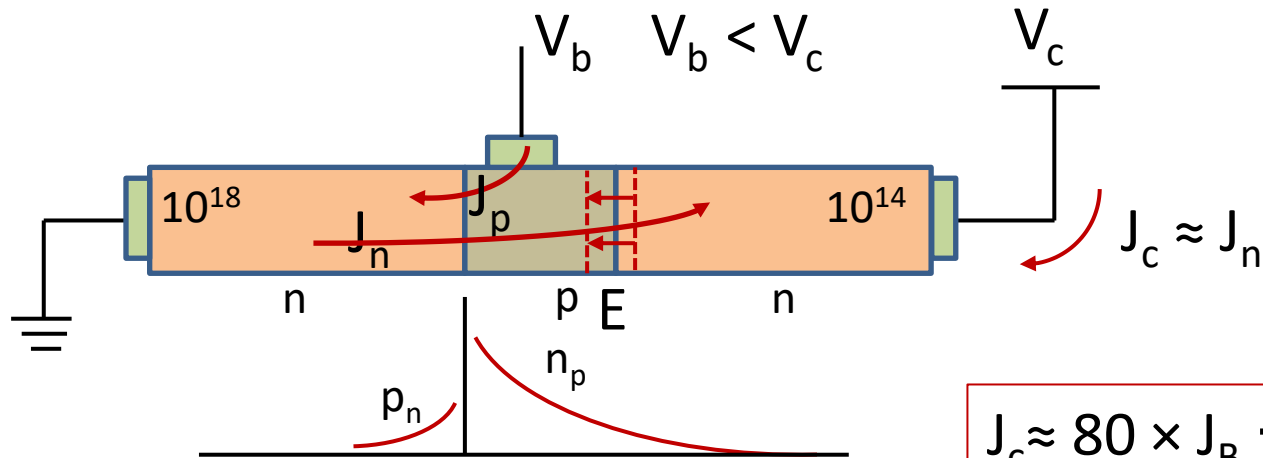
Gain β = collector flux / base electrode flux = $S_n(W_b) / (S_p + S_n(0) - S_n(W_b))$

12.5 Quantitative analysis of BJT gain



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