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ECE606: Solid State Devices
Lecture 29: BJT Design (II)

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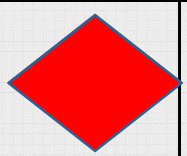
Outline

1) **Problems of classical transistor**
2) Poly-Si emitter
3) Short base transport
4) High frequency response
5) Conclusions

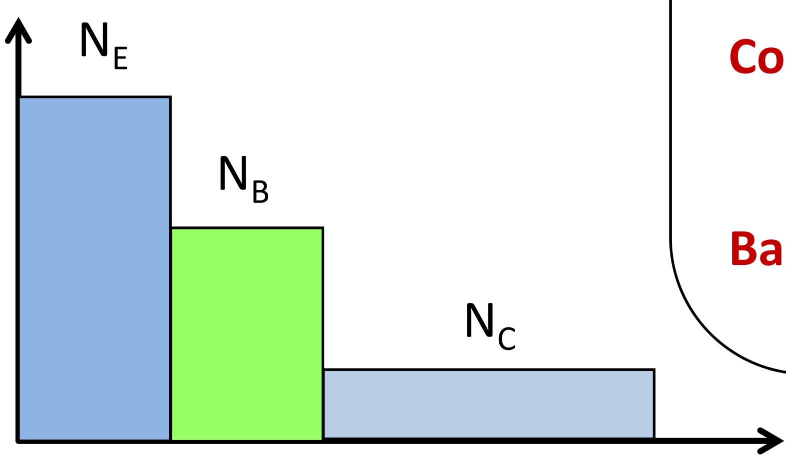
REF: SDF, Chapter 11 and 12

Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT					
MOS					

Doping for Gain

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



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*

How to make better Transistor

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

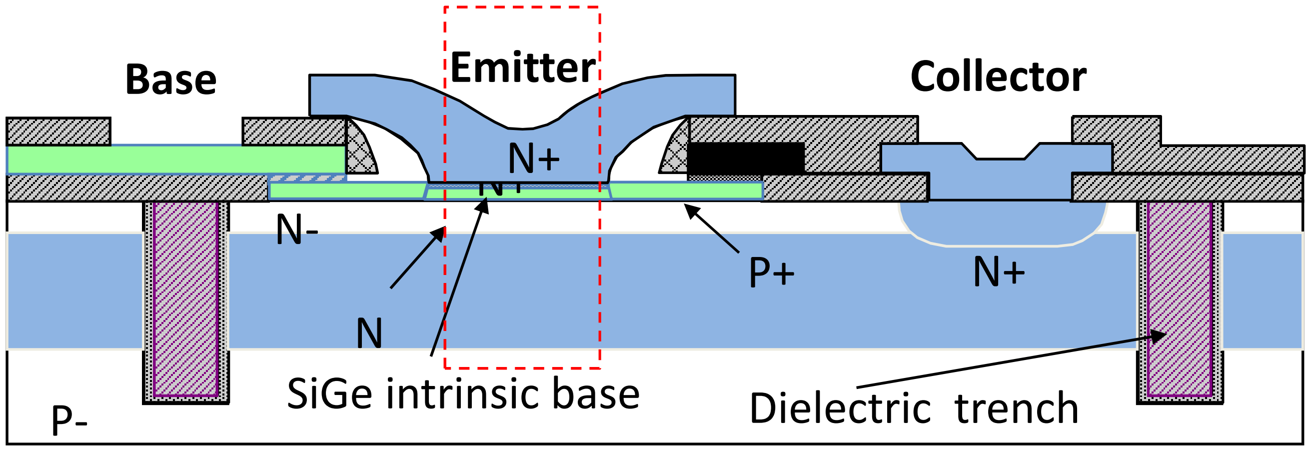
Graded Base transport

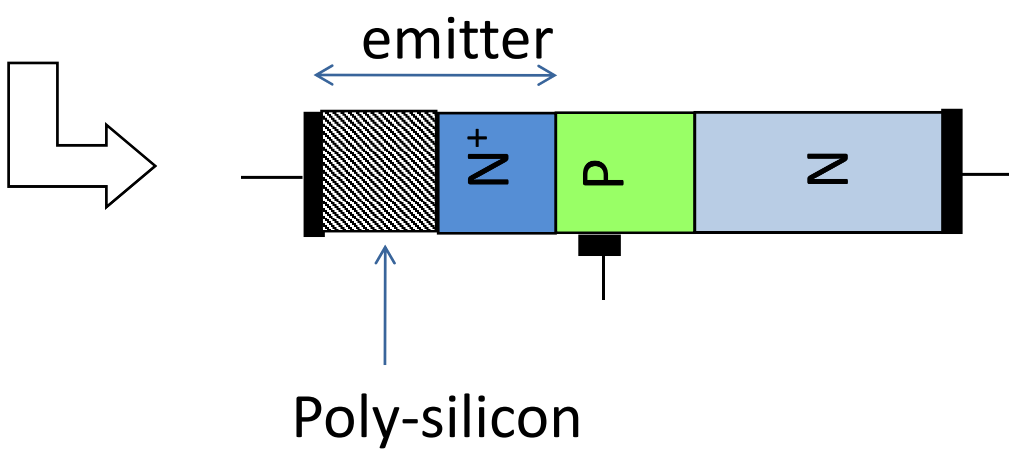
Polysilicon Emitter

Classical Shockley Transistor

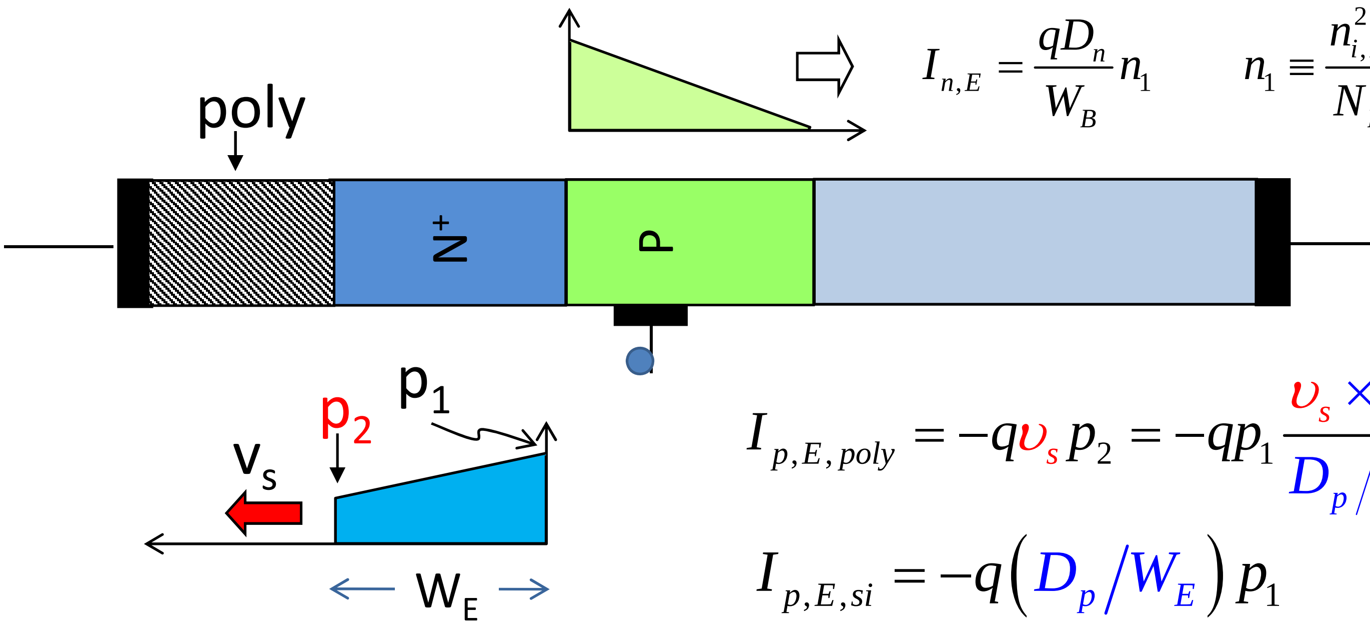
Heterojunction Bipolar Transistor

Poly-silicon Emitter





Poly-silicon Emitter



$$I_{n,E} = \frac{qD_n}{W_B} n_1 \qquad n_1 \equiv \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)$$

$$I_{p,E,poly} = -q\upsilon_s p_2 = -qp_1 \frac{\upsilon_s \times D_p / W_E}{D_p / W_E + \upsilon_s}$$

$$I_{p,E,si} = -q\left(D_p / W_E\right) p_1$$

$$I_{p,E,poly} = -qD_p \frac{p_1 - p_2}{W_E} = -q\upsilon_s p_2$$

$$\frac{I_{p,E,poly}}{I_{p,E,si}} = \frac{\upsilon_s}{D_p / W_E + \upsilon_s}$$

$$\frac{p_2}{p_1} = \frac{D_p / W_E}{D_p / W_E + \upsilon_s}$$

Question: Why does poly only suppress the hole current, not electron current?

Gain in Poly-silicon Transistor

$$I_{p,E,poly} = -qp_1 \frac{\upsilon_s \times D_p / W_E}{D_p / W_E + \upsilon_s} = I_{p,B,poly}$$

$$I_{p,E,si} = -q\left(D_p / W_E\right) p_1$$

$$\frac{I_{p,B,poly}}{I_{p,B,si}} = \frac{\upsilon_s}{D_p / W_E + \upsilon_s} \simeq \frac{I_{B,poly}}{I_{B,si}}$$

$$\beta_{poly} = \frac{I_C}{I_{B,poly}} = \left(\frac{I_C}{I_{B,si}}\right) \times \left[\frac{I_{B,si}}{I_{B,poly}}\right] \approx \left(\frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}\right) \times \left[\frac{D_p / W_E + \upsilon_s}{\upsilon_s}\right]$$

$$\rightarrow \frac{D_n}{W_B}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B} \times \frac{1}{\upsilon_s} \quad (\because \upsilon_s << D_p / W_E)$$

Poly suppresses base current, increases gain …

Outline

1) Problems of classical transistor
2) Poly-Si emitter
3) **Short base transport**
4) High frequency response
5) Conclusions

How to make better Transistor

$$\beta \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,E}^2}{n_{i,B}^2}\frac{N_E}{N_B} \rightarrow \frac{D_n}{W_B}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}\times\frac{1}{\upsilon_s}$$

Polysilicon Emitter

Graded Base transport

Classical Shockley transistor

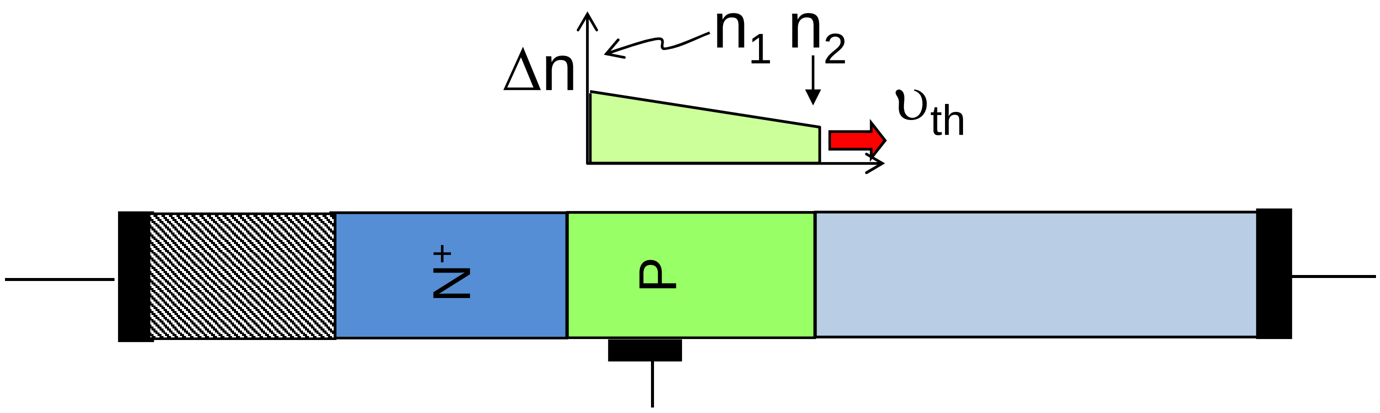
Heterojunction bipolar transistor

Short-base Quasi-ballistic Transistor

$$I_{n,E} = -qD_n \frac{n_1 - n_2}{W_B} = -q\upsilon_{th} n_2$$

$$\frac{n_2}{n_1} = \frac{D_n / W_B}{D_n / W_B + \upsilon_{th}}$$

$$\frac{I_{n,E,ballistic}}{I_{n,E,si}} = \frac{\upsilon_{th}}{D_n / W_B + \upsilon_{th}}$$



Gain in short-base Poly-silicon Transistor

$$\frac{I_{p,B,poly}}{I_{p,B,si}} = \frac{\upsilon_s}{D_p/W_E + \upsilon_s} \simeq \frac{I_{B,poly}}{I_{B,si}} \qquad \frac{I_{n,E,ballistic}}{I_{n,E,si}} = \frac{\upsilon_{th}}{D_n/W_B + \upsilon_{th}}$$

$$\beta_{poly,ballistic} = \frac{I_{C,ballistic}}{I_{B,poly}} = \left[\frac{I_{C,ballistic}}{I_{C,si}}\right] \times \left[\frac{I_{C,si}}{I_{B,si}}\right] \times \left[\frac{I_{B,si}}{I_{B,poly}}\right]$$

$$\approx \left[\frac{\upsilon_{th}}{D_n/W_B + \upsilon_{th}}\right] \times \left[\frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}\right] \times \left[\frac{D_p/W_E + \upsilon_s}{\upsilon_s}\right]$$

$$\rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{\upsilon_s}$$

Quasi-Ballistic transport in very short base limits the gain …

Outline

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Topic Map

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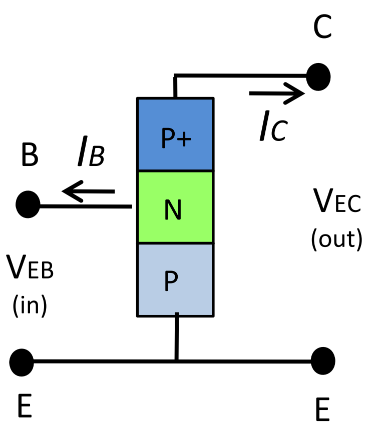
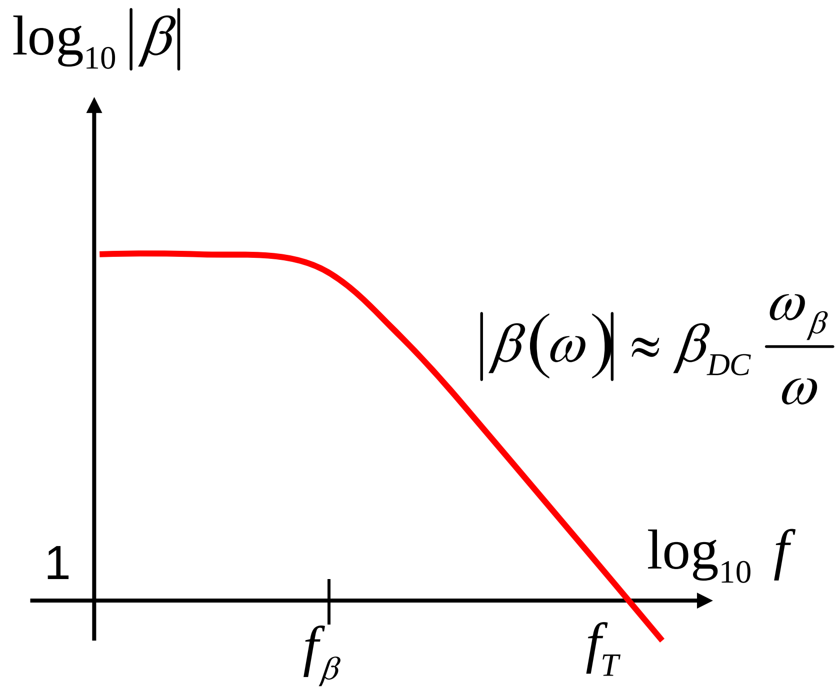
Diode					
Schottky					
BJT/HBT			◆		
MOS					

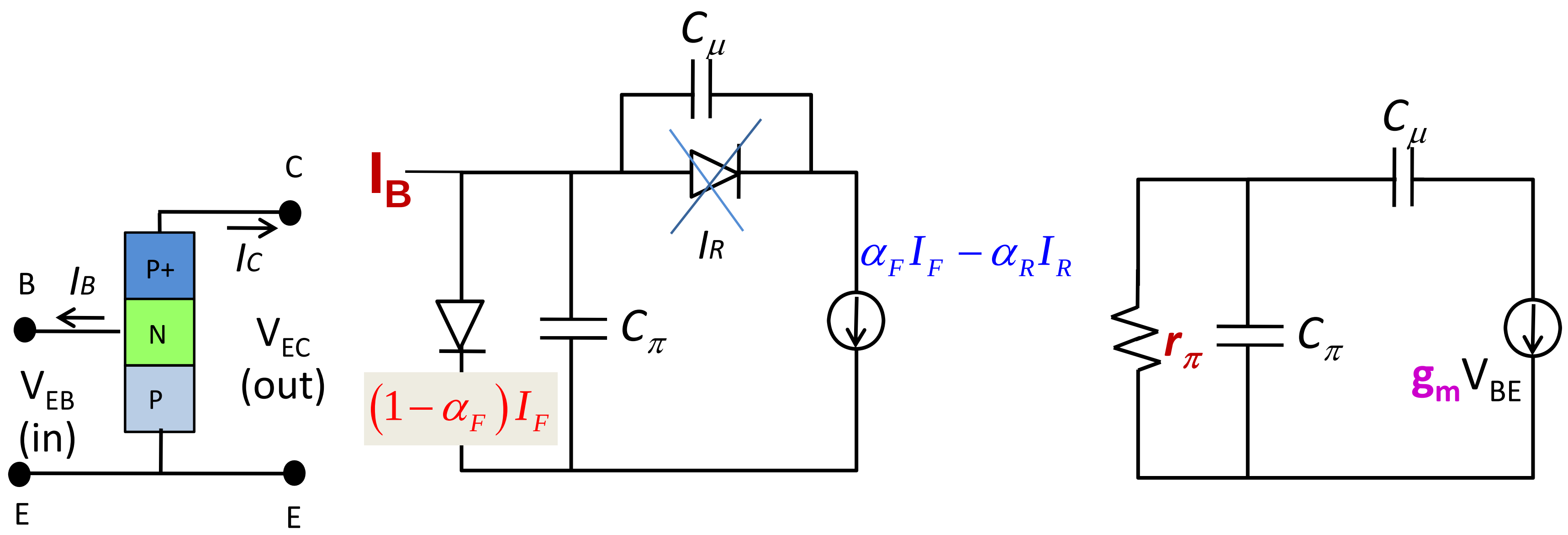
Small Signal Response





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

Small Signal Response (Common Emitter)



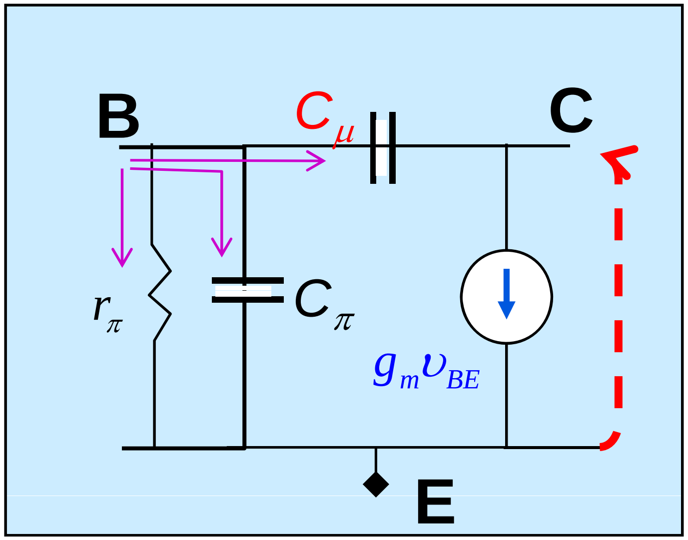
$$\frac{1}{r_\pi} = \frac{dI_B}{dV_{BE}} = \frac{d\left[(1-\alpha_F)I_F\right]}{dV_{BE}} = \frac{qI_B}{k_B T} = \frac{1}{\beta_{DC}}\frac{qI_C}{k_B T}$$

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

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

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

Short Circuit Current Gain



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

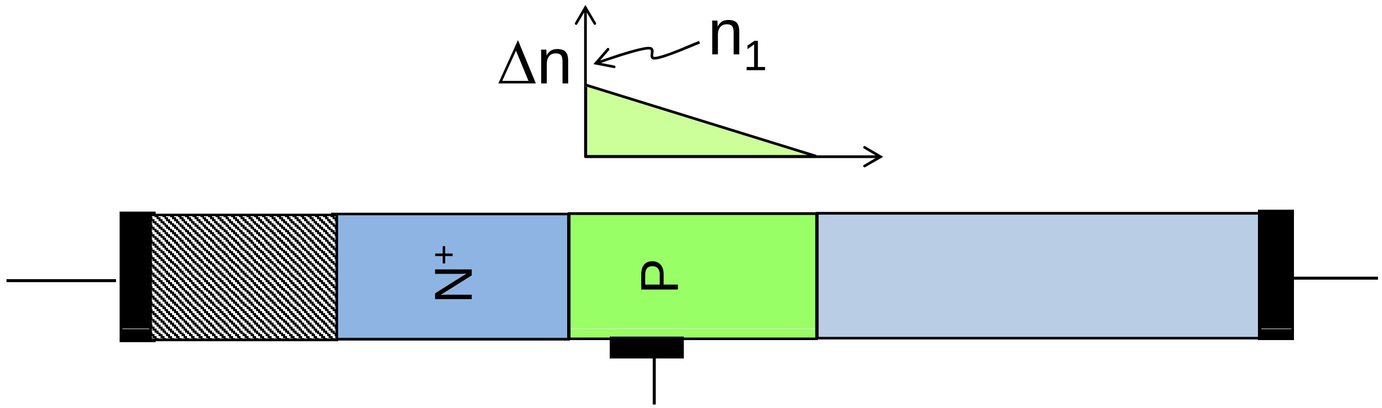
$$\beta(f_T) \equiv 1 = \left| \frac{g_m - j\omega_T C_\mu}{\left(\frac{1}{r_\pi} + j\omega_T C_\pi\right) + j\omega C_\mu} \right| \approx \left| \frac{g_m}{j\omega_T \left(C_\pi + C_\mu\right)} \right|$$

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

$$\frac{k_B T}{q I_C} C_{d,BC} = \frac{C_{d,BC}}{dI_C / dV_{BE}} = \frac{dQ_B}{dI_C}$$

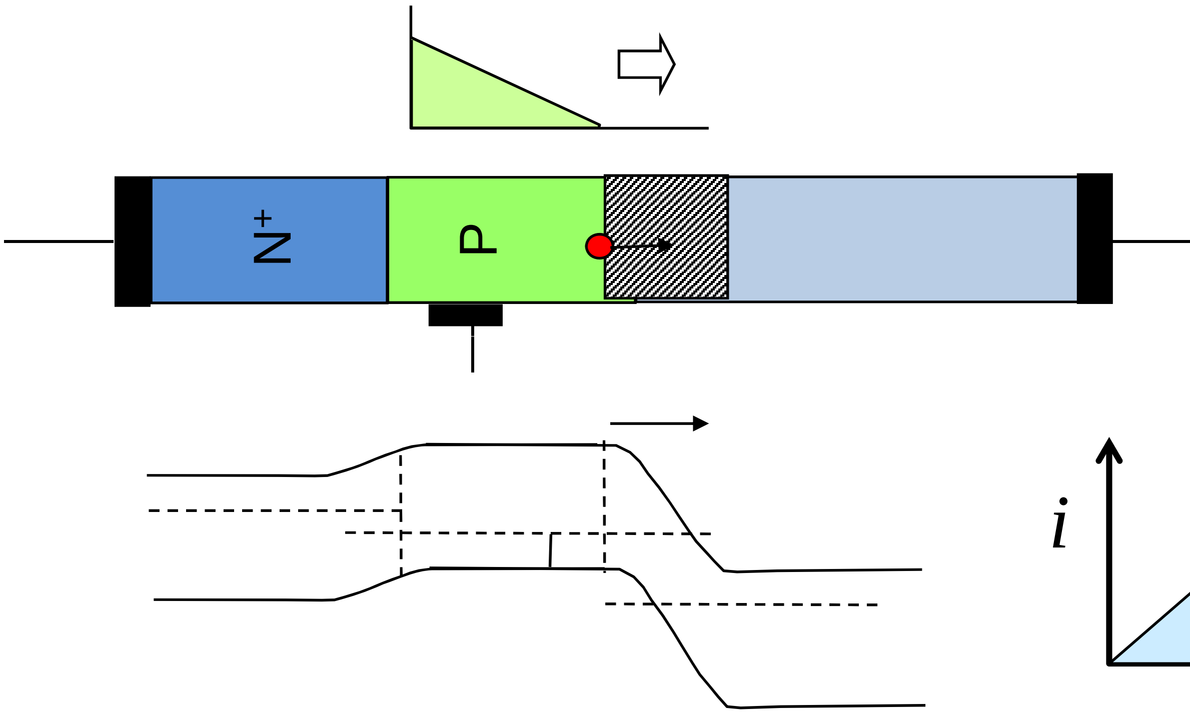
Base Transit Time

Ref. Charge control model

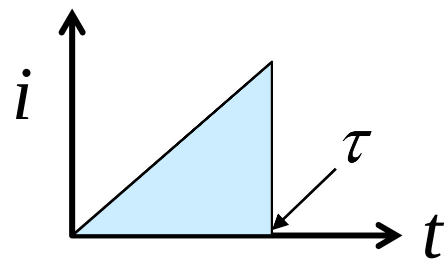


$$\frac{dQ_B}{dI_C} = \frac{Q_B}{I_C} = \frac{q\frac{1}{2}n_1 W_B}{q\frac{n_1}{W_B}} = \frac{W_B^2}{2D_n}$$

Collector Transit Time



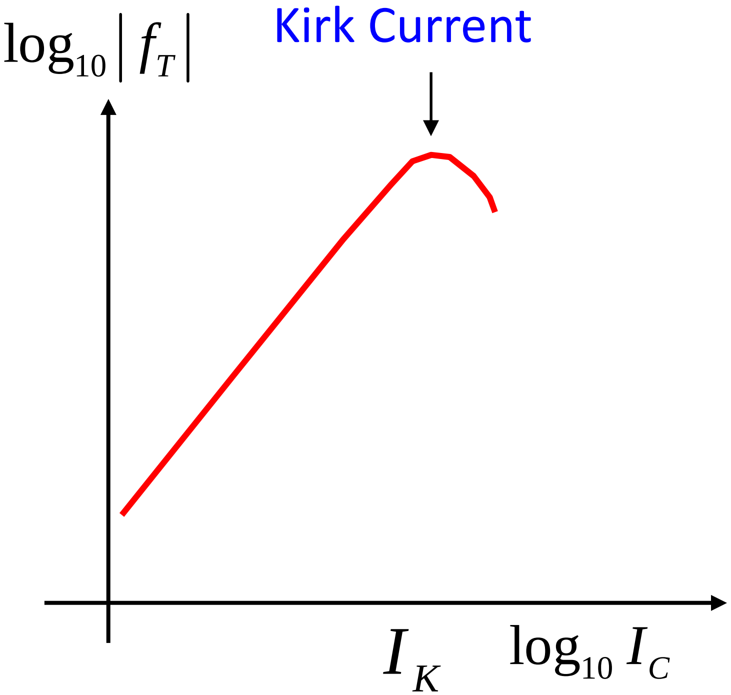
$$\tau = \frac{W_{BC}}{\upsilon_{sat}}?$$



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

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

Putting the Terms Together



Collector transit time (slide 19)

Base transit time (slide 18)

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

Junction charging time (slide 17)

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

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})

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

Summary

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

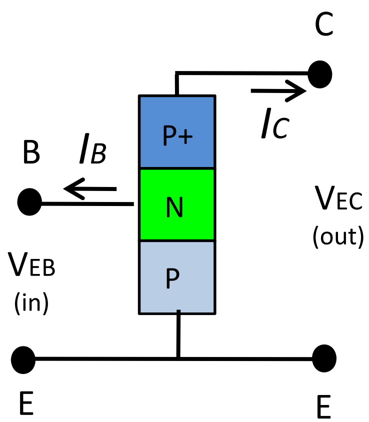
The small signal analysis illustrates the importance of reduced junction capacitance, resistances, and transit times.

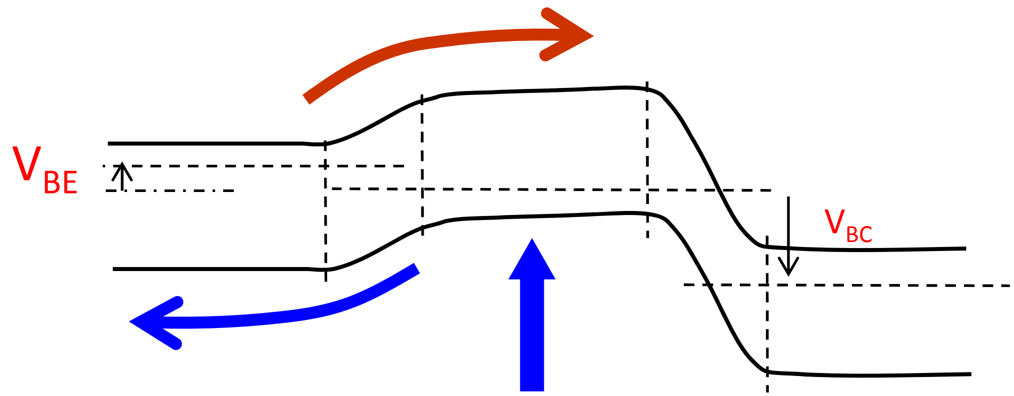
Classical **homojunctions** BJTs can only go so far, further improvement is possible with **heterojunction** bipolar transistors.

Aside:

On Base-Collector Breakdown Voltages

Essence of Current Gain





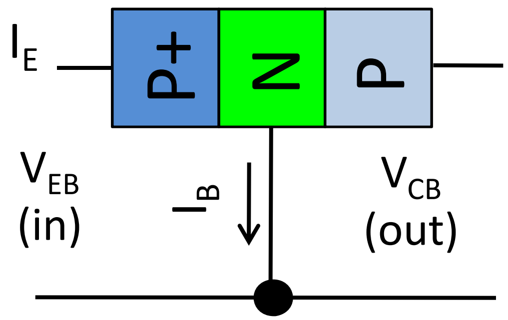
Input → I_B; Response ← $e^{qV_{BE}\beta}$; Response → Input

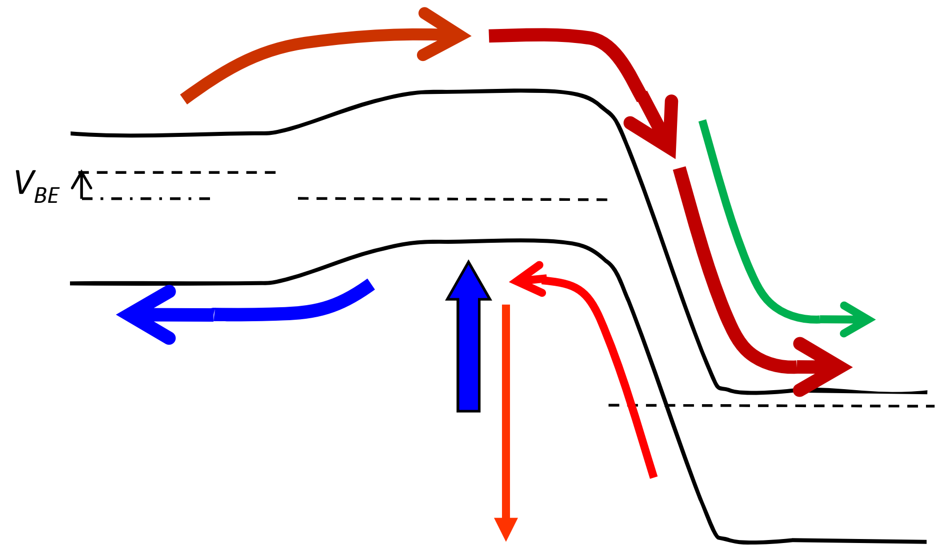
$$I_B \approx \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV_{BE}\beta}-1\right)$$

Input → $e^{qV_{BE}\beta}$; I_E → Response

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

Collector Breakdown (Common Base, Fixed I_E)

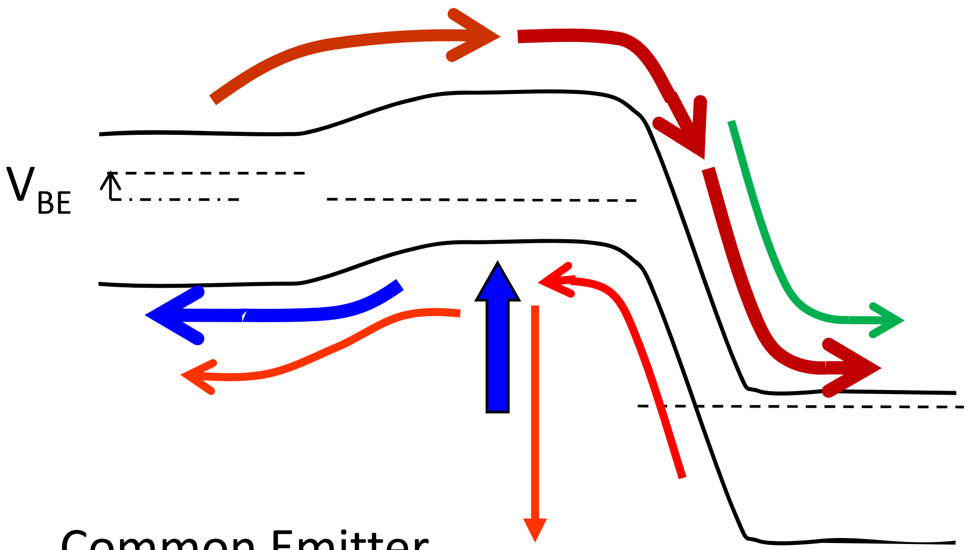




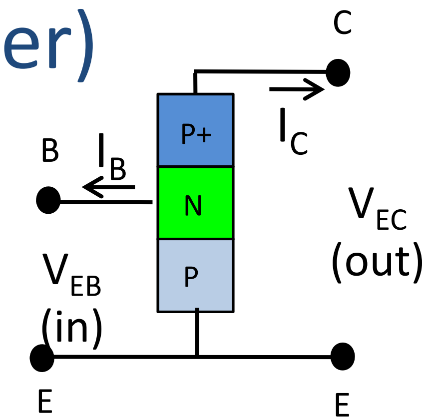
Common Base

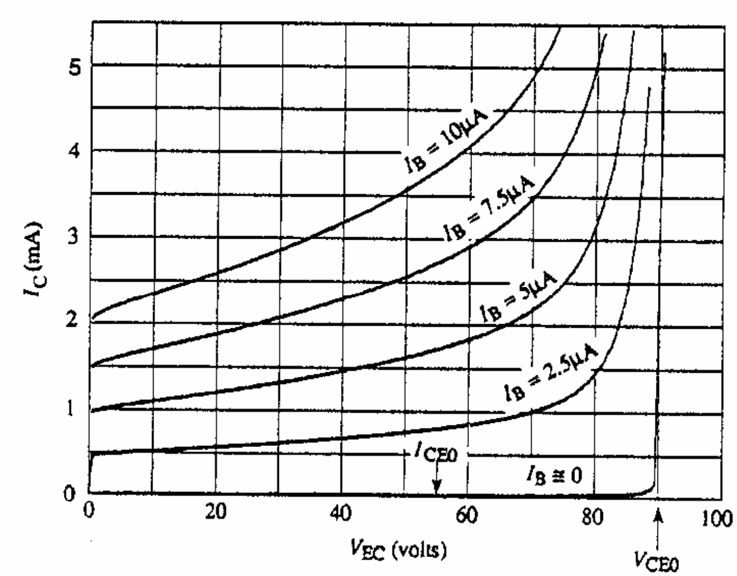
(I_E fixed, I_B variable)

Collector Breakdown (Common Emitter)



Common Emitter
(I_E variable, I_B fixed)





Common emitter breakdown voltage is smaller than common base breakdown voltage.