Section 26

Bipolar Junction Transistor – High Frequency Response

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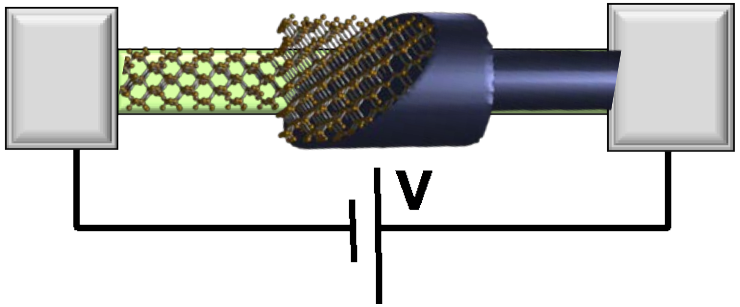
School of Electrical and
Computer Engineering

Section 26
Bipolar Junction Transistor - High Frequency Response



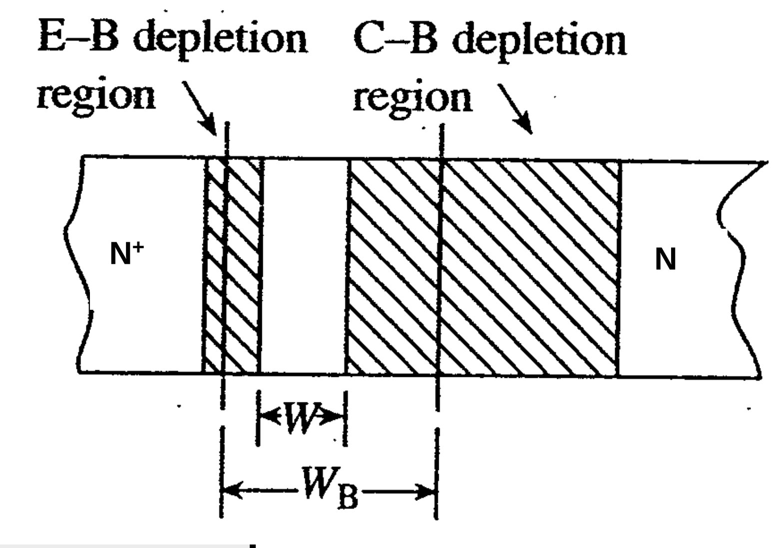
I = G × V

= q × n × v × A

charge density velocity area

$$\beta_{DC} = \frac{I_C}{I_B}$$

	Equilibrium	**DC**	**Small signal**	**Large Signal**	**Circuits**
PN Diode	◆	◆	◆	◆	
Schottky Diode	◆	◆	◆		
BJT/ HBT	◆	◆	🟥		
MOS					



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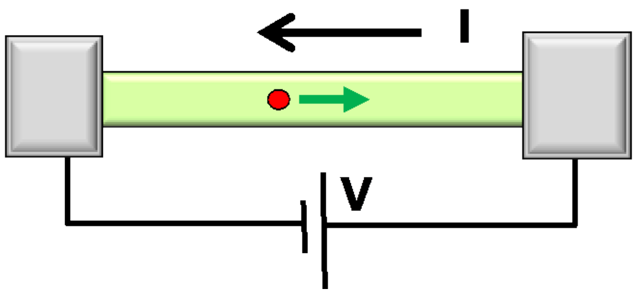
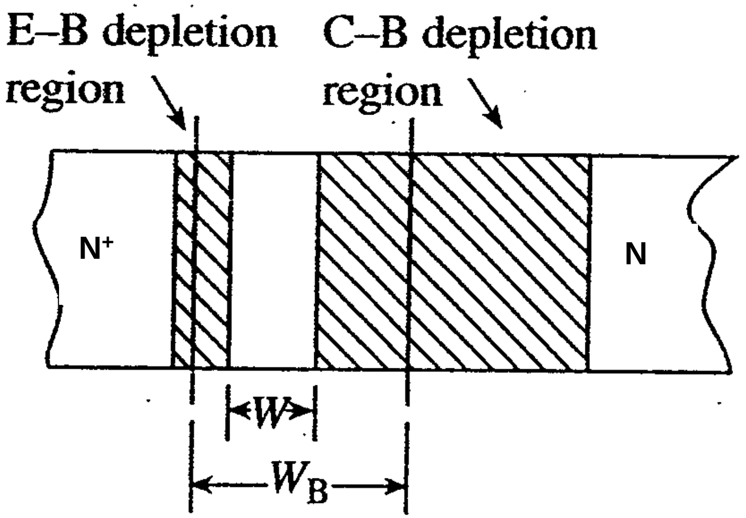


$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



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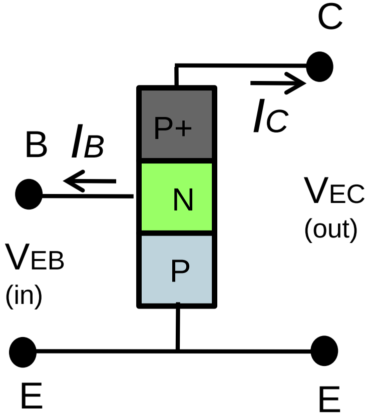
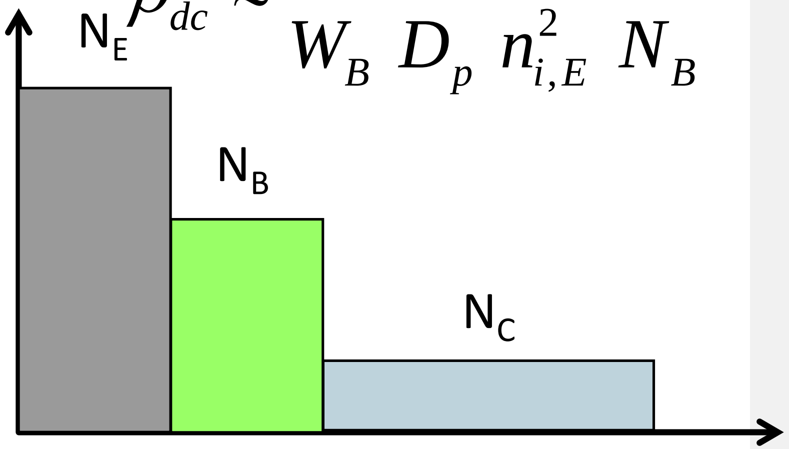
- 25 BJT Design
- 26 BJT High Frequency Response
  - »Small signal circuit model – Common Emitter
  - »Short circuit current gain
  - »Charge control model – Base transit time
  - »Collector transit time

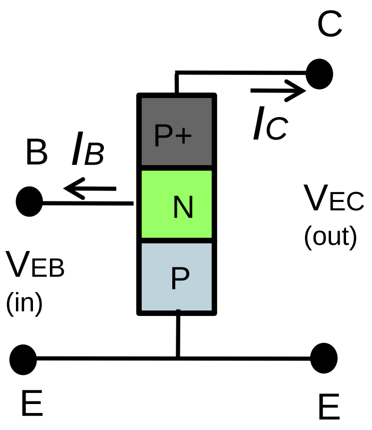


$$\beta_{DC} = \frac{I_C}{I_B}$$



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

Doping for Gain



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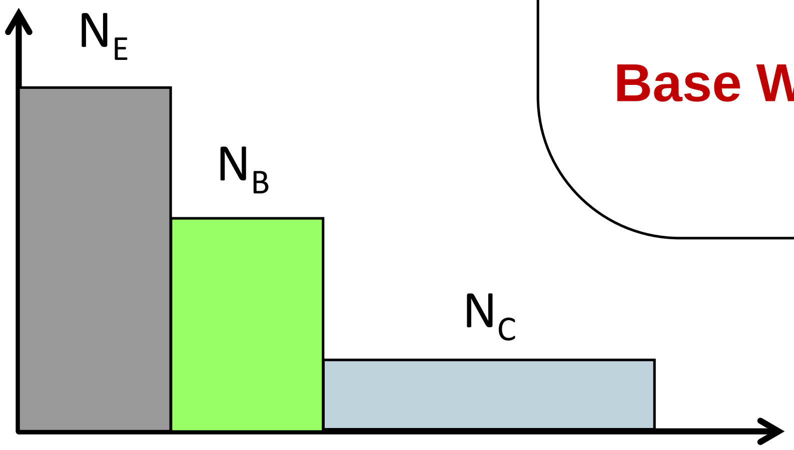
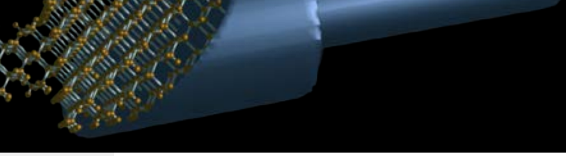


Emitter doping: As high as possible without *band gap narrowing*

Base doping: As low as possible, without *current crowding, Early effect*

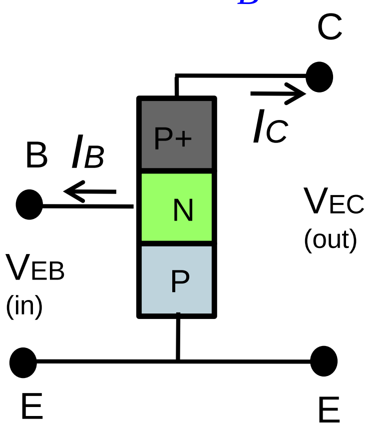
Collector doping: Lower than base doping *without Kirk Effect*

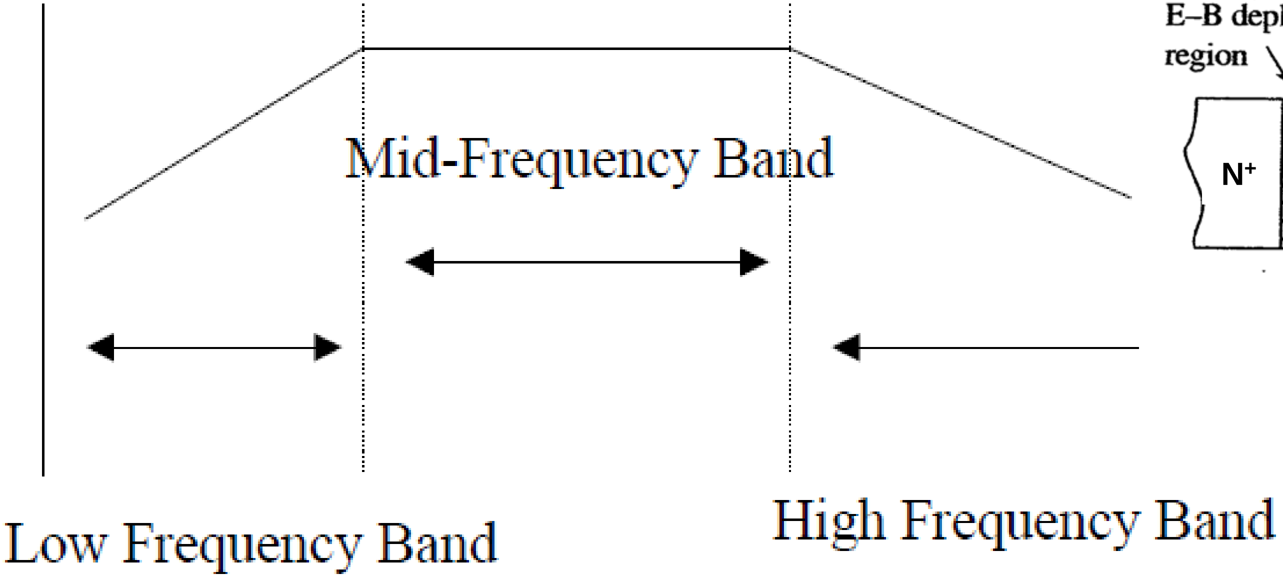
Base Width: As thin as possible without *punch through*

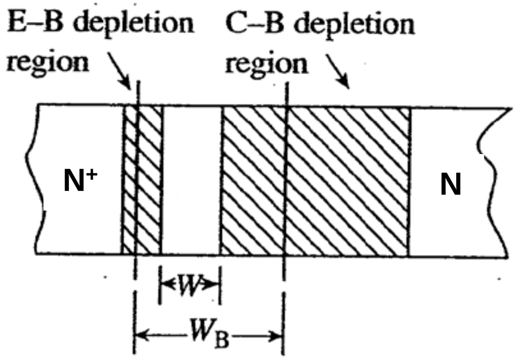


Frequency Response

$$\beta_{DC} = \frac{I_C}{I_B}$$

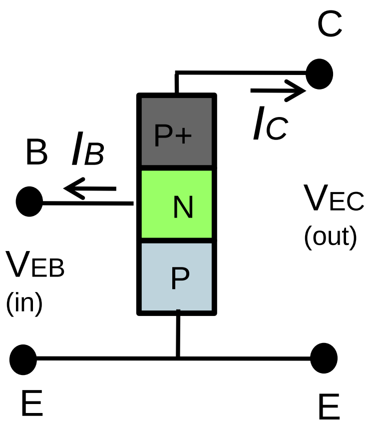




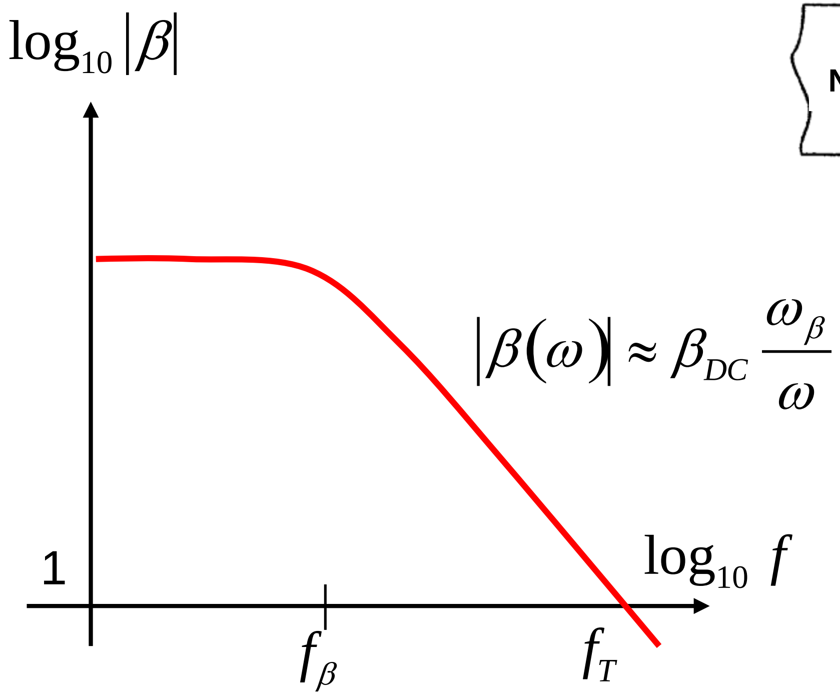


- Flat / uniform frequency response is desired
- Frequency response not flat –
  - There is a low frequency ramp-up and a high frequency reduction
  - Frequency response depends on external circuit and internal device capacitances
- Circuit: low frequency band reduction s due to the coupling and bypass capacitors selected.
- Device: high frequency gain reduction
  - due to the internal capacitance of the amplifying device, e.g., BJT, FET, etc.
  - represented by capacitors in the small signal equivalent circuit for these devices.
  - essentially open circuits in the low and mid bands.

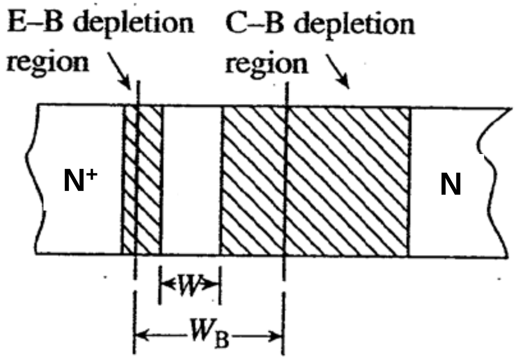
Small Signal Response



$$\beta_{DC} = \frac{I_C}{I_B}$$



$$|\beta(\omega)| \approx \beta_{DC}\frac{\omega_\beta}{\omega}$$



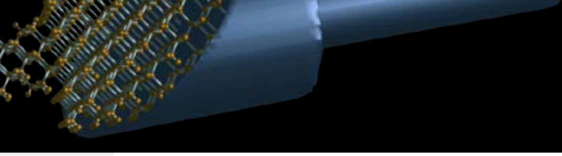
$$\frac{1}{2\pi f_T} = \left[\frac{W_B^2}{2D_n} + \frac{W_{BC}}{2\upsilon_{sat}}\right] + \frac{k_B T}{qI_C}\left[C_{j,BC} + C_{j,BE}\right]$$

Desire high f_T

⇒High I_C

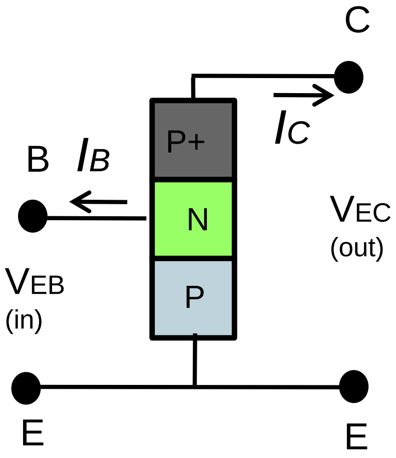
⇒Low capacitances

⇒Low widths

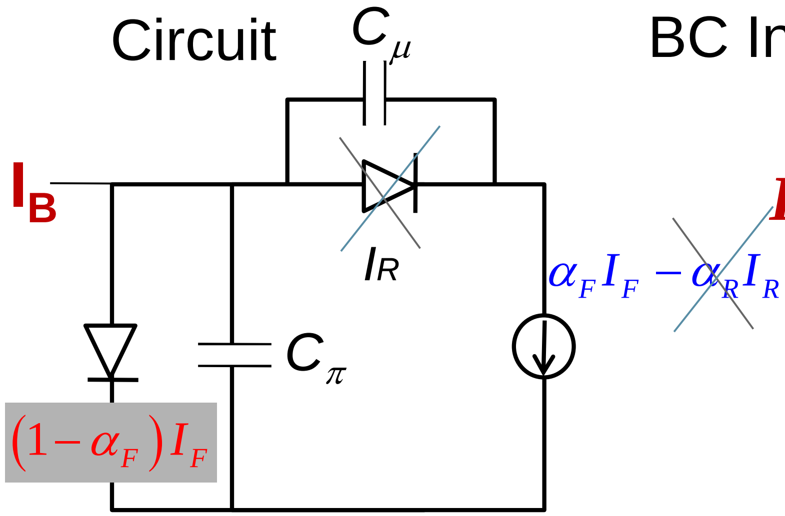


Small Signal Response (Common Emitter)
From Ebers Moll Model

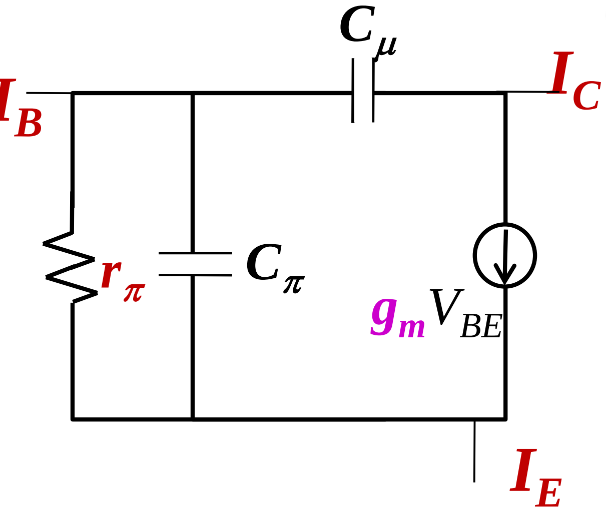
$$\beta_{DC} = \frac{I_C}{I_B}$$

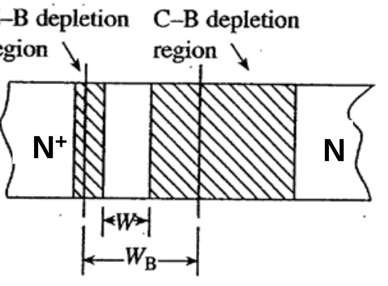


General Circuit



=> AC small signal Circuit
BC In reverse bias, I_R=0





$$I_F = I_{F0}\left(e^{qV_{BE}/kT} - 1\right)$$

$$I_B = (1-\alpha_F)I_{F0}\left(e^{qV_{BE}/kT} - 1\right)$$

$$\frac{1}{r_\pi} = \frac{dI_B}{dV_{BE}} = \frac{d\left[(1-\alpha_F)I_F\right]}{dV_{BE}} = \frac{qI_B}{k_B T} = \frac{1}{\beta_{DC}}\frac{qI_C}{k_B T}$$

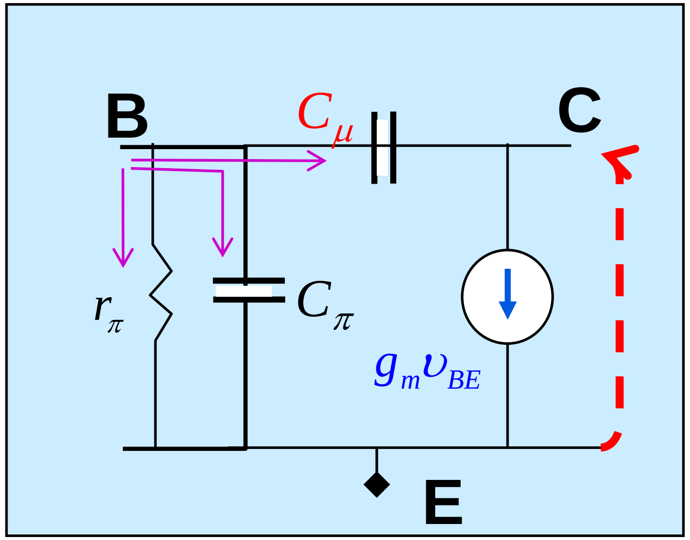
$$g_m = \frac{d(\alpha_F I_F)}{dV_{BE}} \qquad g_m = \frac{qI_C}{k_B T}$$

$$\delta(\alpha_F I_F) = g_m \delta V_{BE} = g_m \upsilon_{BE}$$

Short Circuit Current Gain

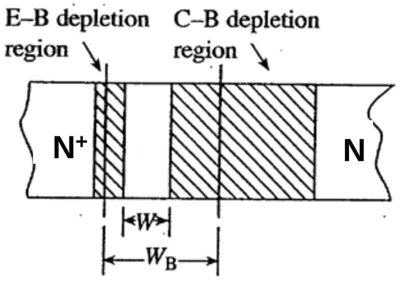
$$\beta_{DC} = \frac{I_C}{I_B}$$

$$g_m = \frac{qI_C}{k_B T}$$

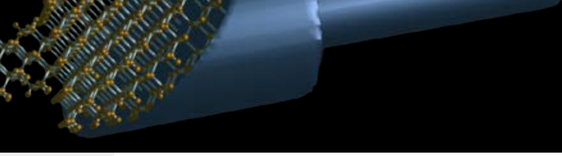


$$\beta(f) = \frac{i_C}{i_B} = \frac{g_m \upsilon_{BE} + j\omega C_\mu \upsilon_{CB}}{\left(\frac{1}{r_\pi}\upsilon_{BE} + j\omega C_\pi \upsilon_{BE}\right) + j\omega C_\mu \upsilon_{BC}}$$

$$\beta(f_T) \equiv 1 = \left| \frac{g_m - \cancel{j\omega_T C_\mu}}{\left(\cancel{\frac{1}{r_\pi}} + j\omega_T C_\pi\right) + j\omega C_\mu} \right|$$



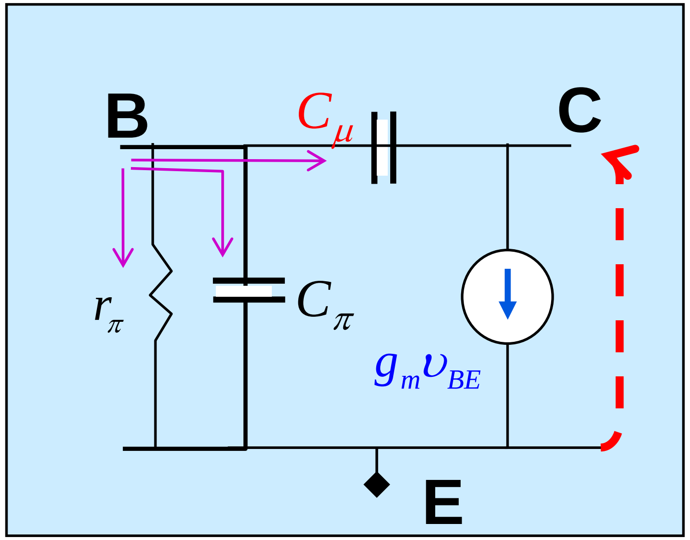
Neglect small terms

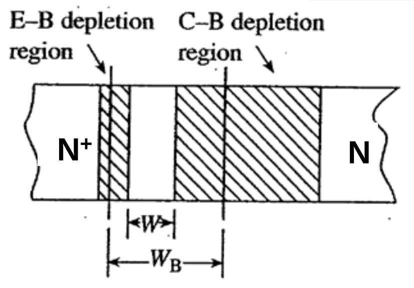


Short Circuit Current Gain

$$\beta_{DC} = \frac{I_C}{I_B}$$

$$g_m = \frac{qI_C}{k_B T}$$



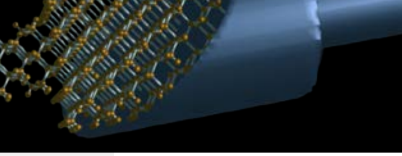


$$\beta(f) = \frac{i_C}{i_B} = \frac{g_m \upsilon_{BE} + j\omega C_\mu \upsilon_{CB}}{\left(\frac{1}{r_\pi}\upsilon_{BE} + j\omega C_\pi \upsilon_{BE}\right) + j\omega C_\mu \upsilon_{BC}}$$

$$\beta(f_T) \equiv 1 = \left|\frac{g_m - \cancel{j\omega_T C_\mu}}{\left(\cancel{\frac{1}{r_\pi}} + j\omega_T C_\pi\right) + j\omega C_\mu}\right| \approx \left|\frac{g_m}{j\omega_T \left(C_\pi + C_\mu\right)}\right|$$

Neglect small terms

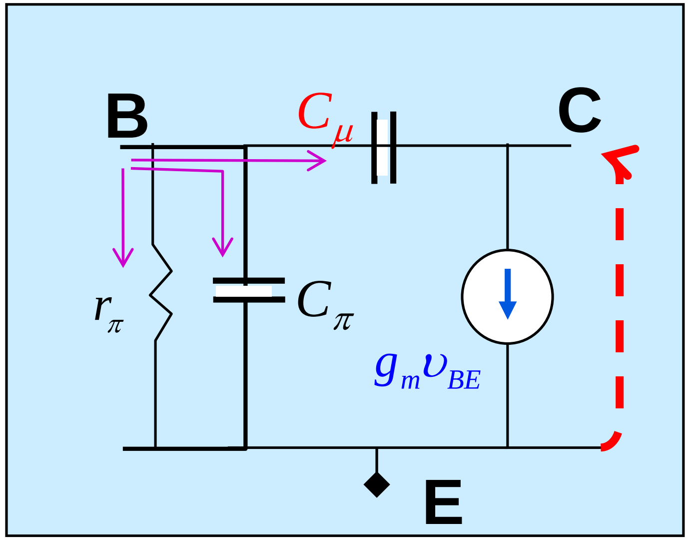
$$\frac{1}{\omega_T} \equiv \frac{1}{2\pi f_T} = \frac{C_\pi + C_\mu}{g_m}$$

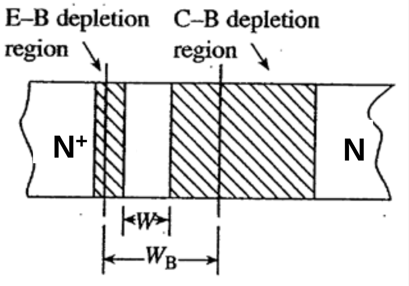


Short Circuit Current Gain

$$\beta_{DC} = \frac{I_C}{I_B}$$

$$g_m = \frac{qI_C}{k_BT}$$





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Neglect small terms

$$\frac{1}{\omega_T} \equiv \frac{1}{2\pi f_T} = \frac{C_\pi + C_\mu}{g_m} = \boxed{\frac{k_BT}{qI_C}\left(C_{j,BC} + C_{j,BE}\right)} + \boxed{\frac{k_BT}{qI_C}\left(C_{d,BC} + \cancel{C_{d,BE}}\right)}$$

BE forward bias neglect $C_{d,BE}$

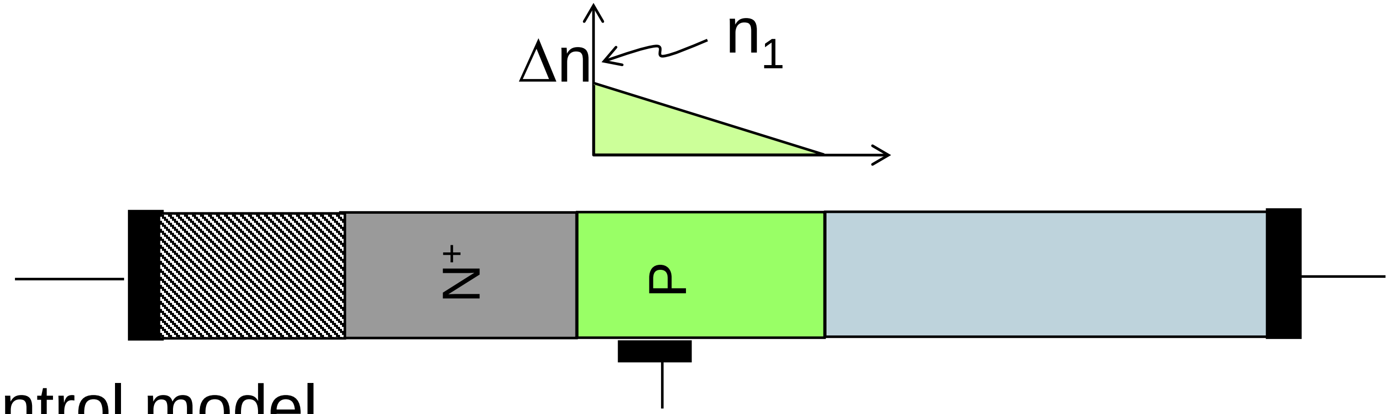
$$g_m = \frac{dI_C}{dV_{BE}}$$

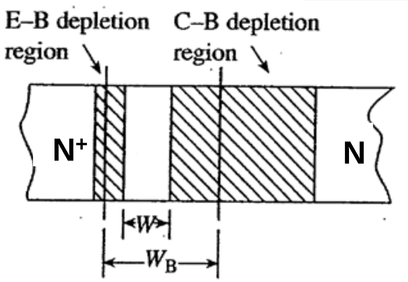
$$Q_B = C_{d,BC}\, V_{BE}$$

$$\downarrow$$

$$\frac{k_BT}{qI_C} C_{d,BC} = \frac{C_{d,BC}}{dI_C / dV_{BE}} = \frac{dQ_B}{dI_C}$$

Base Transit Time





Ref. Charge control model

$$\frac{dQ_B}{dI_C} = \frac{Q_B}{I_C} = \frac{q\frac{1}{2}n_1W_B}{q\frac{n_1}{W_B}} = \frac{W_B^2}{2D_n}$$

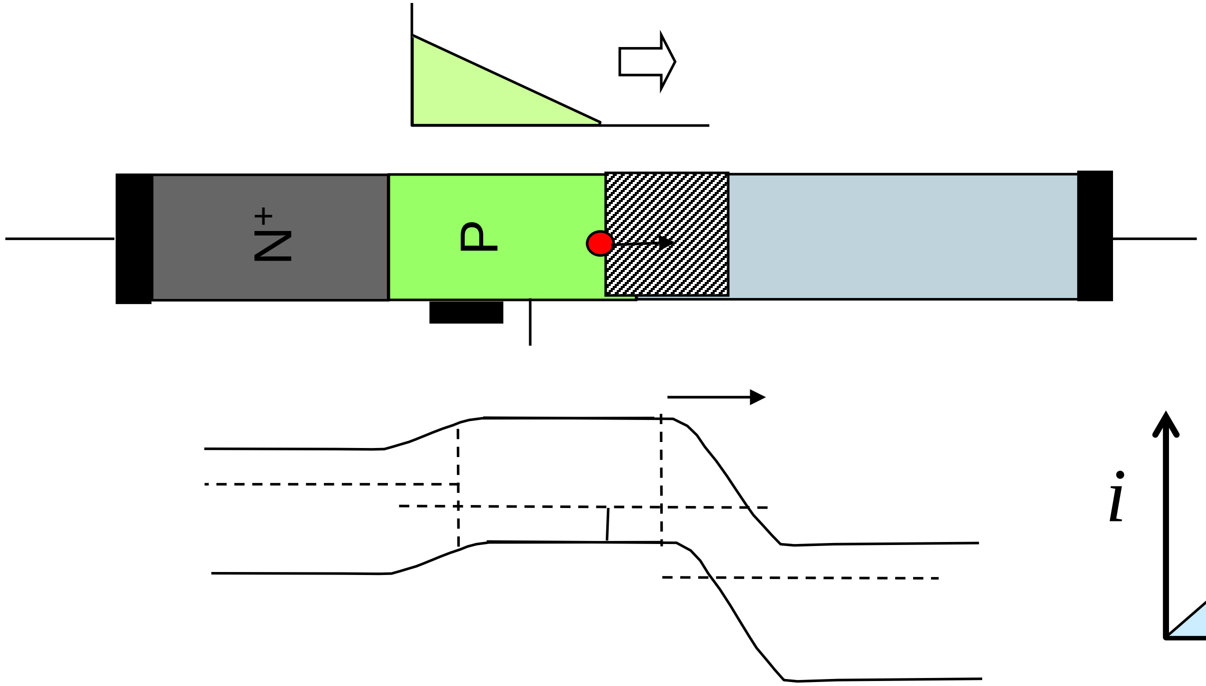
Base transit time

$$\frac{k_BT}{qI_C}C_{d,BC} = \frac{C_{d,BC}}{dI_C/dV_{BE}} = \frac{dQ_B}{dI_C}$$

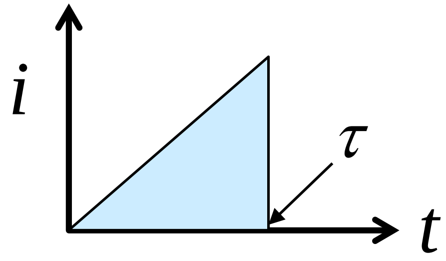
Collector Transit Time

Electrons injected into collector depletion region – very high fields more than diffusion => drift => acceleration of carriers

Charge imaged in collector



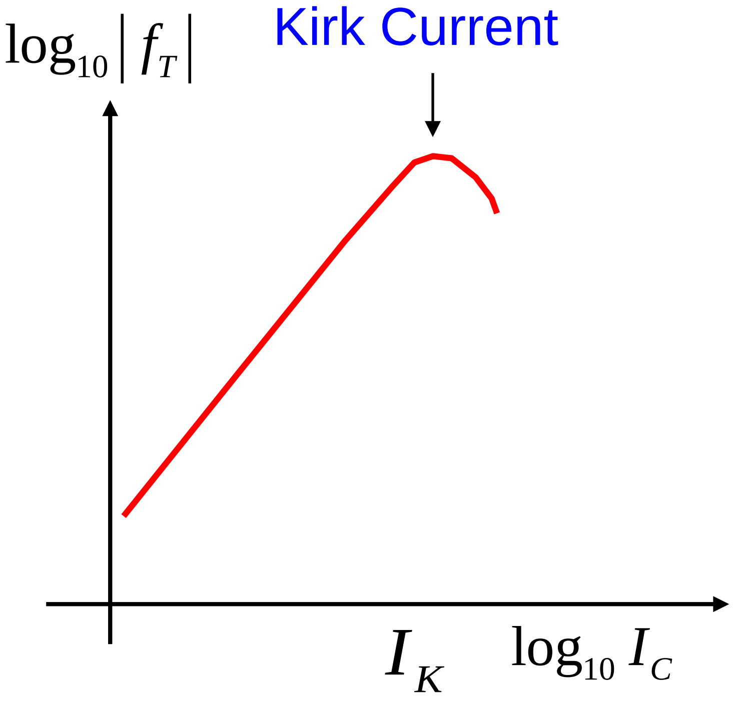
$$\tau = \frac{W_{BC}}{\upsilon_{sat}}?$$



$$\boxed{\tau_{eff,BC} = \frac{q}{i} = \frac{\tau}{2} = \frac{W_{BC}}{2\upsilon_{sat}}}$$

$$\frac{1}{2}\times i\times\tau = q$$

Putting the Terms Together

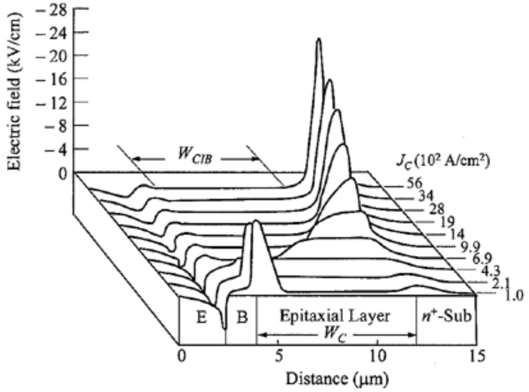


Collector transit time

Base transit time

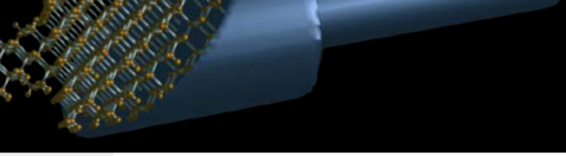
$$\frac{1}{2\pi f_T} = \left[\frac{W_B^2}{2D_n} + \frac{W_{BC}}{2\upsilon_{sat}}\right] + \frac{k_B T}{qI_C}\left[C_{j,BC} + C_{j,BE}\right]$$

Junction charging time



Do you see the motivation to reduce W_B and W_{BC} as much as possible?
What problem would you face if you push this too far ?

Increasing I_C too high reduces W_{BC} and increases the overall capacitance
=> frequency rolls off….



High Frequency Metrics

(current-gain cutoff frequency, f_T)

$$\tau = \frac{1}{2\pi f_T} = \frac{W_B^2}{2D_n} + \frac{W_{BC}}{2\upsilon_{sat}} + \frac{k_B T/q}{I_C}\left(C_{j,BE} + C_{j,BC}\right) + \left(R_{ex} + R_c\right)C_{cb}$$

(power-gain cutoff frequency, f_{max})

$$f_{\max} = \sqrt{\frac{f_T}{8\pi R_{bb} C_{cbi}}}$$

BJT - Summary

$$\tau = \frac{1}{2\pi f_T} = \frac{W_B^2}{2D_n} + \frac{W_{BC}}{2\upsilon_{sat}} + \frac{k_B T/q}{I_C}\left(C_{j,BE} + C_{j,BC}\right) + \left(R_{ex} + R_c\right)C_{cb}$$

We have discussed various modifications of the classical BJTs and explained why improvement of performance has become so difficult in recent years.

Poly-Si Emitter was a critical invention.

The small signal analysis illustrates the importance of reduced junction capacitance, resistances, and transit times.

Classical **homojunctions** BJTs can only go so far, further improvement is possible with **heterojunction** bipolar transistors.

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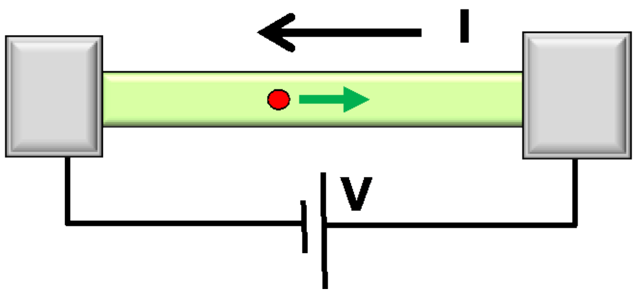

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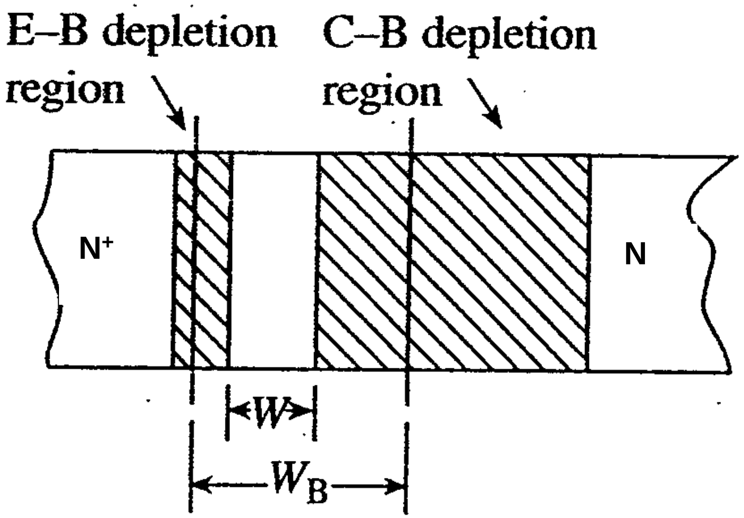

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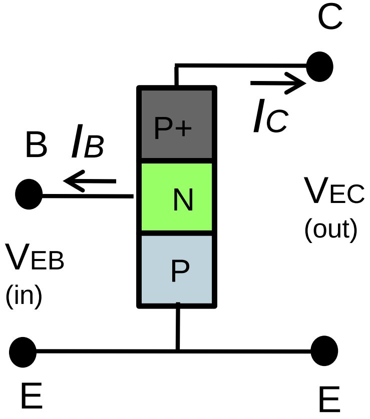
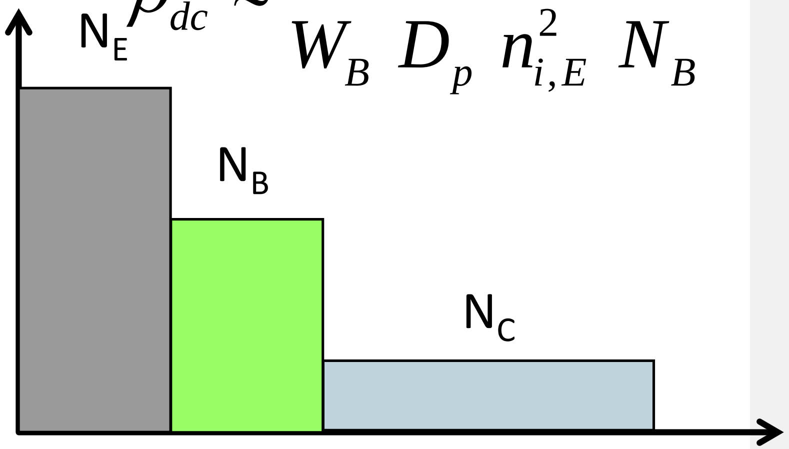


$$\beta_{DC} = \frac{I_C}{I_B}$$



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