Section 25
Bipolar Junction Transistor – Design

25.2 Base Doping Design

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PURDUE UNIVERSITY

School of Electrical and
Computer Engineering

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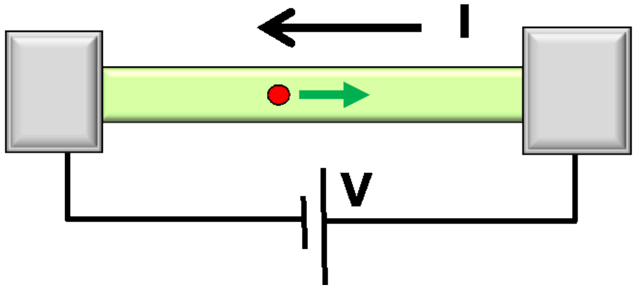

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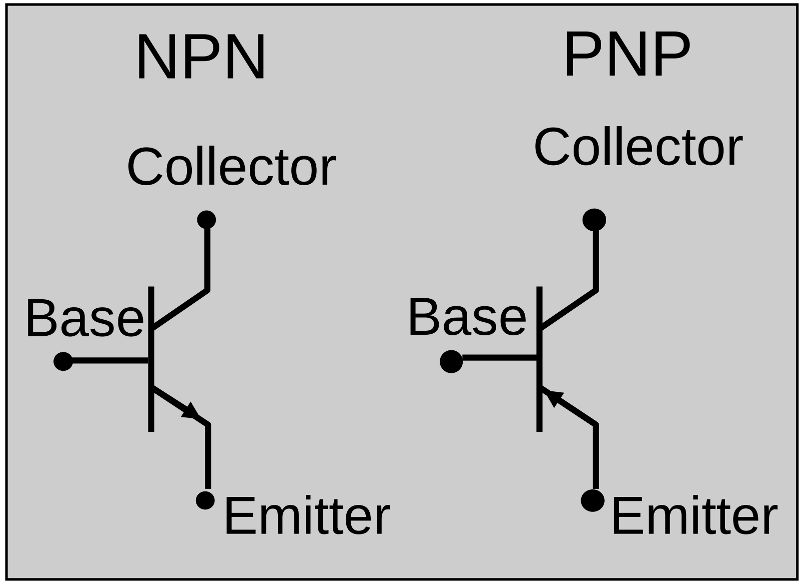
charge density velocity area



- 25.1 Current gain in BJTs
- 25.2 Base Doping Design
  - » Current Crowding – Non-Uniform Turn-On
  - » Punch-through
  - » Base Width Modulation
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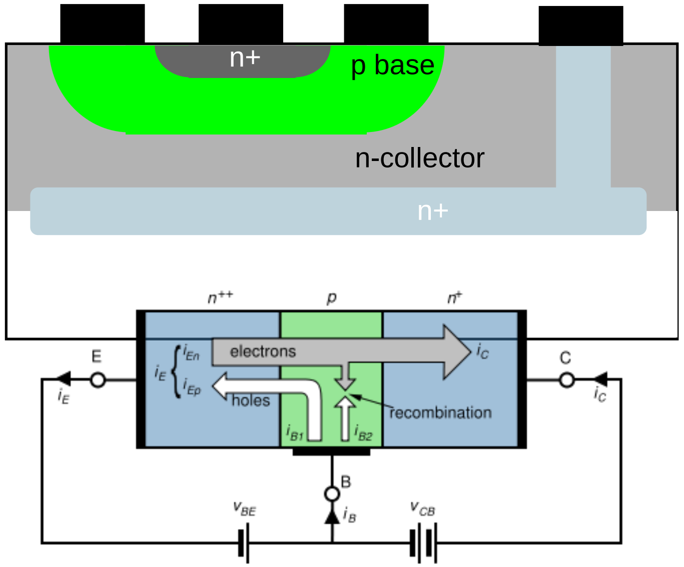
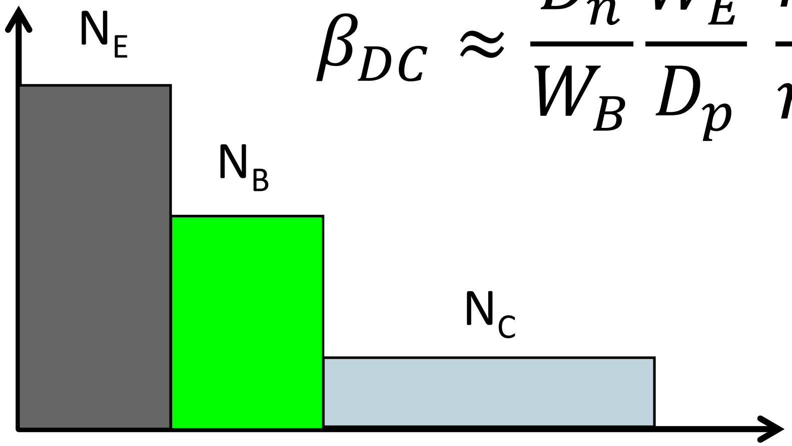
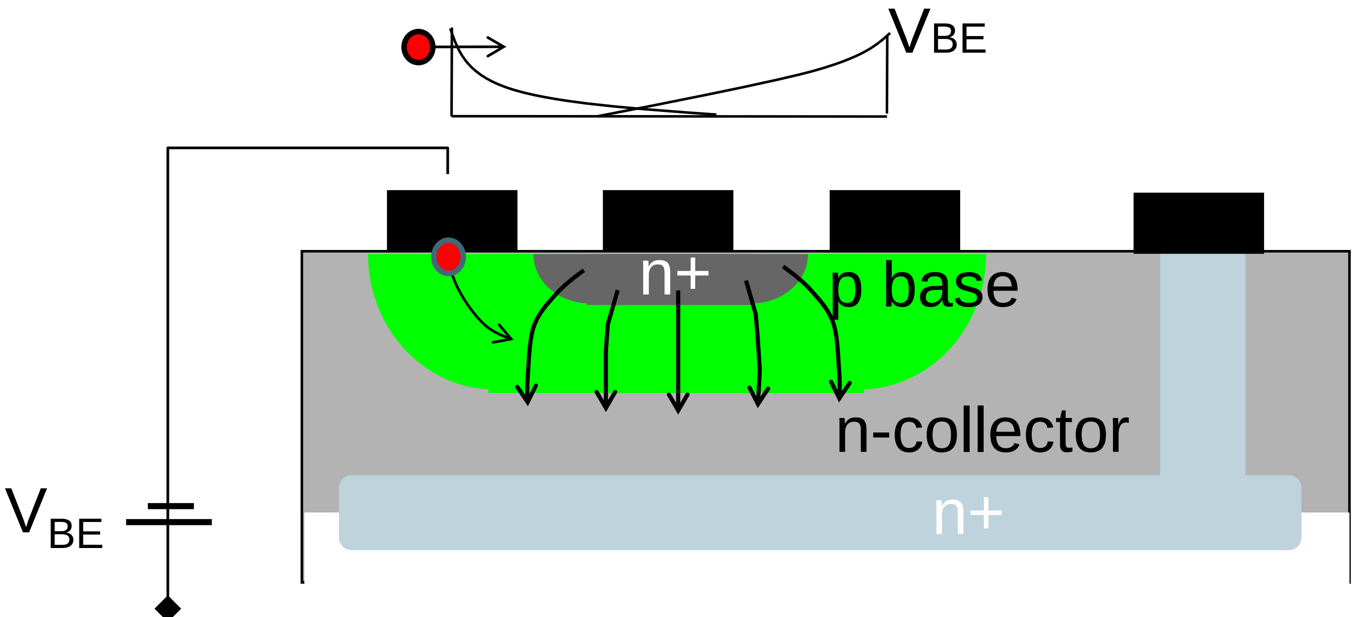
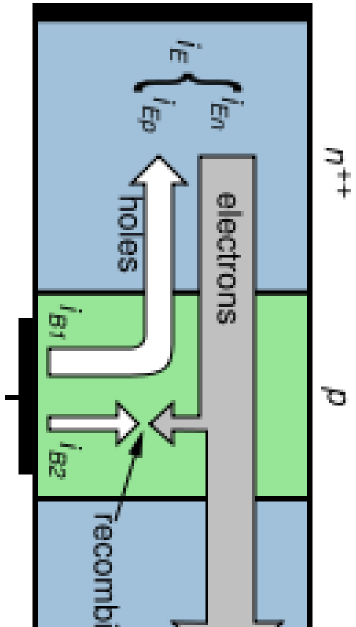




$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

Problem of Low Base Doping: Current Crowding - Non-Uniform Turn-On





Double diffused junction configuration:
Emitter doping must compensate / overcome the base doping

$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

Low doping in base
=> resistance along the current path
=> potential drop

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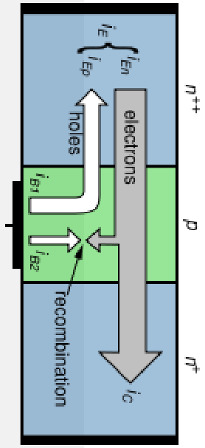

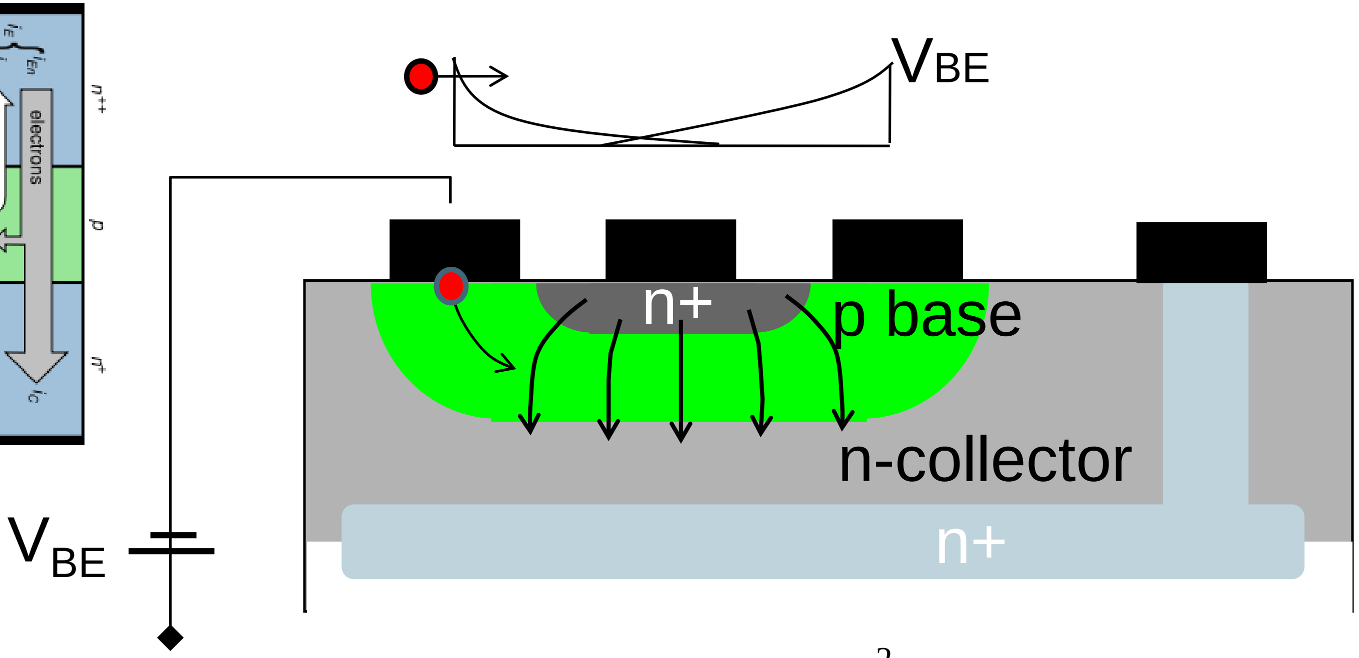

$$\beta = \frac{I_C}{I_B} = \frac{\int J_C(x)dx}{\int J_B(x)dx} = \frac{\int \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}{\int \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}$$

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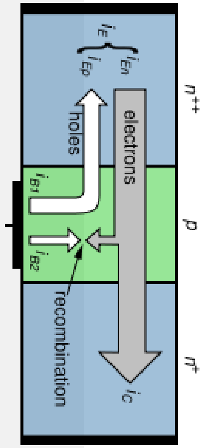
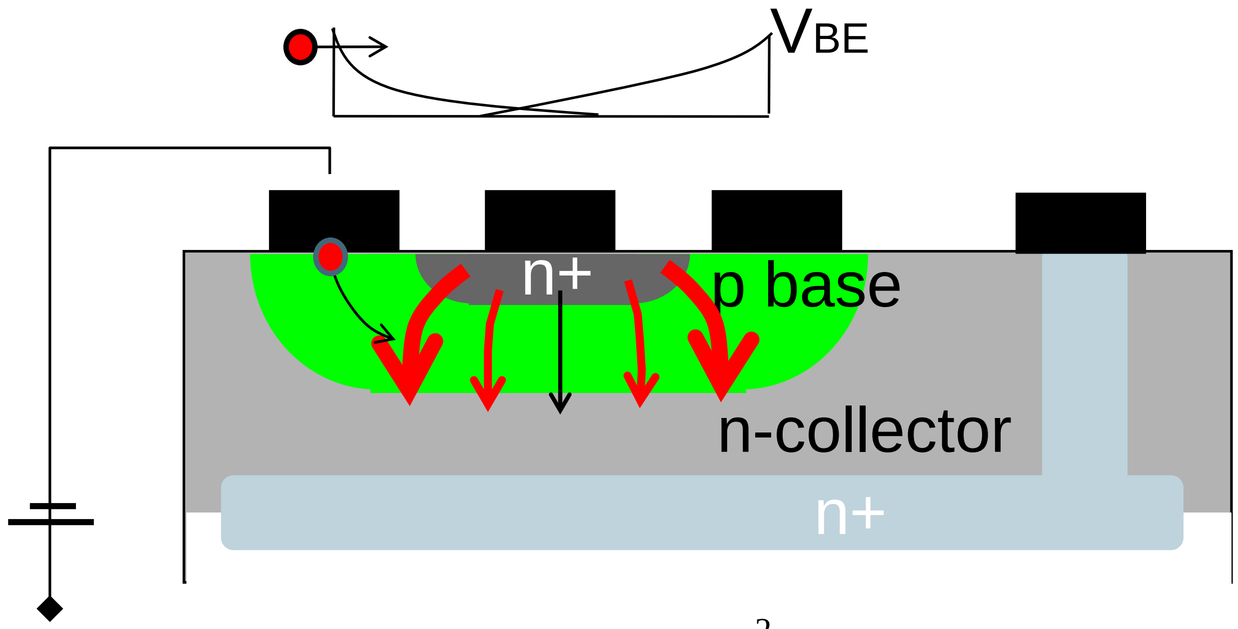
=> Spatially dependent
=> More current in the corners

The larger current density near the emitter may cause localized heating and high injection effects

Problem of Low Base Doping:
Current Crowding - Non-Uniform Turn-On





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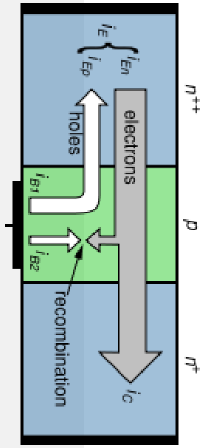
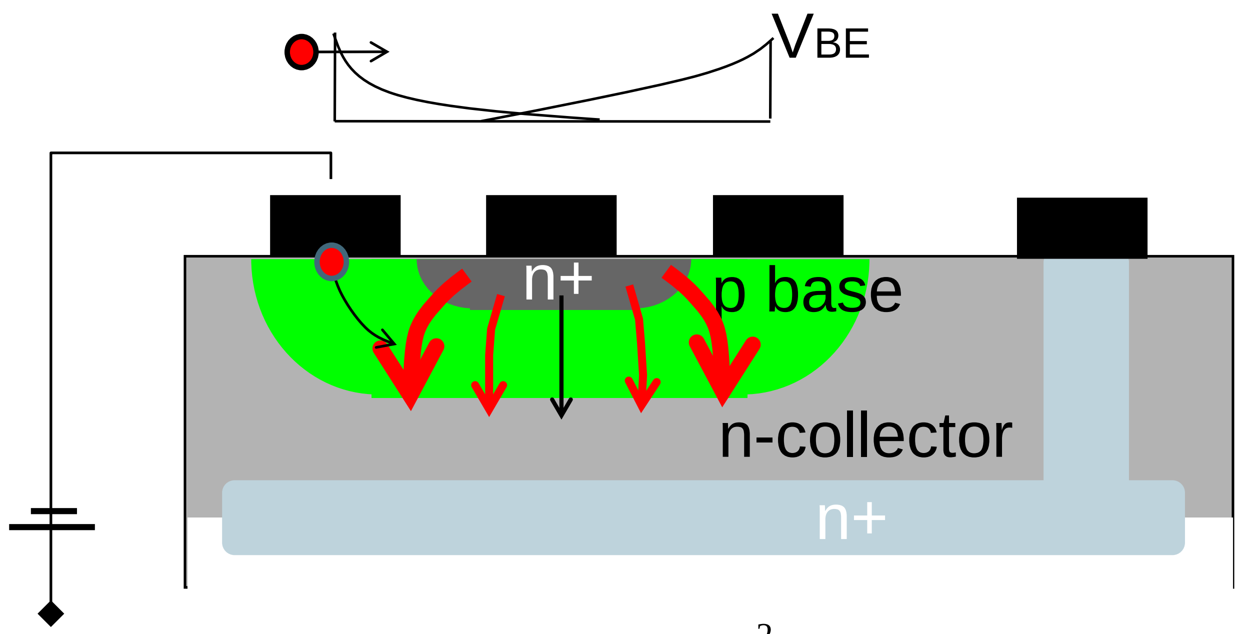
Non-zero base resistance results in a lateral potential difference under the emitter region

For an n-p-n transistor as shown, the potential decreases from edge of the emitter towards the center (the emitter is highly doped and can be considered an equipotential region)

Problem of Low Base Doping: Current Crowding - Non-Uniform Turn-On





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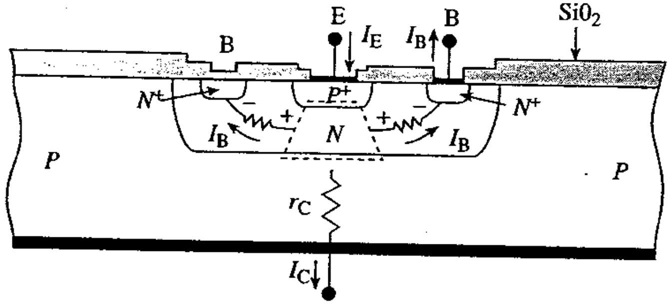
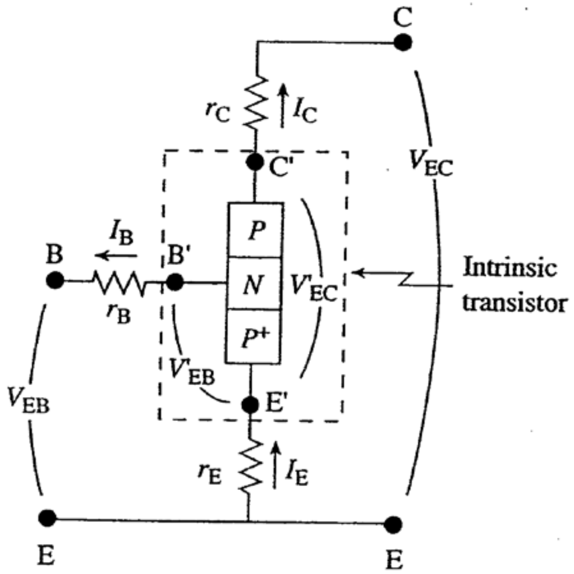
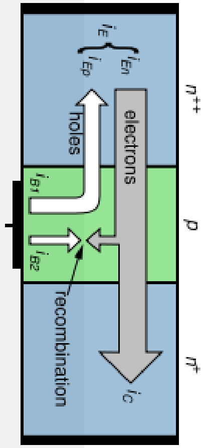
Sketches from text book

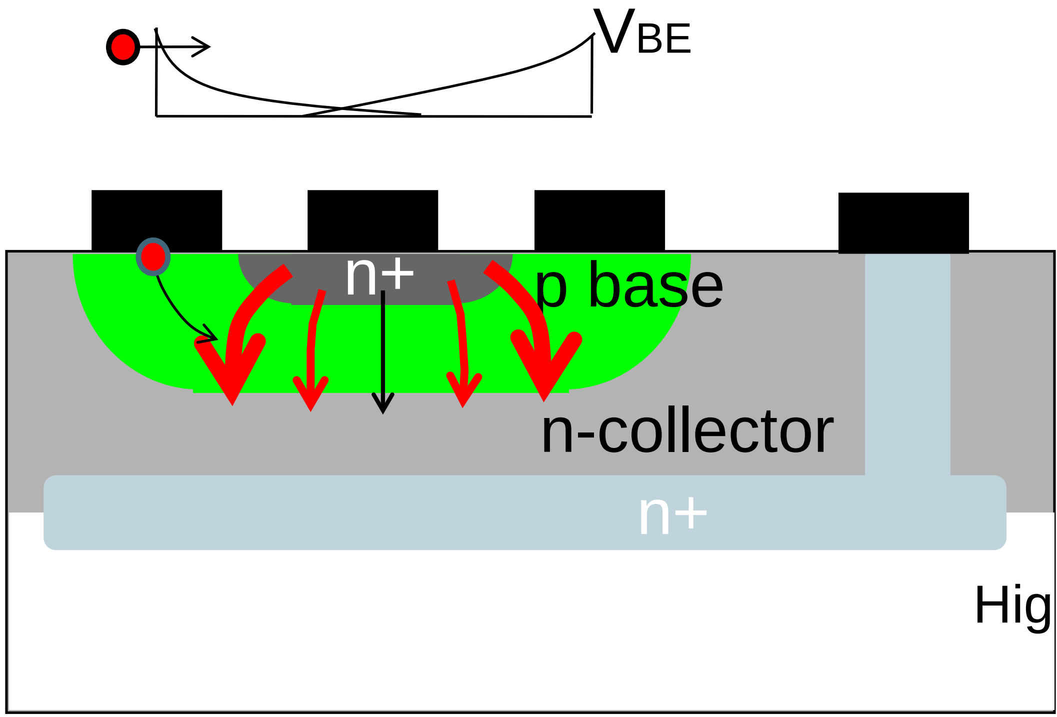




If the base doping is kept to small values, it will have a high resistance:
Lesser ability to conduct means higher resistance

Low Base Doping: Non-uniform Turn-on





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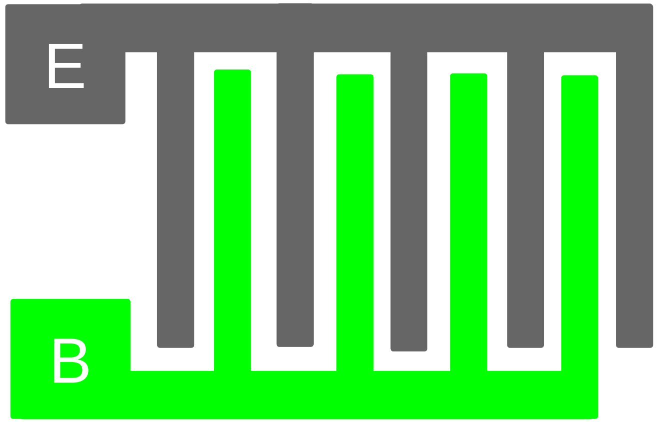
Non-uniform current inefficient

High current at the edge can cause burn-out



Interdigitated designs for almost all high power transistors (E-B distance minimized)

Low Base Doping: Current Crowding

Key facts:

1. Current crowding is due to 2D nature of BJTs
2. It is a function of the doping concentration
3. As base doping concentration increases, resistivity decreases
   - Consequence: Current gain goes smaller
     → Emitter current injection efficiency decreases

$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

The larger current density near the emitter may cause localized heating and high injection effects

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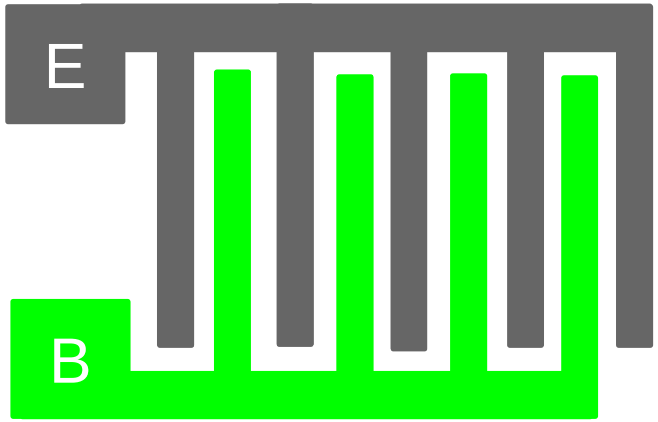

Interdigitated designs for almost all high power transistors (E-B distance minimized)

Possible Solution: Emitter widths are fabricated with an inter-digitated design
→ Many narrow emitters connected in parallel to achieve the required emitter area

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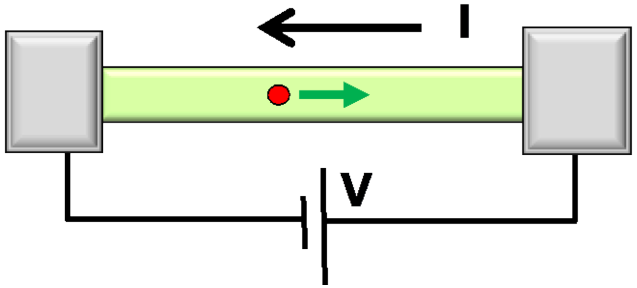

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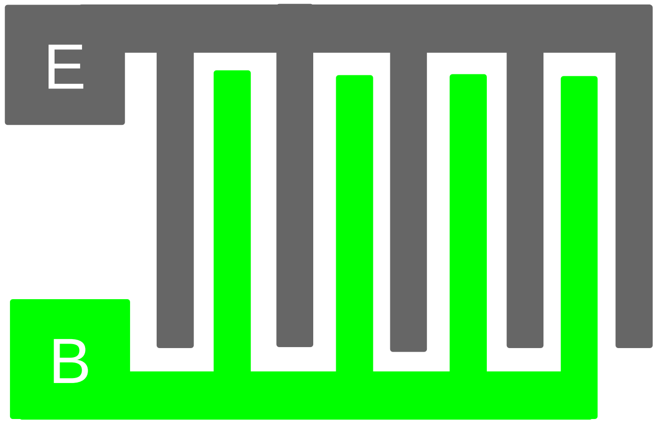
charge density velocity area



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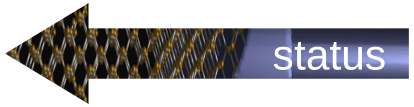

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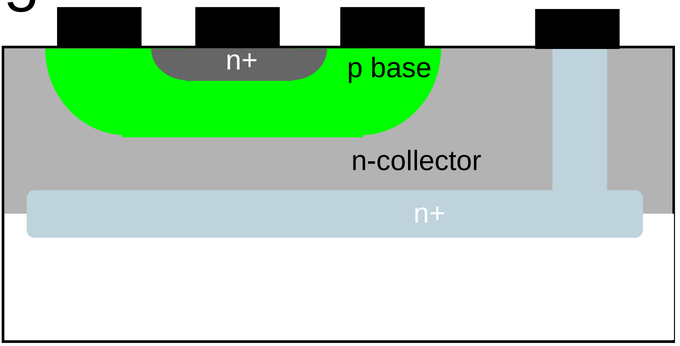

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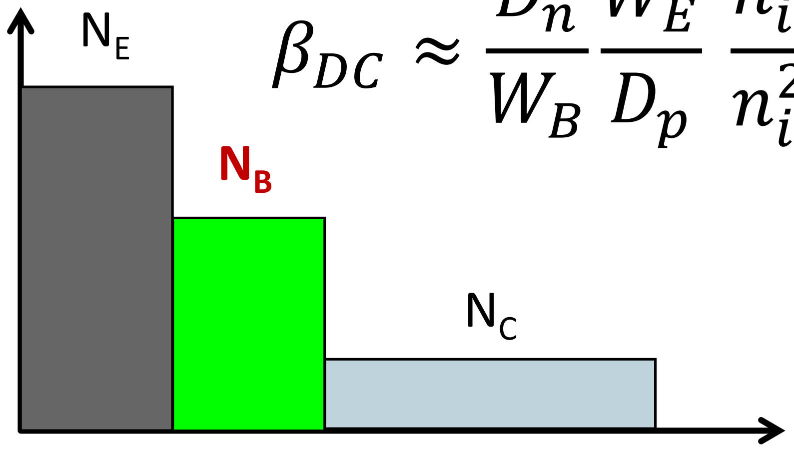

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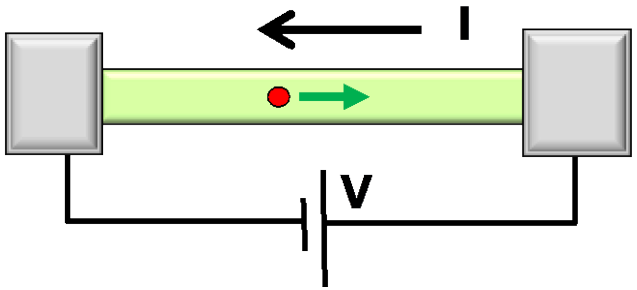

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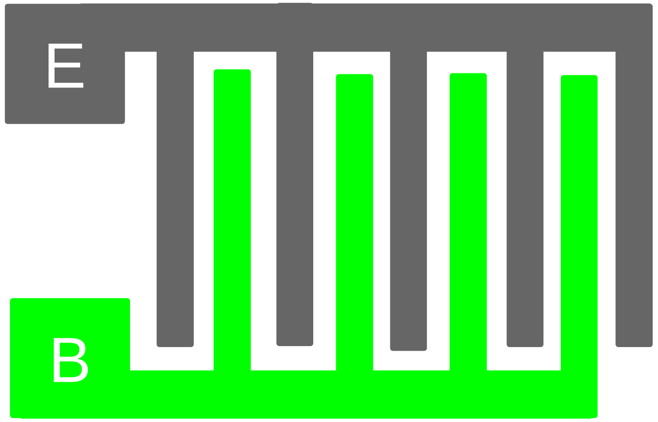

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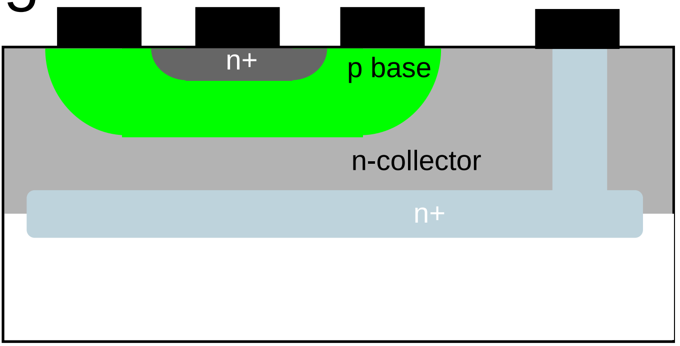

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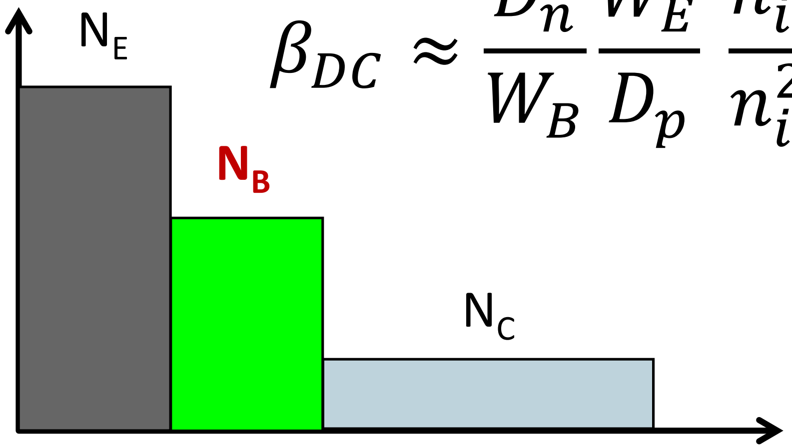

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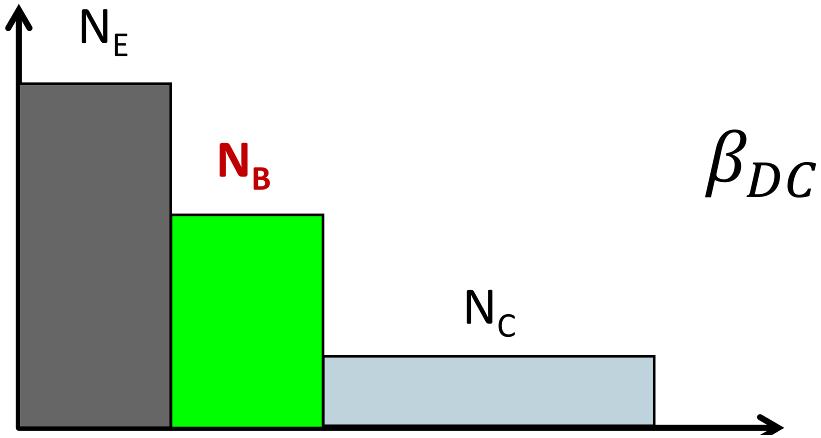
Problem of Low Base Doping: Punch-through



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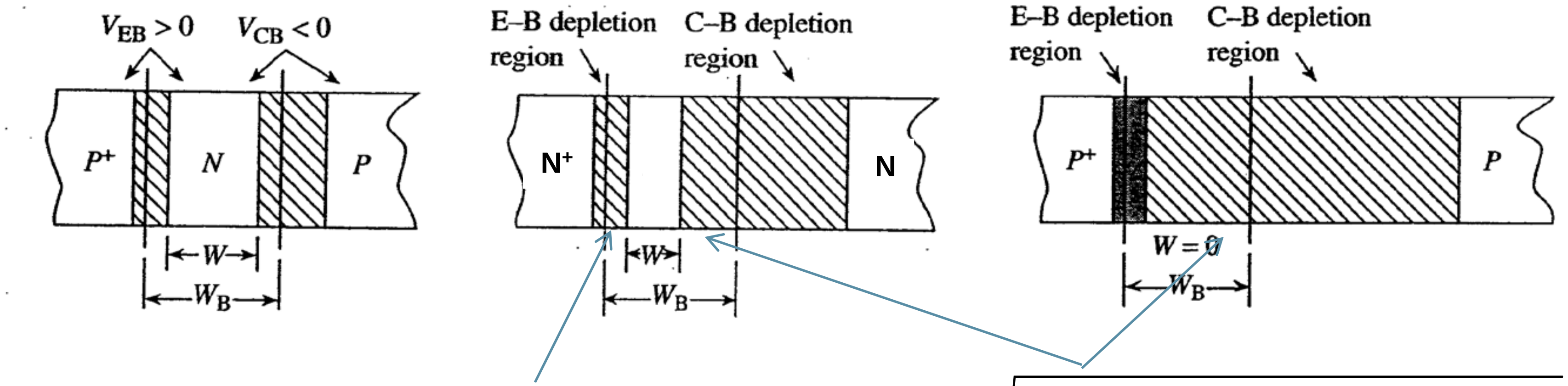

$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{BE}\right)}$$

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

V_{BE} is positive (forward bias)

V_{BC} is negative (reverse bias)
=> $x_{p,BC}$ grows

Low base doping is not a good idea!

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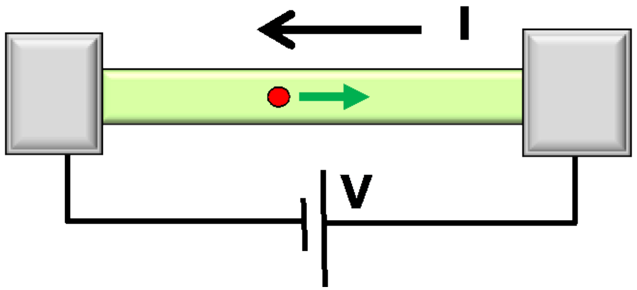

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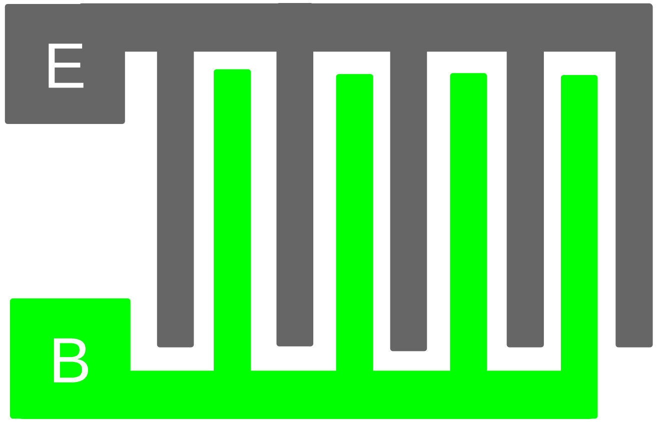

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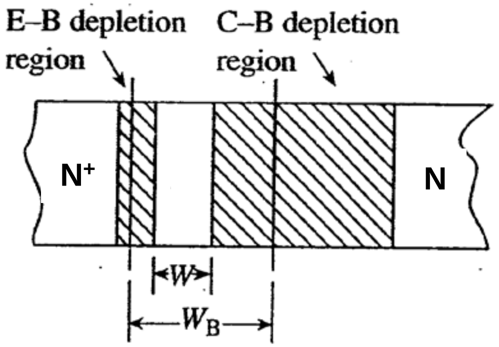

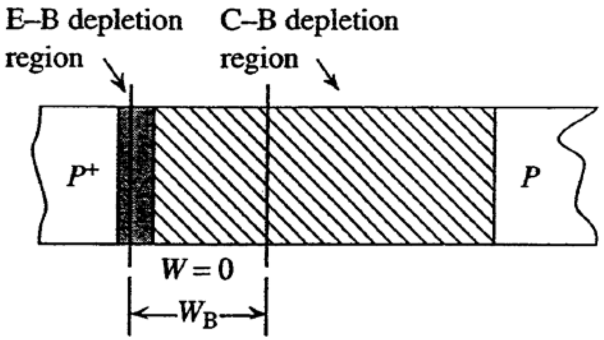

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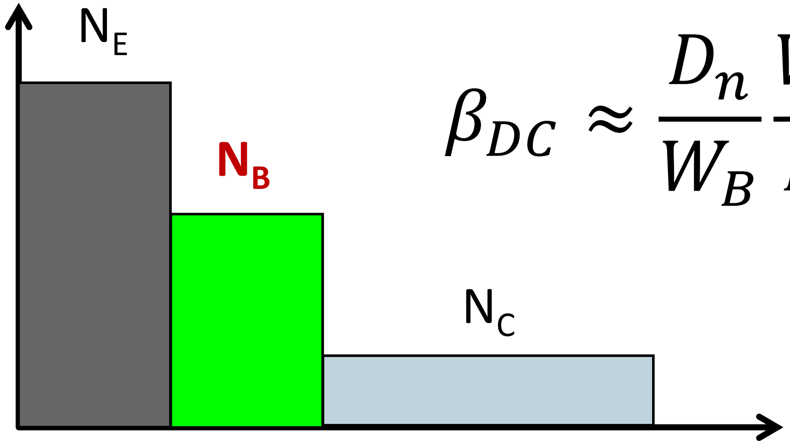

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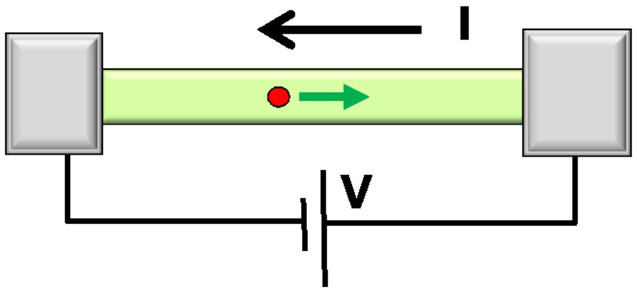

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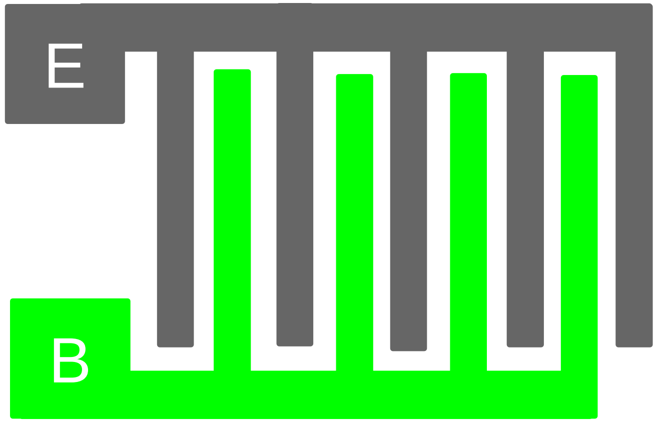

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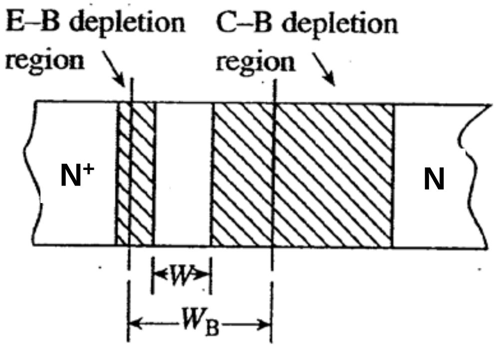

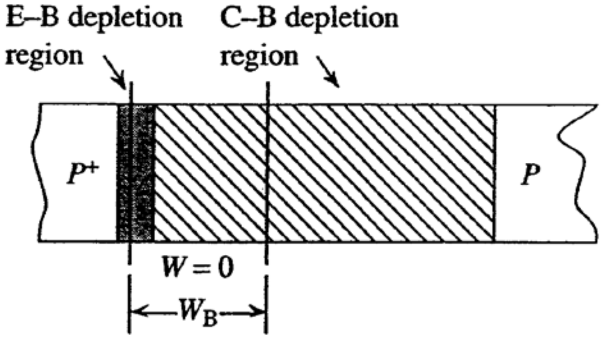

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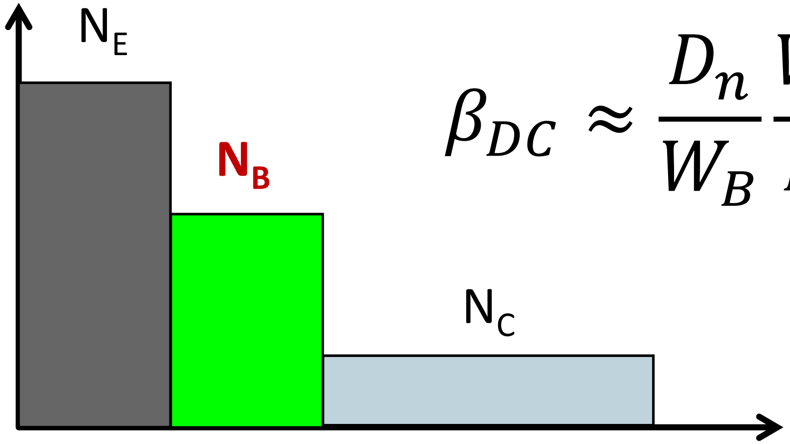

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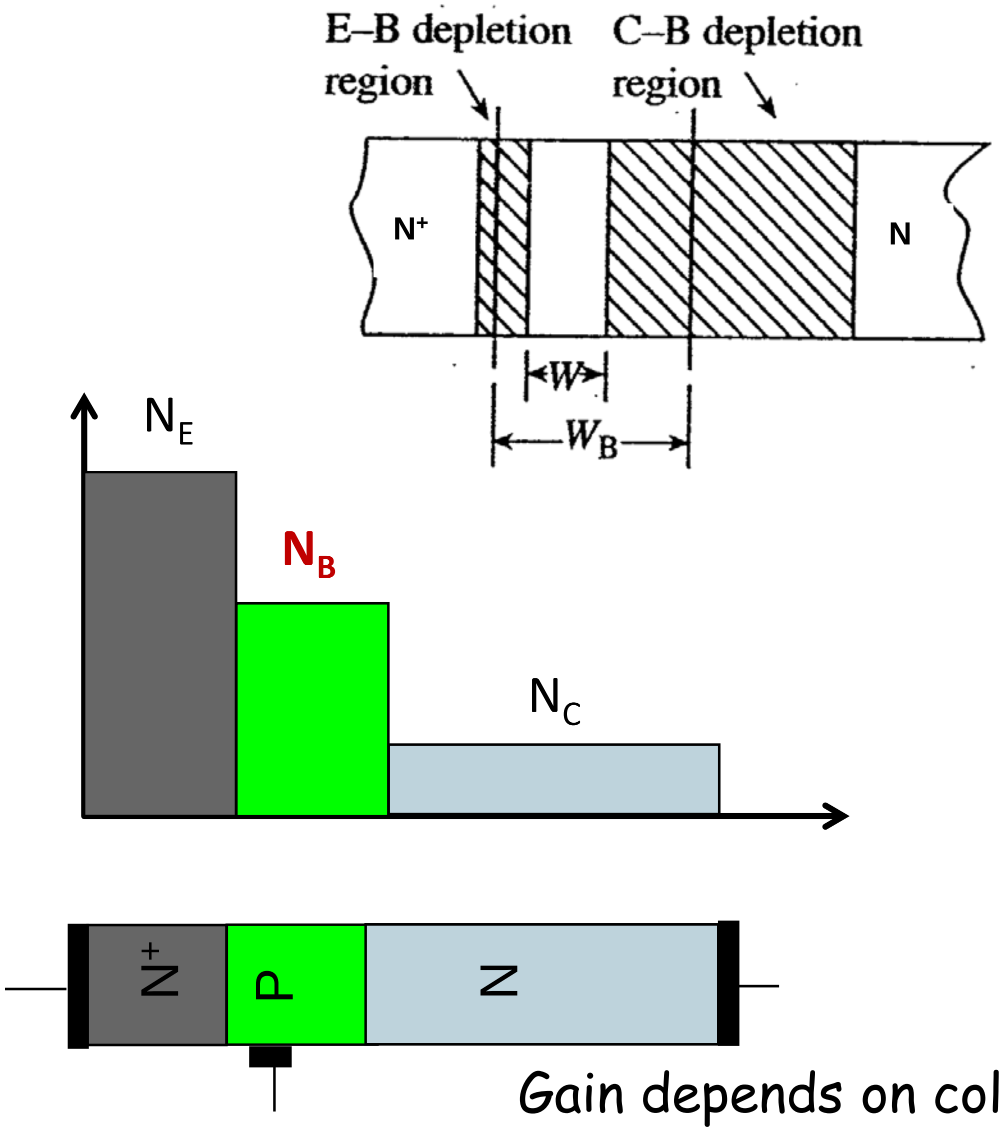
Problem of low Base-doping:
Base Width Modulation



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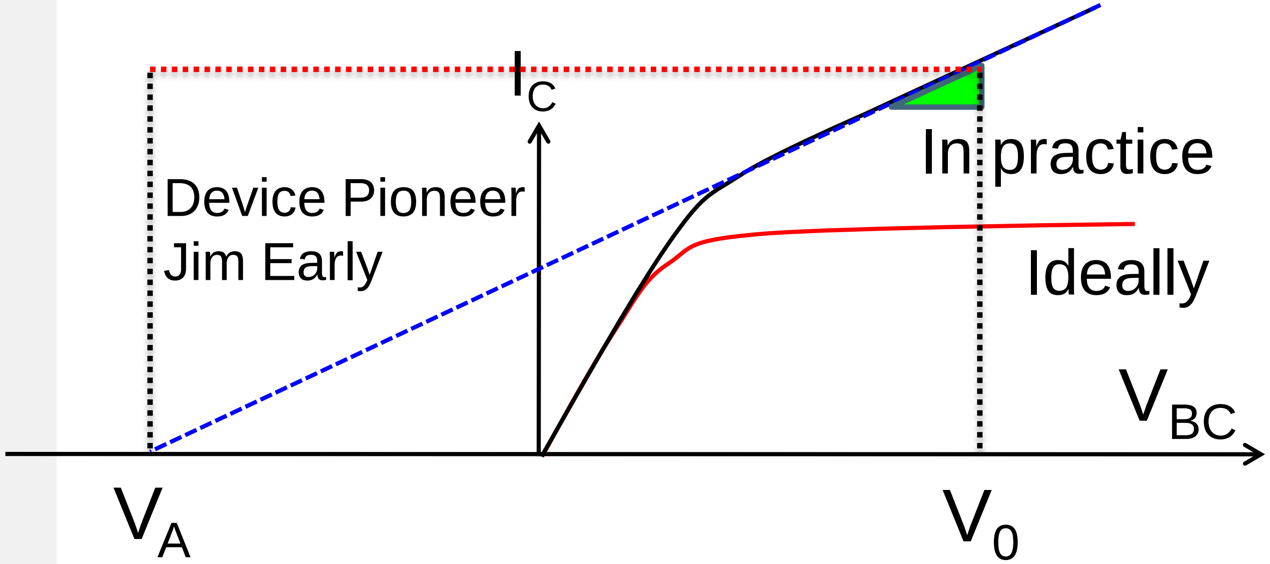
Electrical base region is smaller than the metallurgical region!

$$\beta_{DC}\approx\frac{D_n}{W_B-x_{p,B}-x_{p,C}}\frac{W_E}{D_p}\frac{N_E}{N_B}$$

Gain depends on collector voltage (bad) …
Depletion region width modulation

Problem of low Base-doping: Base Width Modulation



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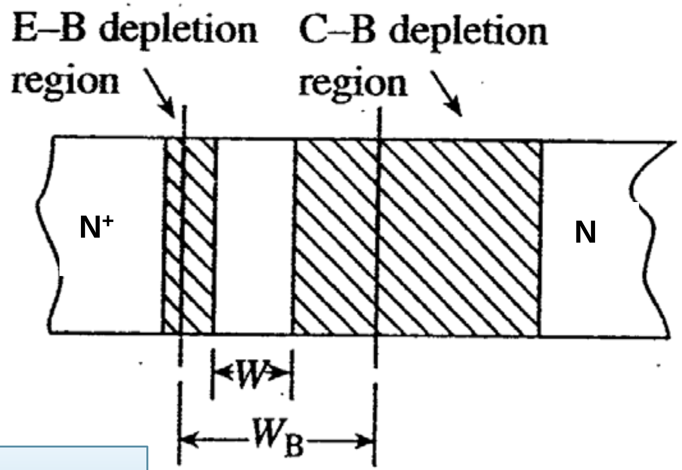
$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}}\frac{W_E}{D_p}\frac{N_E}{N_B}$$

- Fix V_{BE}
- Increase $V_{CE} = V_{BE} + V_{BC}$

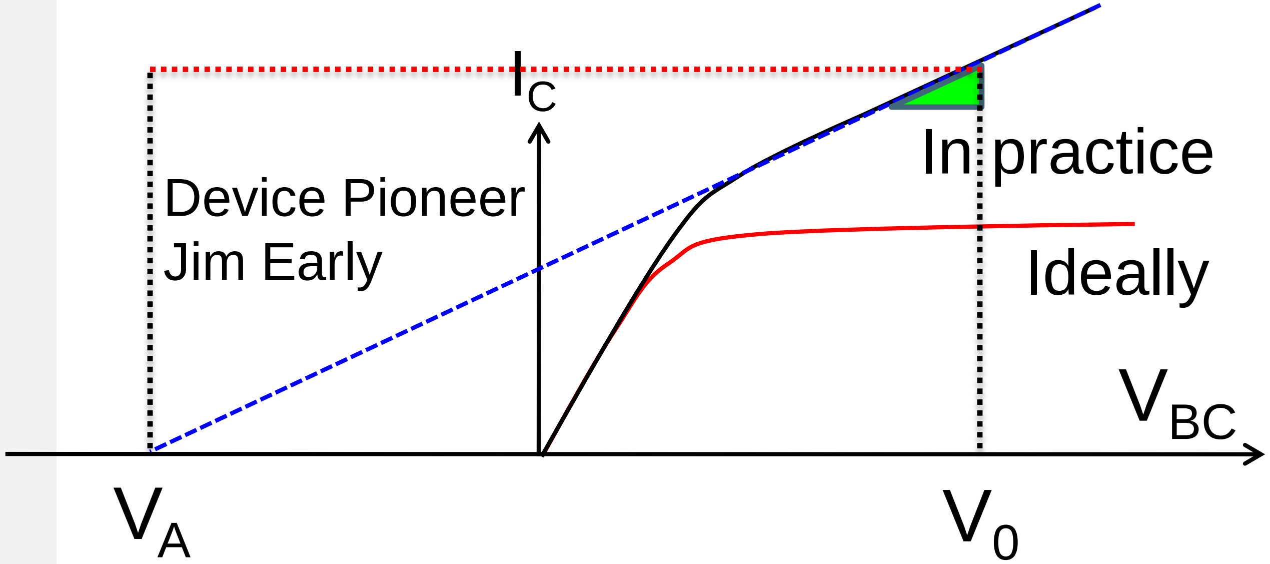
=> increase depletion at BC junction

=> increase total current I_C



- Draw a tangential to the transistor *I-V* at the point of interest.
- The Early voltage: $(V_0 – V_A)$ in figure above

Problem of low Base-doping:
Base Width Modulation



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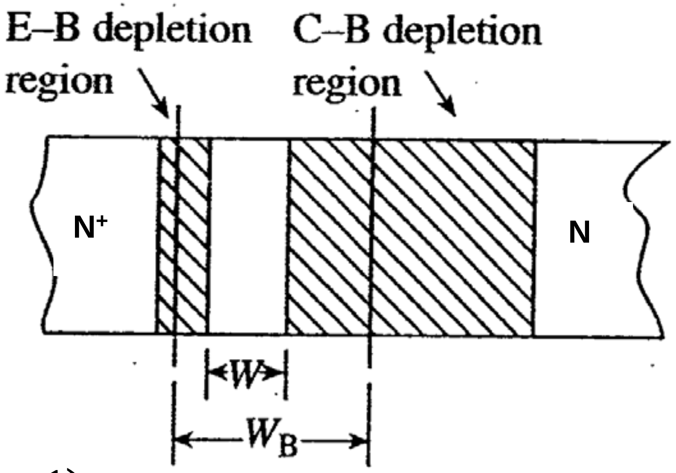
$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}}\frac{W_E}{D_p}\frac{N_E}{N_B}$$

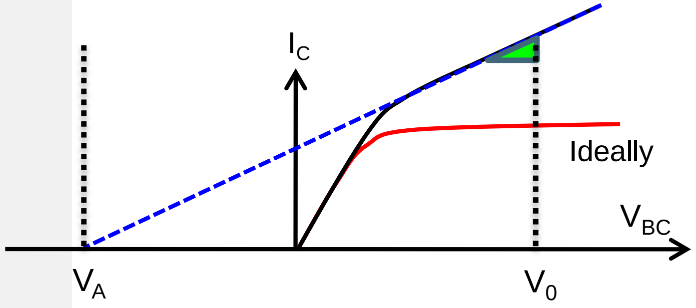
$$\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC}+V_A} \approx \frac{I_C}{V_A}$$

$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p.B} - x_{p.C}}\frac{W_E}{D_p}\cancel{\frac{n^2{}_{i,B}}{n^2{}_{i,E}}}\frac{N_E}{N_B}$$

$$I_{n,C} = -\frac{qD_n}{W_B'}\frac{n^2{}_{i,B}}{N_B}\left(e^{(qV_{BE}/kT)}-1\right) + \frac{qD_n}{W_B'}\frac{n^2{}_{i,B}}{N_B}\left(e^{(qV_{BC}/kT)}-1\right)$$



Punch-through and Early Voltage



$$\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC}+V_A} \approx \frac{I_C}{V_A}$$

$$\frac{dI_C}{dV_{BC}} = \frac{dI_C}{d\left(qN_BW_B\right)}\frac{d\left(qN_BW_B\right)}{dV_{BC}}$$

$$= \frac{1}{qN_B}\left(\frac{dI_C}{dW_B}\right)\left[\frac{dQ_B}{dV_{BC}}\right]$$

$$= -\frac{1}{qN_B}\left(\frac{I_C}{W_B}\right)C_{CB}$$

$$-\frac{C_{CB}}{qN_B}\frac{I_C}{W_B} \approx \frac{I_C}{V_A}$$

$$\Rightarrow V_A = -\frac{qN_BW_B}{C_{CB}} \qquad \rightarrow \infty$$

Need higher N_B and W_B or …

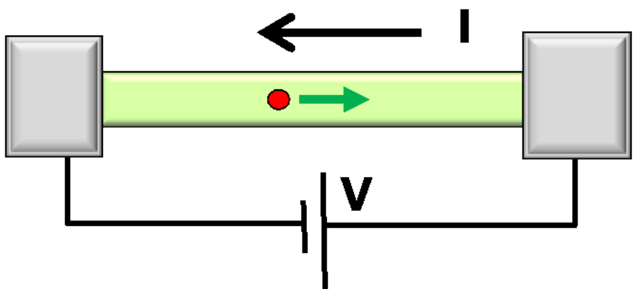
$$C_{CB} = \frac{\kappa_s\varepsilon_0}{x_{n,C}+x_{p,B}}$$

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

$$= \frac{\xi}{W_B}$$

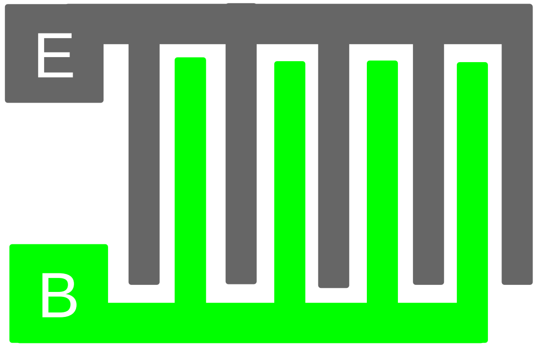
$$\frac{dI_C}{dW_B} = \frac{d}{dW_B}\left(\frac{\xi}{W_B}\right) = -\frac{\zeta}{W_B{}^2} \qquad = -\frac{I_C}{W_B}$$

Section 25
Bipolar Junction Transistor - Design



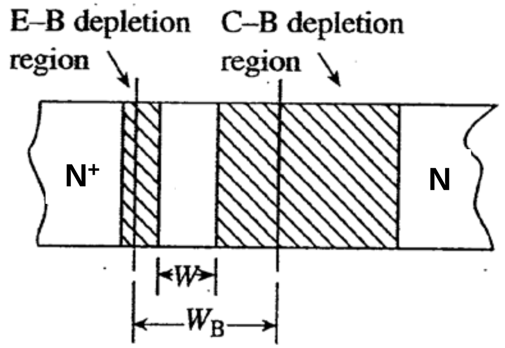
$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



- 25.1 Current gain in BJTs
- 25.2 Base Doping Design
  - » Current Crowding – Non-Uniform Turn-On
  - » Punch-through
  - » Base Width Modulation
- 25.3
- 25.4
- 25.5
- 25.6

status

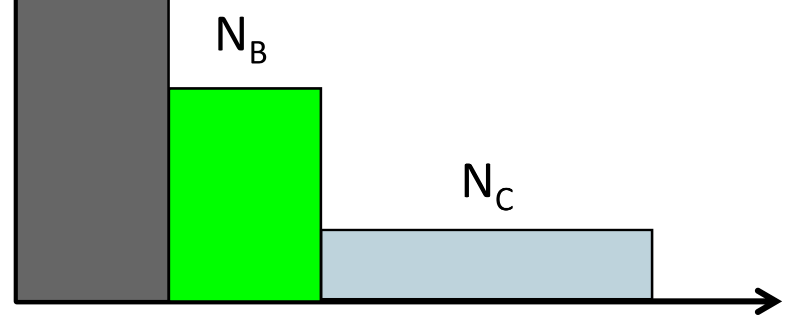


$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{BE}\right)}$$

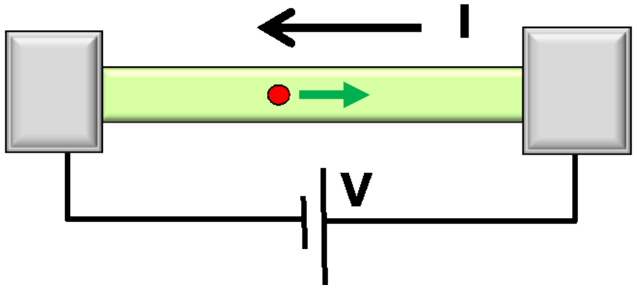
$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{BC}\right)}$$

$$V_A = -\frac{qN_BW_B}{C_{CB}} \qquad C_{CB} = \frac{\kappa_s\varepsilon_0}{x_{n,C}+x_{p,B}}$$

$$\beta \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$



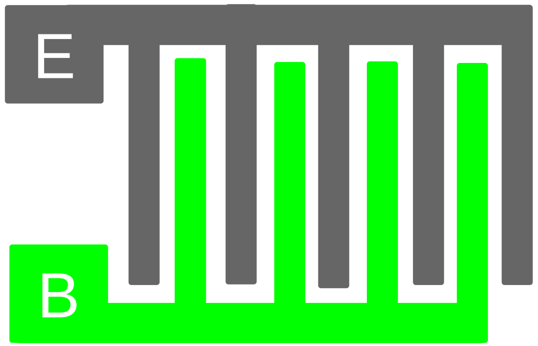
Section 25
Bipolar Junction Transistor - Design

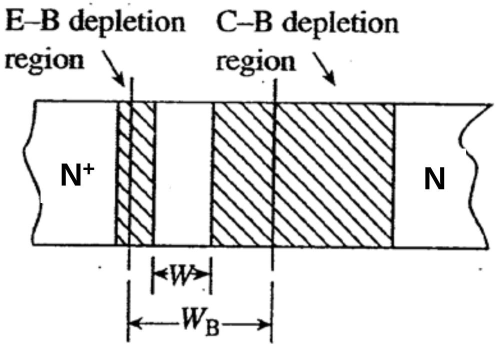


I = G × V

= q × n × v × A

charge density velocity area





- 25.1 Current gain in BJTs
- 25.2 Base Doping Design
  - » Current Crowding – Non-Uniform Turn-On
  - » Punch-through
  - » Base Width Modulation
- 25.3 Collector Doping Design (Kirk Effect, Base Pushout)
- 25.4
- 25.5
- 25.6

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

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

$$V_A = -\frac{qN_BW_B}{C_{CB}} \qquad C_{CB} = \frac{\kappa_s\varepsilon_0}{x_{n,C}+x_{p,B}}$$

$$\beta \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$