Essentials of MOSFETs

Unit 5: Additional Topics

Lecture 5.5: Heterostructure Bipolar Transistors (HBTs)

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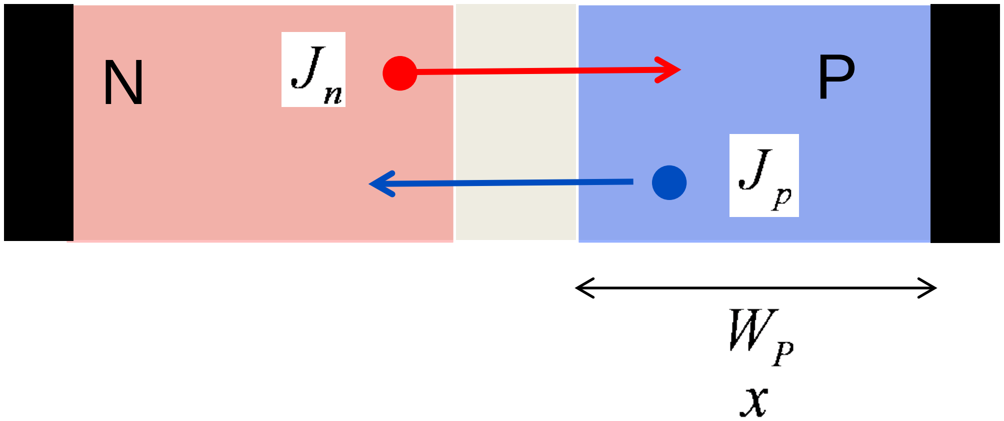
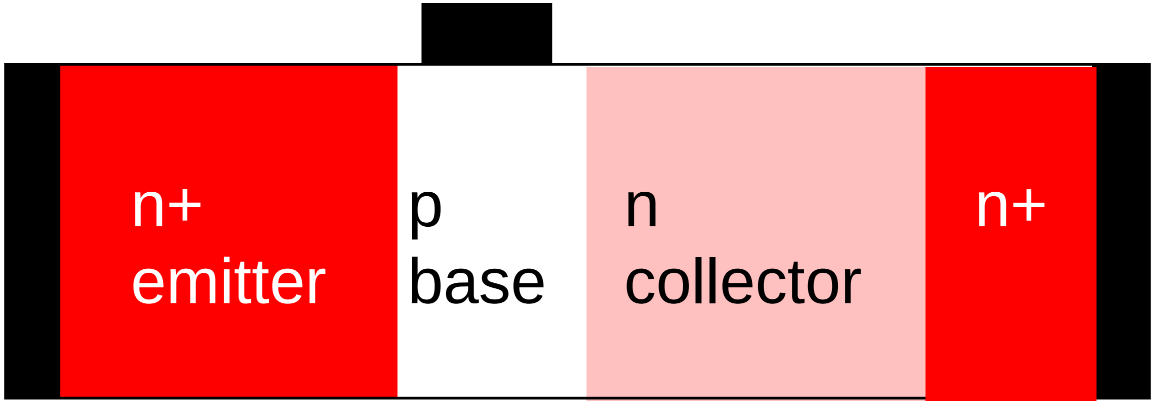
Currents in a PN junction

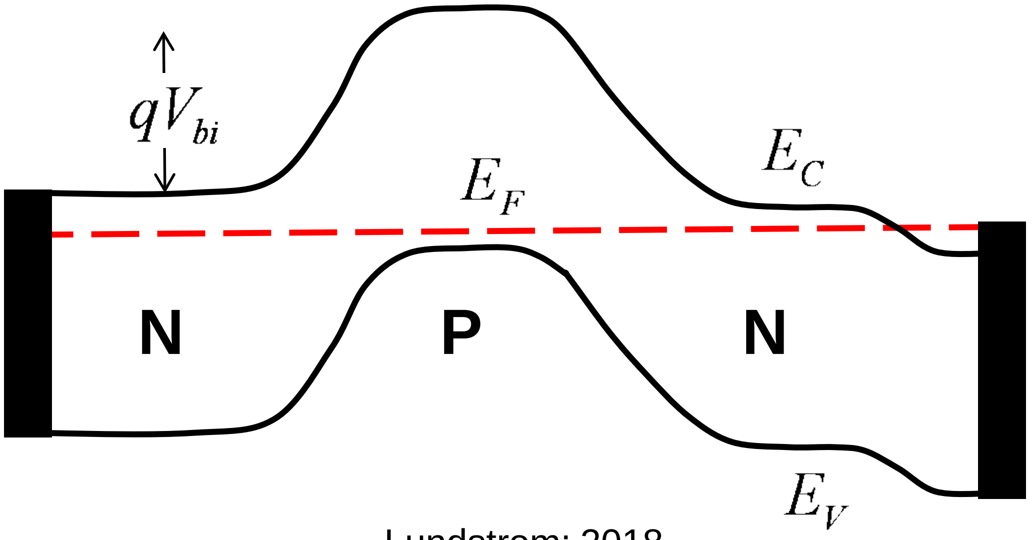


$$J_n = q\frac{D_n}{W_P}\frac{n_{iP}^2}{N_A}\left(e^{qV_A/k_BT} - 1\right)$$

$$J_p = q\frac{D_p}{W_N}\frac{n_{iN}^2}{N_D}\left(e^{qV_A/k_BT} - 1\right)$$

Equilibrium E-band diagram: bipolar transistor





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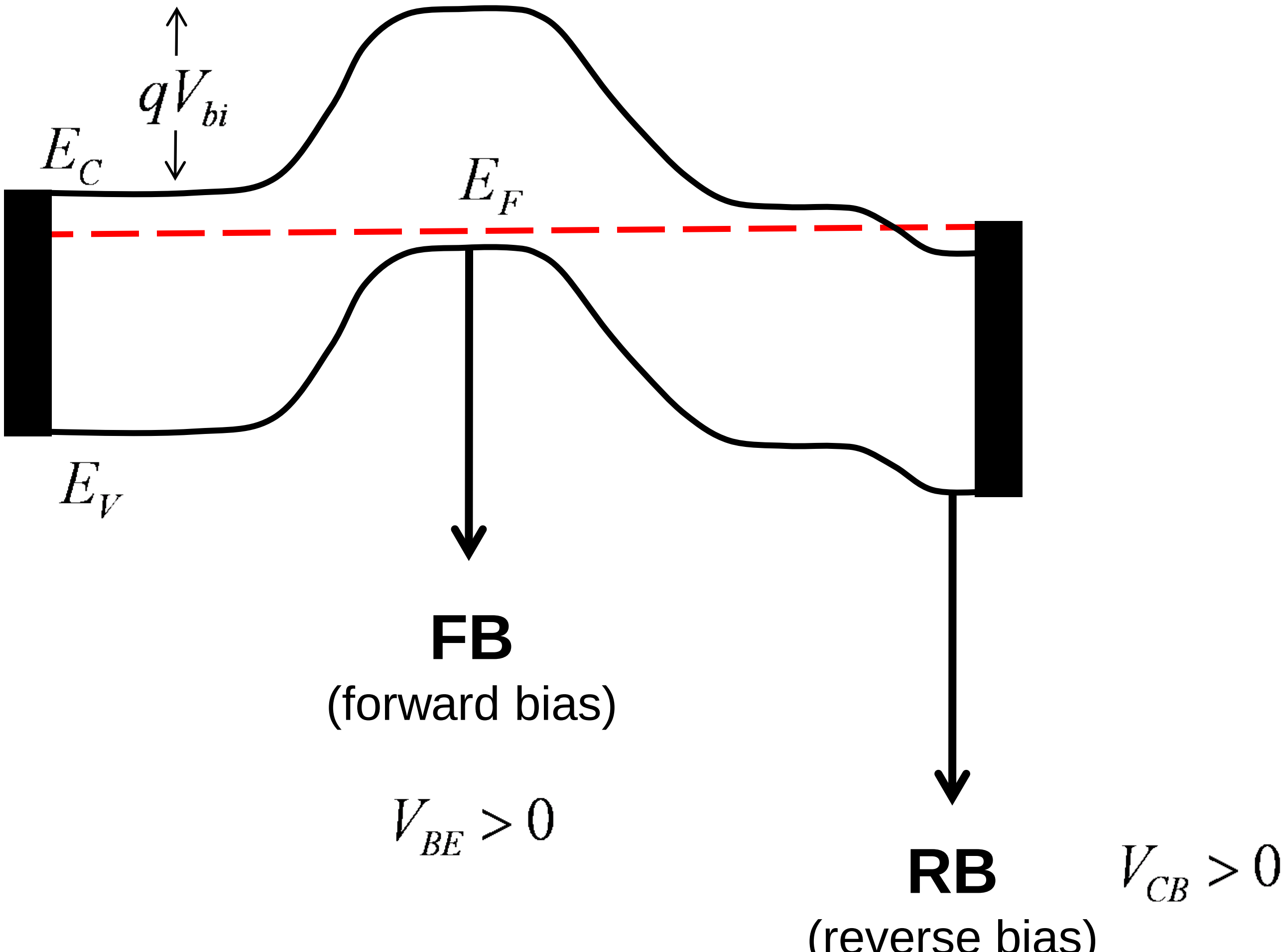
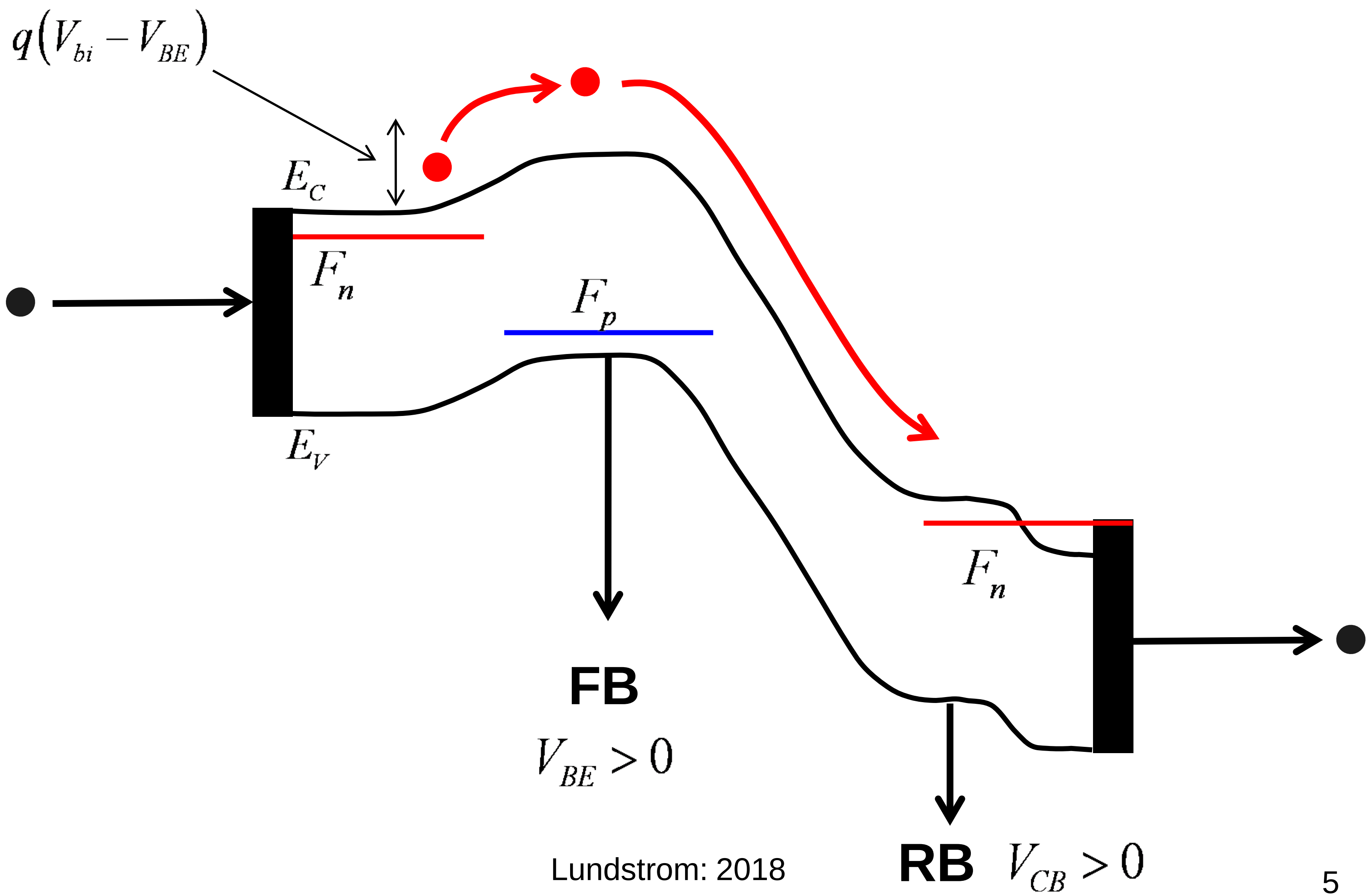
The BJT: a barrier controlled device



The BJT: a barrier controlled device

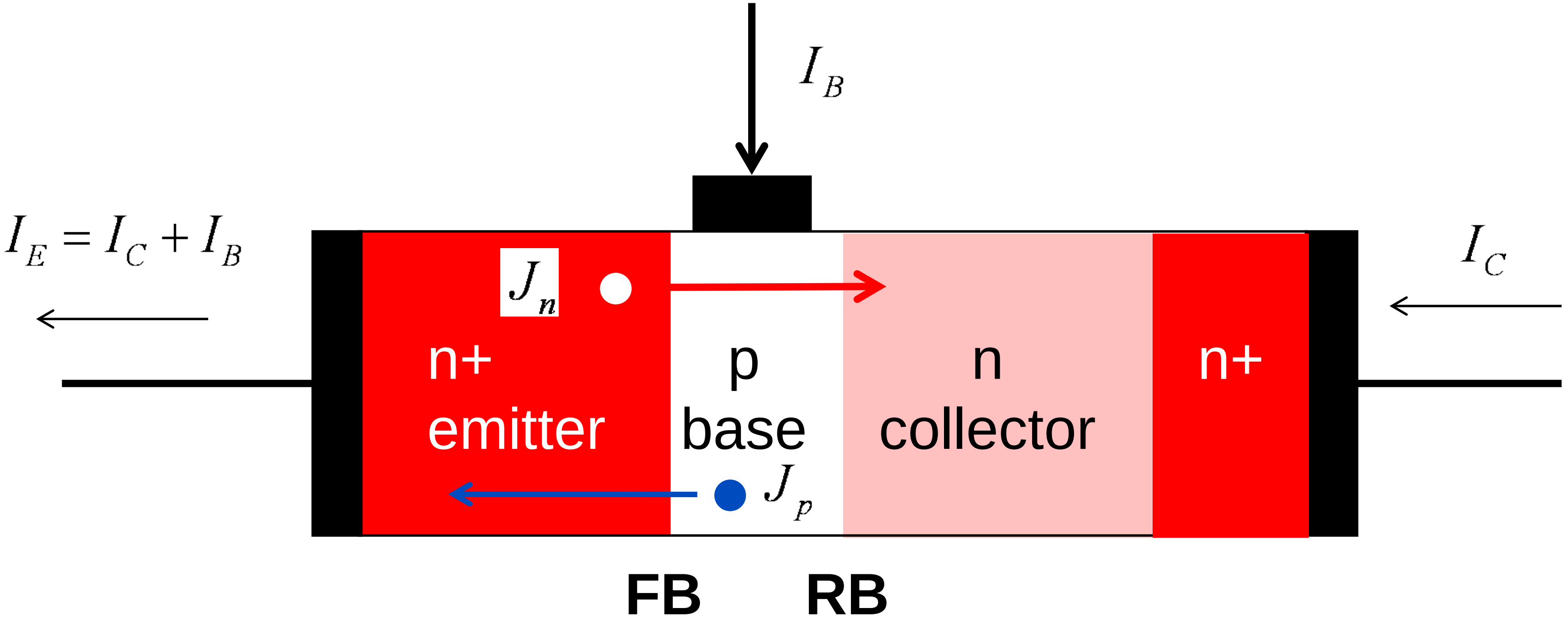


MOSFETs and BJTs

"The Insulated Gate Field Effect Transistor – A Bipolar Transistor in Disguise," *RCA Review*, vol. 34, pp. 80-94, 1973.

"Although both the Insulated Gate Field-Effect transistor (IGFET) and the bipolar transistor both operate on charge control principles, these device are widely believed to be intrinsically different in the details of their operation."

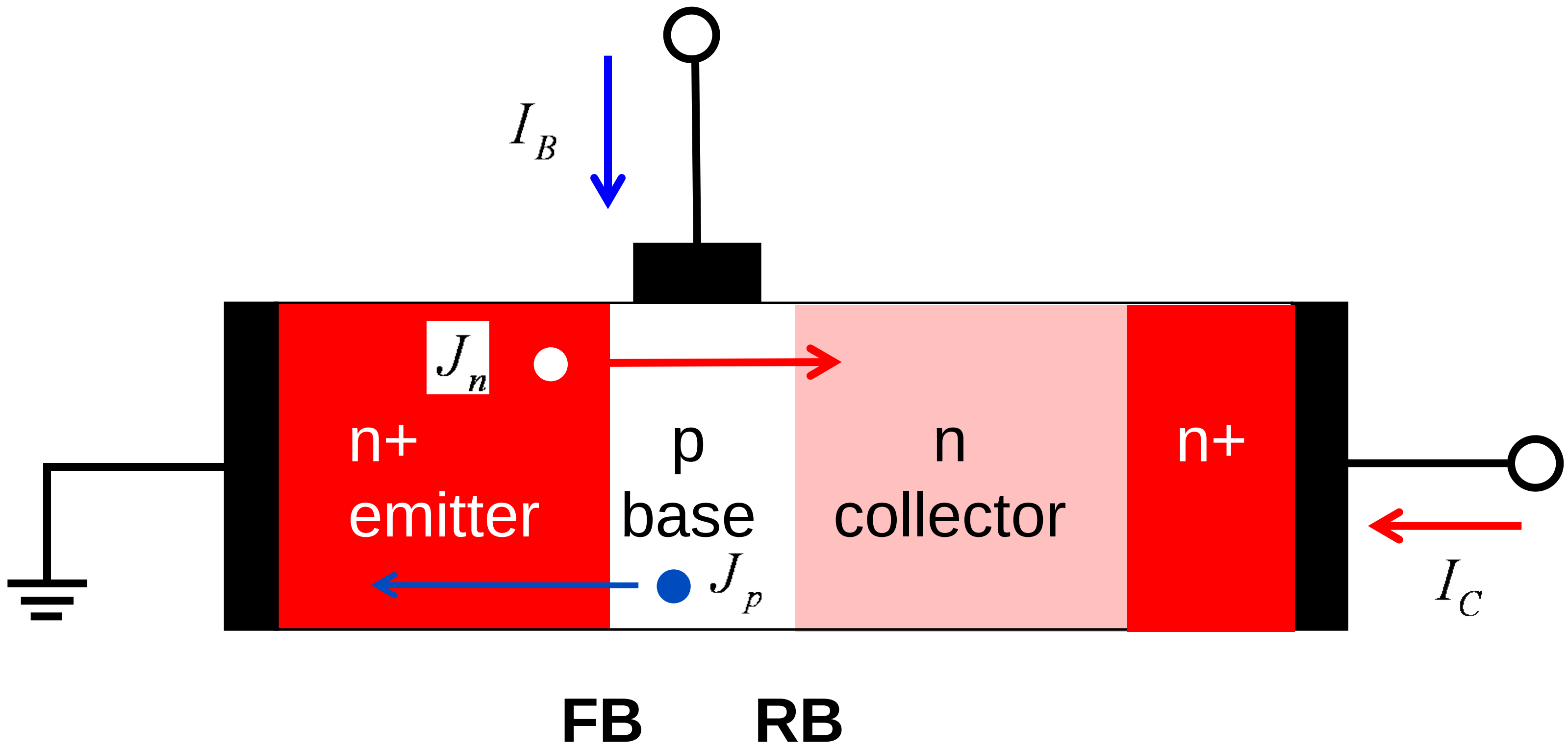
Forward active region of operation



$$I_C = A_E J_n = qA_E \frac{D_n}{W_B}\frac{n_{iB}^2}{N_{AB}}\left(e^{qV_{BE}/k_BT} - 1\right) \qquad I_B = A_E J_p = qA_E \frac{D_p}{W_E}\frac{n_{iE}^2}{N_{DE}}\left(e^{qV_{BE}/k_BT} - 1\right)$$

Lundstrom: 2018

A current controlled device?



$$I_B = qA_E \frac{D_p}{W_E} \frac{n_{iE}^2}{N_{DE}} \left(e^{qV_{BE}/k_B T} - 1 \right) \qquad V_{BE} \propto \ln\left(I_B\right)$$

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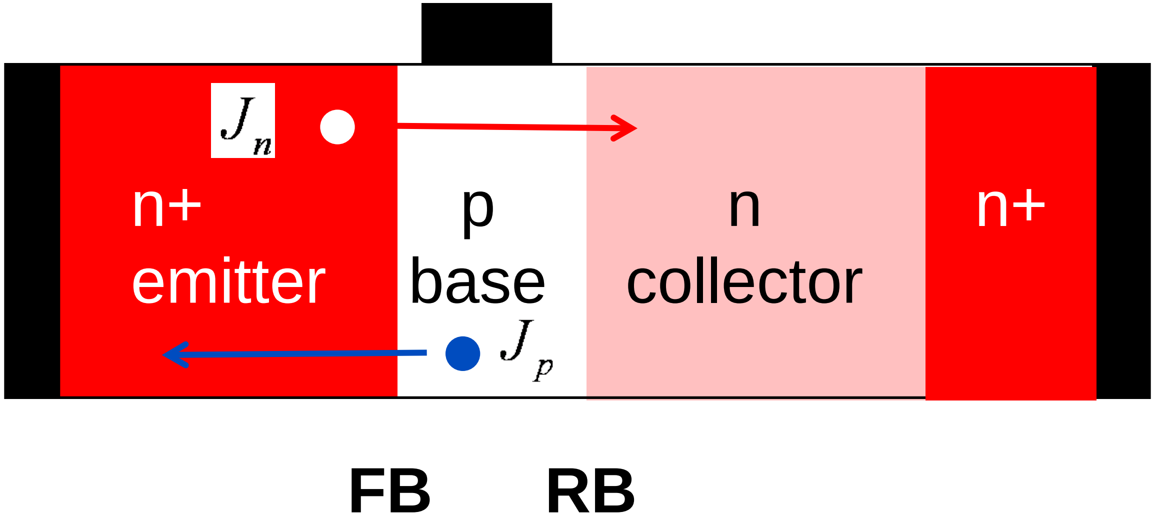
Current gain



$$I_C = qA_E \frac{D_n}{W_B} \frac{n_{iB}^2}{N_{AB}} \left(e^{qV_{BE}/k_BT} - 1 \right)$$

$$I_B = qA_E \frac{D_p}{W_E} \frac{n_{iE}^2}{N_{DE}} \left(e^{qV_{BE}/k_BT} - 1 \right)$$

$$\frac{I_C}{I_B} = \left[\frac{D_n}{D_P} \frac{W_E}{W_B} \frac{N_{DE}}{N_{AB}} \frac{n_{iB}^2}{n_{iE}^2} \right] = \beta$$

$$I_C = \beta I_B$$

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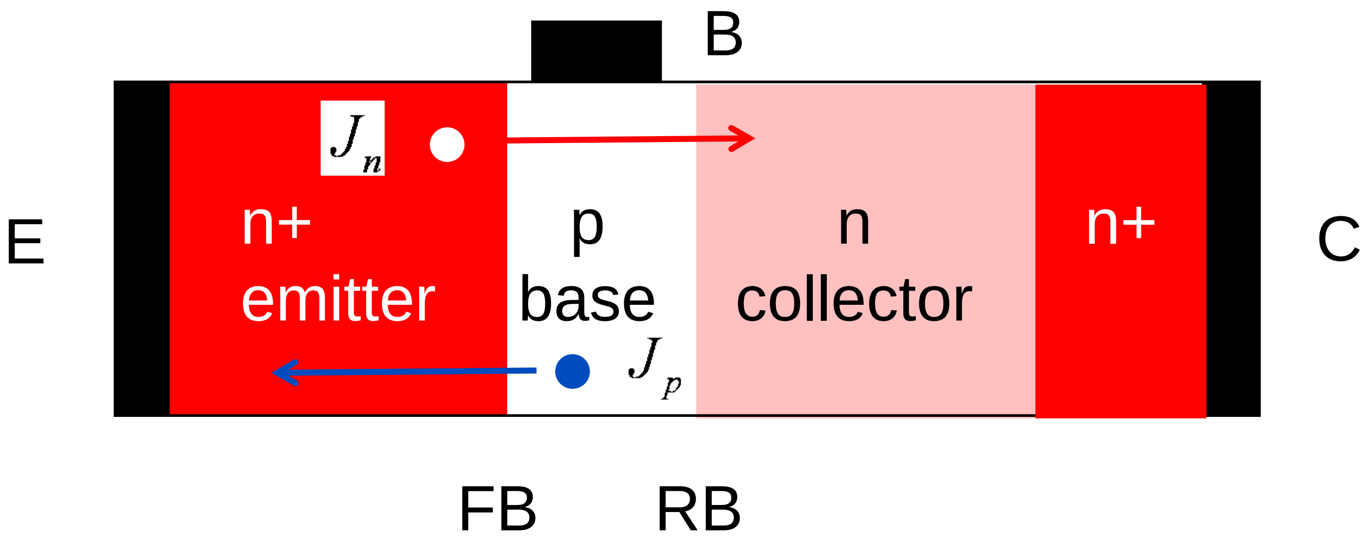
Forward active region



$$\beta = \frac{I_C}{I_B} = \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} \frac{n_{iB}^2}{n_{iE}^2}$$

(In the forward active region of operation)

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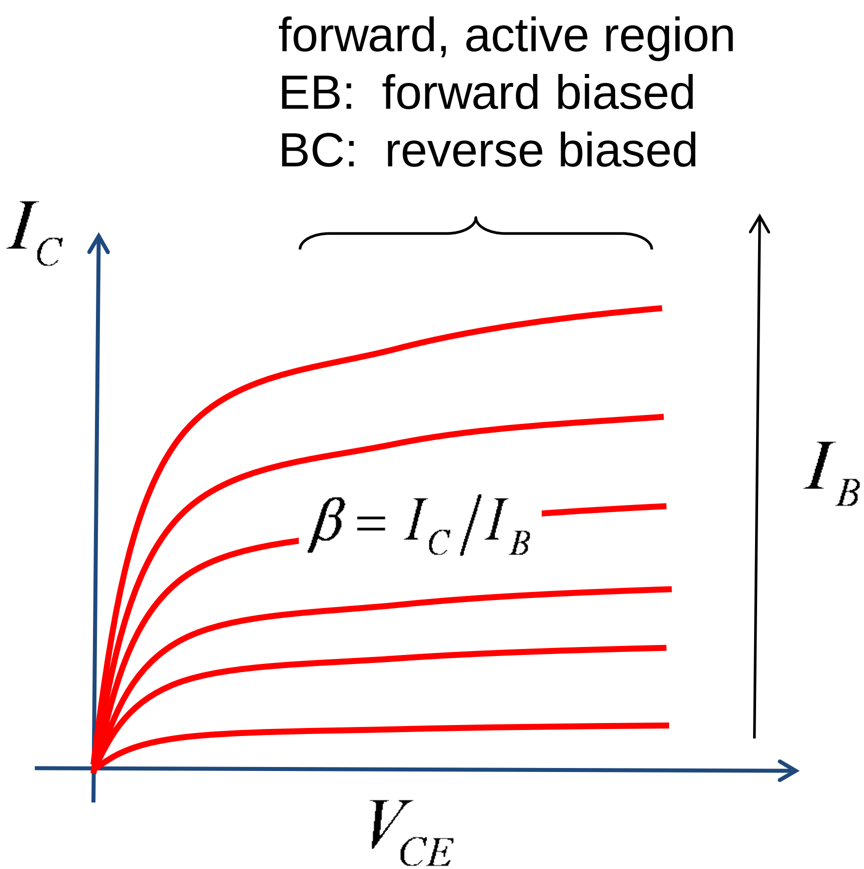
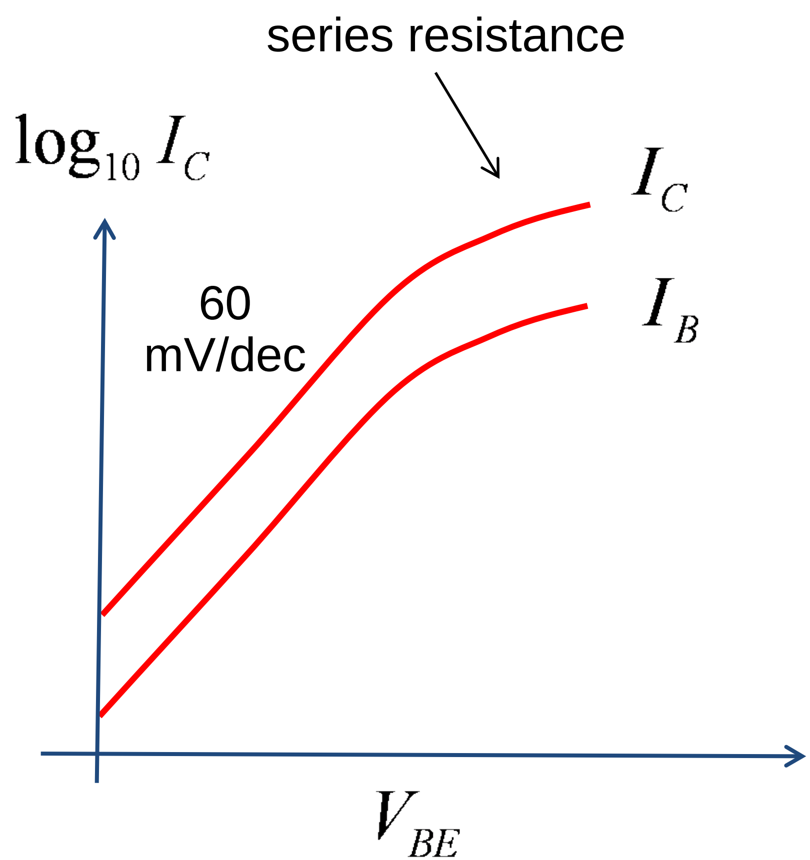
IV characteristics



output characteristic



transfer characteristic

MOSFETs vs. BJTs

For analog / RF applications, two important figures of merit are:

Transconductance

$$g_m = \left.\frac{\partial I_C}{V_{BE}}\right|_{V_{CE}}$$

$$g_m = \left.\frac{\partial I_D}{V_{GS}}\right|_{V_{DS}}$$

Gain-bandwidth product

$$f_T = \frac{g_m}{2\pi C_{tot}}$$

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Transconductance

MOSFET

Saturation region:

$$I_D = k_n \left(V_{GS} - V_T \right)$$

$$g_m = \partial I_D / \partial V_{GS} \big|_{V_{DS}}$$

$$g_m = k_n$$

$$\boxed{g_m = \frac{I_D}{\left(V_{GS} - V_T \right)}}$$

BJT

Forward active region:

$$I_C = I_{C0} e^{qV_{BE}/k_B T}$$

$$g_m = \partial I_C / \partial V_{BE} \big|_{V_{CE}}$$

$$g_m = \frac{I_{C0}}{\left(k_B T / q \right)} e^{qV_{BE}/k_B T}$$

$$\boxed{g_m = \frac{I_C}{k_B T / q}}$$

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MOSFET vs. BJT transconductance

MOSFET

$$g_m = \frac{I_D}{\left(V_{GS} - V_T\right)}$$

$$I_D = 1\ \text{mA}$$

$$V_{GS} = 1.0\ \text{V} \qquad V_T = 0.2\ \text{V}$$

$$g_m = 2.5\ \text{mS}$$

BJT

$$g_m = \frac{I_C}{k_B T / q}$$

$$I_C = 1\ \text{mA}$$

$$k_B T / q = 0.026\ \text{V}$$

$$g_m = 40\ \frac{\text{mA}}{\text{V}} = 40\ \text{mS}$$

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Importance of series resistance

$$f_T = \frac{g_m}{2\pi C_{tot}}$$

$$2\pi f_T = \frac{g_m}{C_{tot}} = \frac{1}{\tau}$$

$$\tau = t_t + \frac{C_{par}}{g_m}$$

$$\tau = \frac{C_{tot}}{g_m} = \frac{C_{eb}}{g_m} + \frac{C_{par}}{g_m}$$

$$\boxed{\tau = t_t + \frac{C_{par} k_B T / q}{I_C}}$$

$$\frac{C_{eb}}{g_m} = \frac{\partial Q_n / \partial V_{BE}}{\partial I_C / \partial V_{BE}} = t_t$$

(Need high drive currents and low parasitic resistance.)

Lundstrom: 2018

MOSFETs vs. BJTs

BJTs are superior RF/analog devices. A typical BJT has more than 10X the transconductance of a typical MOSFET.

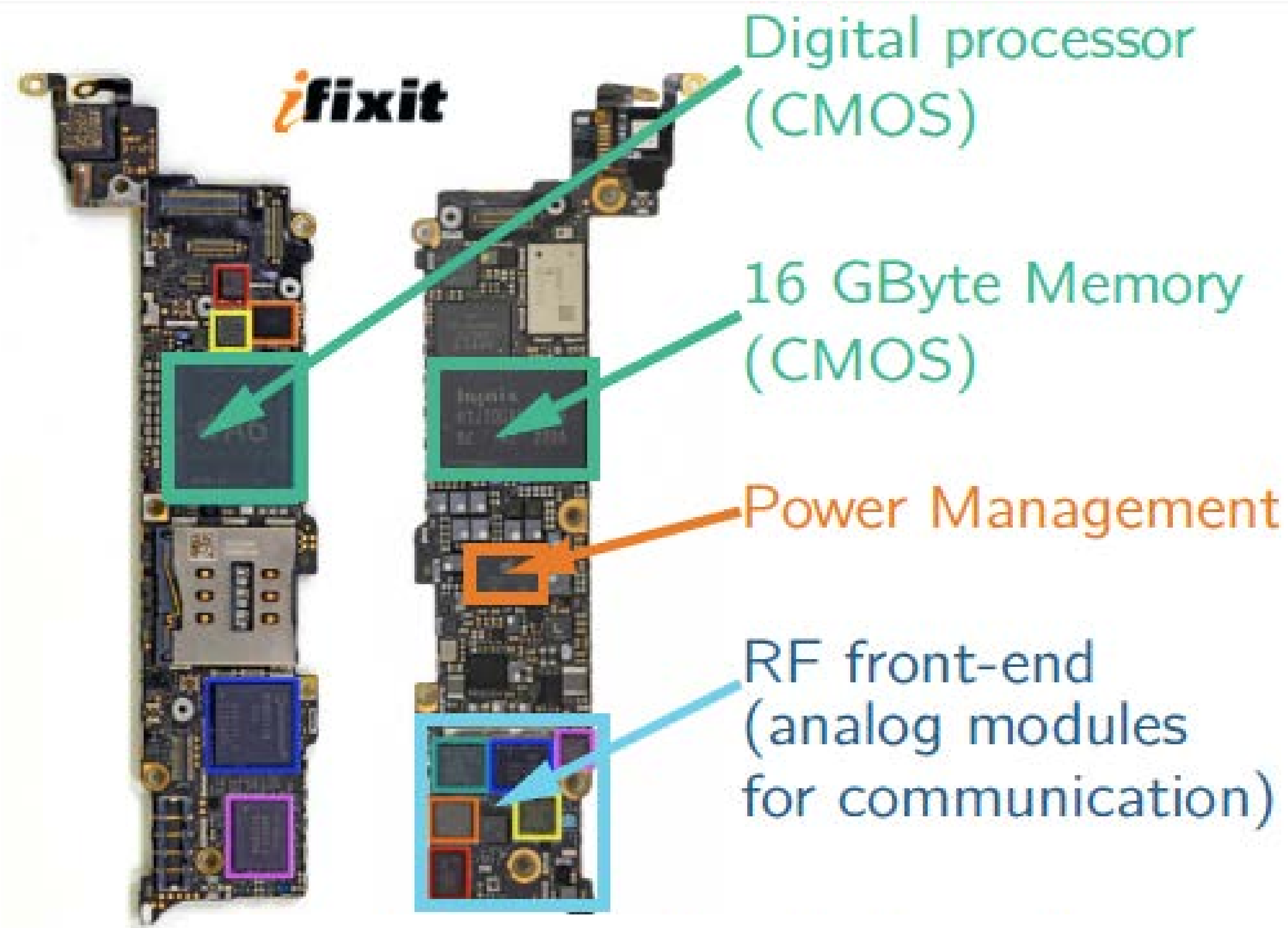
Both devices can achieve high f_T.

$$f_T = \frac{g_m}{2\pi C_{tot}}$$

BJTs offer higher drive currents (higher g_m)

→ Well-suited for RF power amplifiers

SiGe HBTs



Circuit board of an iPhone 5

Martin Claus
TU-Dresden

Heterojunction bipolar transistors

Modern bipolar transistors are Heterojunction Bipolar Transistors (HBTs).

1) What is an HBT?

2) Why are they useful?

Design trade-offs for homojunction BJTs

$$\boxed{\beta = \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} \frac{n_{iB}^2}{n_{iE}^2}}$$

For homojunction BJT's: $n_{iE} = n_{iB}$

For high current gain: $N_{DE} >> N_{AB}$

Would prefer a thin, heavily doped base.

-thin for speed

-heavily doped for base resistance

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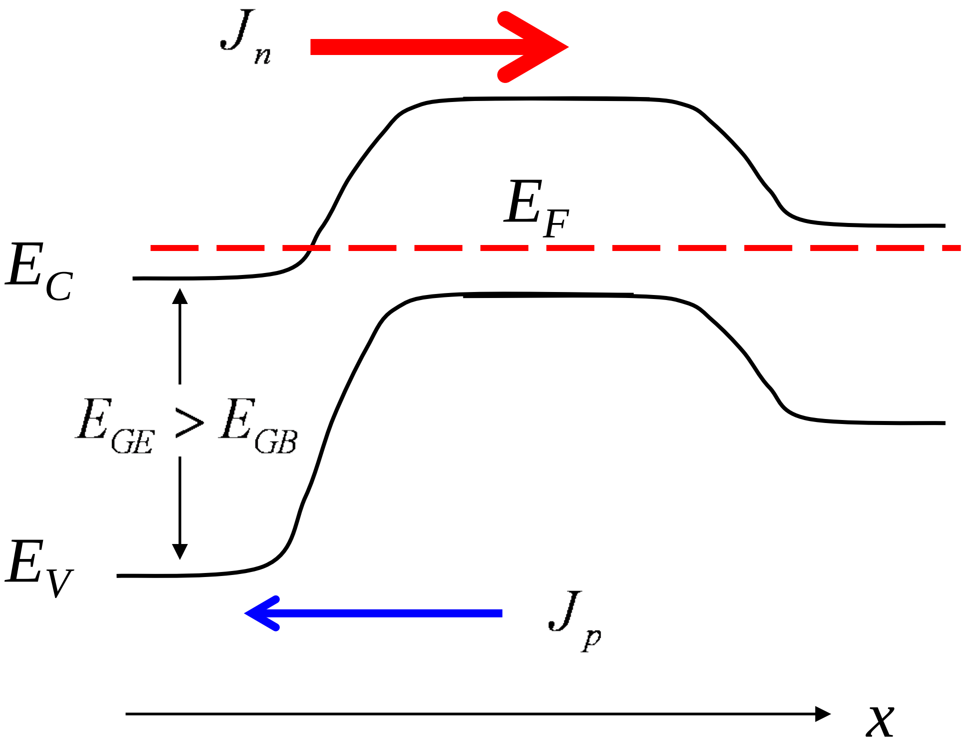
Heterojunction bipolar transistors (HBTs)



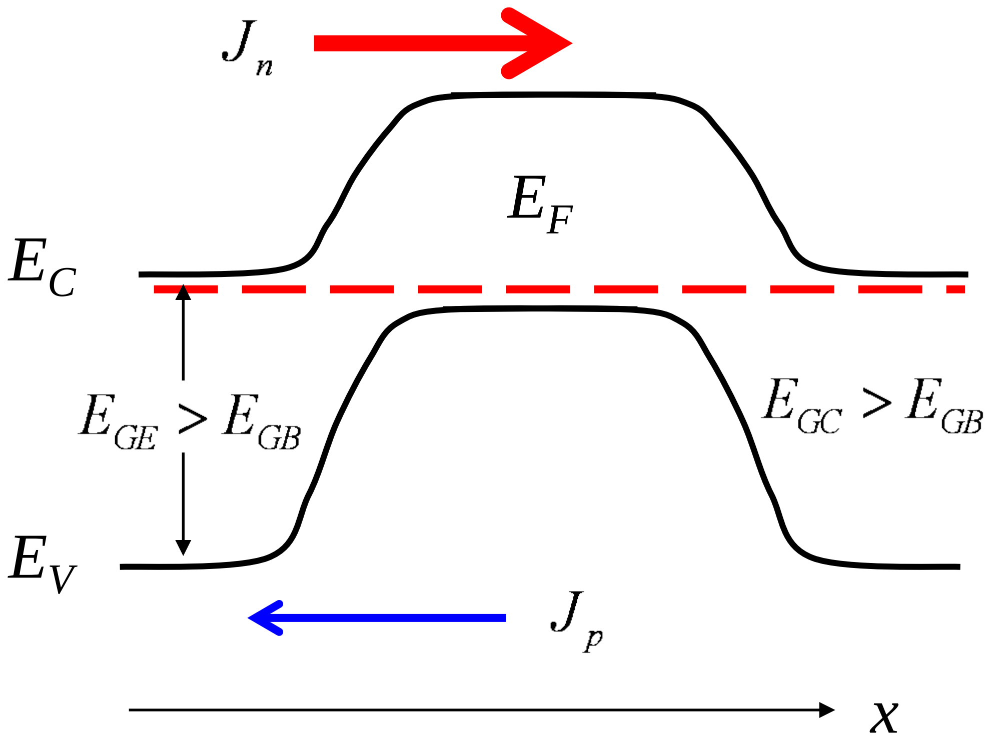
wide bandgap emitter

$$\beta = \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} \frac{n_{iB}^2}{n_{iE}^2}$$

$$n_i^2 = N_C N_V e^{-E_G/k_B T}$$

$$\beta \approx \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} e^{\Delta E_G/k_B T}$$

Double HBT (DHBT)



- symmetrical operation
- reduced collector offset voltage
- higher collector breakdown voltage

Modern III-V HBTs

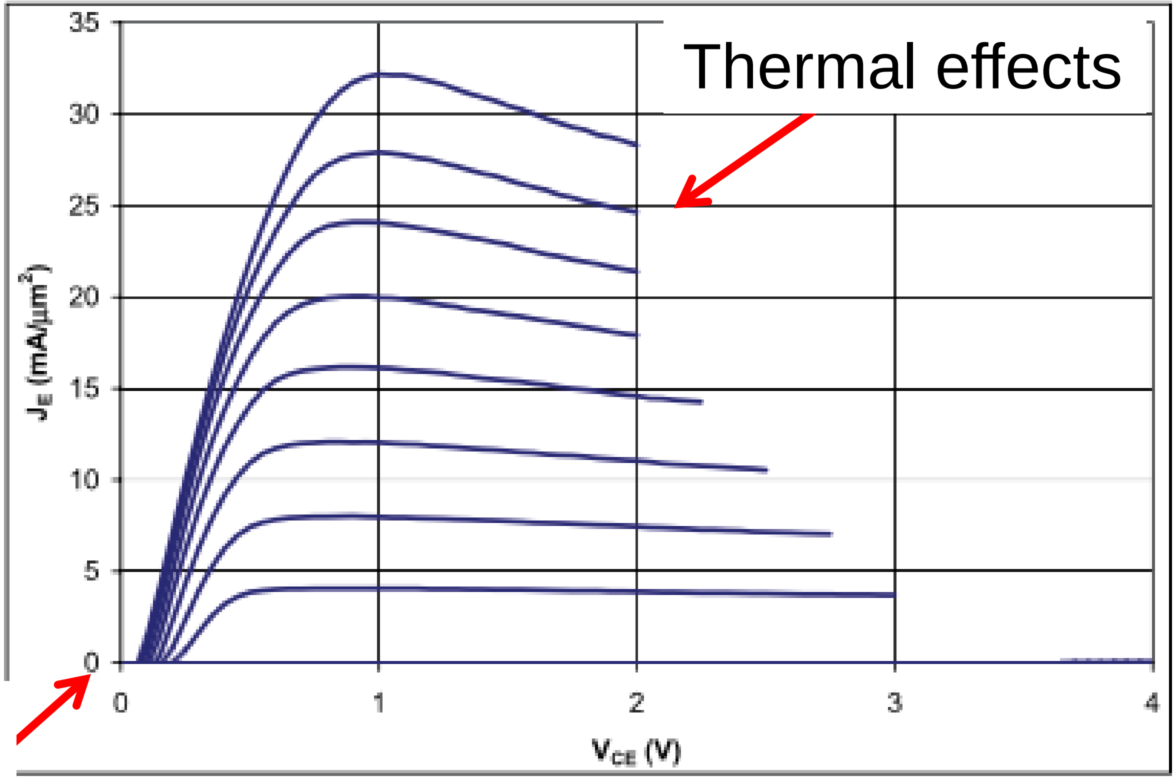
For a good review of the current state-of-the-art, see:

M. Urteaga, Z. Griffith, M. Seo, J. Hacker, and M. Rodwell, “InP HBT Technologies for THz Integrated Circuits,” *Proc. IEEE*, Vol. 105, pp.1051-1067, 2017.

For a discussion about the critical role of parasitics, see:

J. C. Rode, H.-W. Chiang, P. Choudhary, V.Jain, B. J. Thibeault, W. J. Mitchell, M. J. W. Rodwell, M. Urteaga, D. Loubychev, A. Snyder, Y. Wu, J. M. Fastenau, and A. W. K. Liu, “Indium Phosphide Heterobipolar Transistor Technology Beyond 1-THz Bandwidth,” *IEEE Trans. Electron Dev*., Vol. 62, pp. 2779-2785, 2015.

Output characteristics

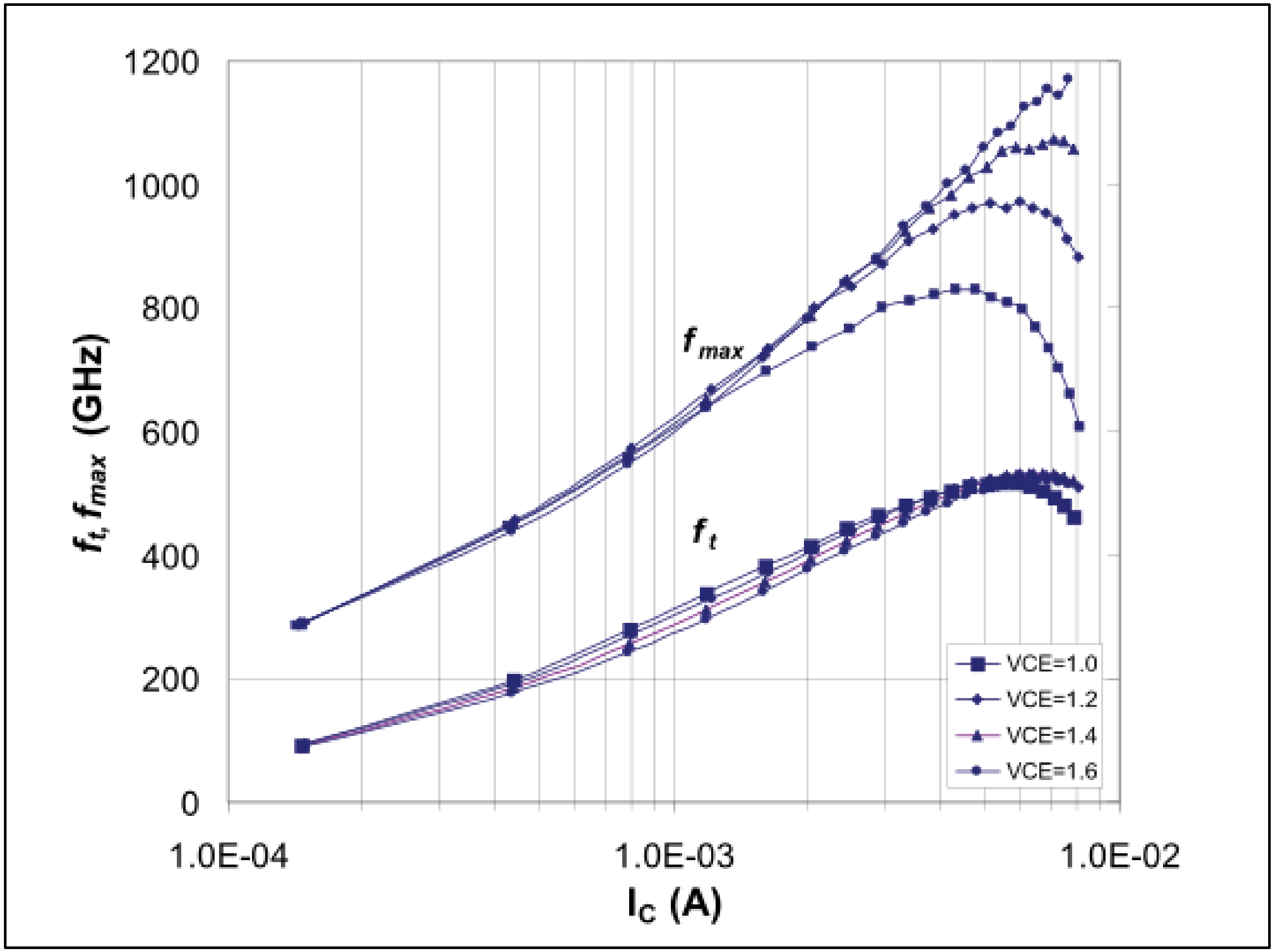


Collector-emitter offset voltage

130 nm technology

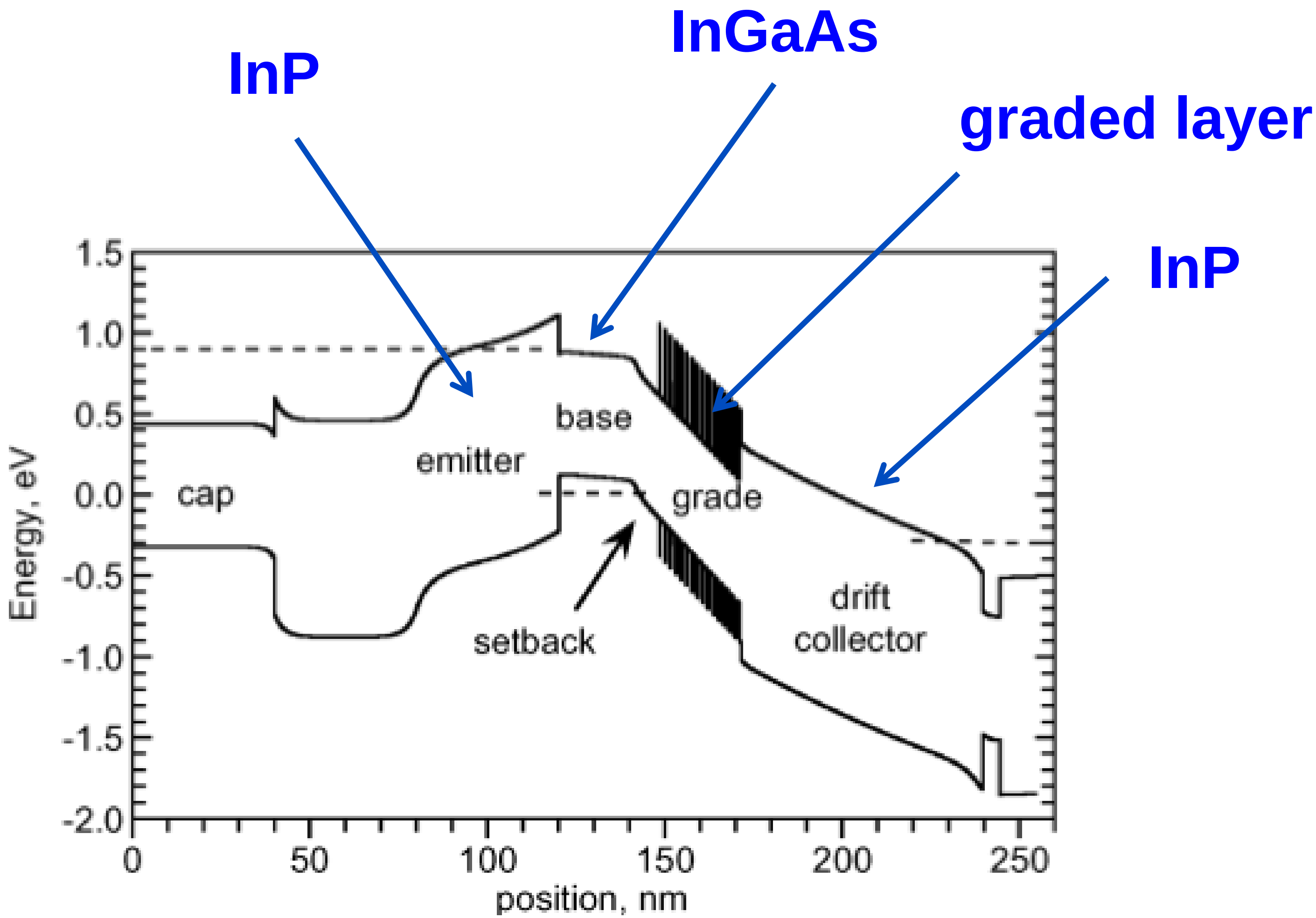
From M. Urteaga, et al., *Proc. IEEE*, **105**, 1051, 2017.

f_T and f_{max} vs. I_C



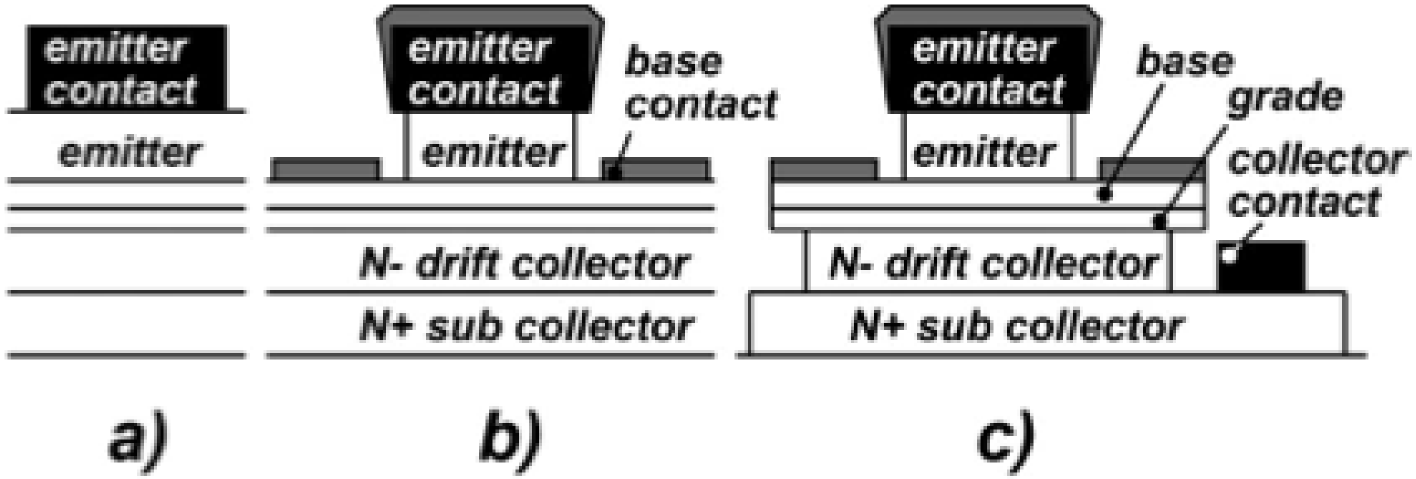
From M. Urteaga, et al., *Proc. IEEE*, **105**, 1051, 2017.

DHBT: InP: InGaAs: InP



From M. Rodwell, et al., *Proc. IEEE*, **96**, 271, 2008.

Mesa fabrication process



a) Emitter metal deposition
b) Emitter etch and self-aligned base contact metal deposition
c) Base mesa etch, collector mesa etch, collector contact deposition

From M. Rodwell, et al., *Proc. IEEE*, **96**, 271, 2008.

InP HBTs

Key scaling challenges:

- emitter & base contact resistivity
- current density→ device heating
- parasitic capacitances
- current gain (surface recombination)

Summary

1) III-V HBTs are an important technology for high-frequency RF power applications.

2) SiGe HBTs are a critical technology for wireless electronics

3) HBTs offer speeds close to that of HEMTs (f_T = 600 GHz, f_{max} = 1200 GHz).

4) Compared to HEMTs, HBTs deliver higher power and integration density.

5) HBTs operate in the same "barrier controlled mode" as Si MOSFETs.

Thanks to Mark Rodwell (UCSB), for his help in putting together this lecture.

Next topic

Whatever the type of transistor, a good compact circuit model is needed to design circuits.

We briefly discussed compact circuit models in Unit 1. In the next lecture, we'll say a little more about compact models for circuit design.