Section 27
Heterojunction Bipolar Transistor

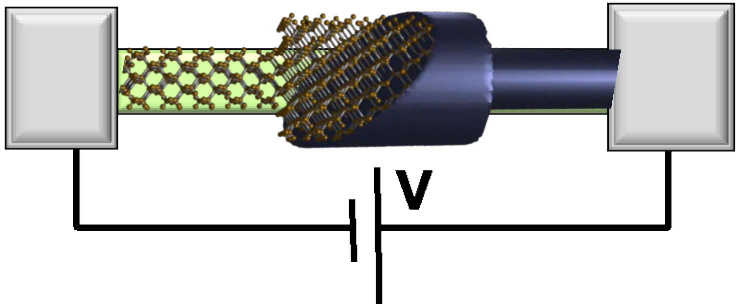
Gerhard Klimeck

gekco@purdue.edu

PURDUE UNIVERSITY

School of Electrical and Computer Engineering

Section 27
Heterojunction Bipolar Transistor



I = G x V

= q x n x v x A

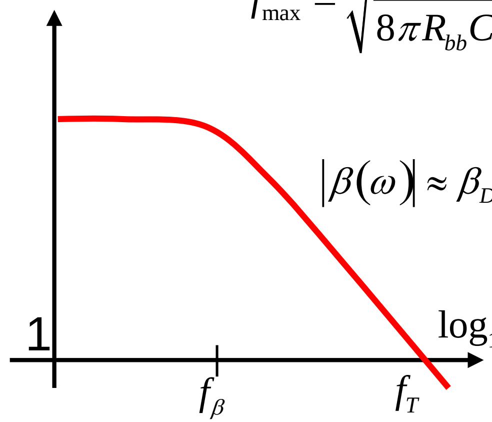
charge density velocity area

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

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

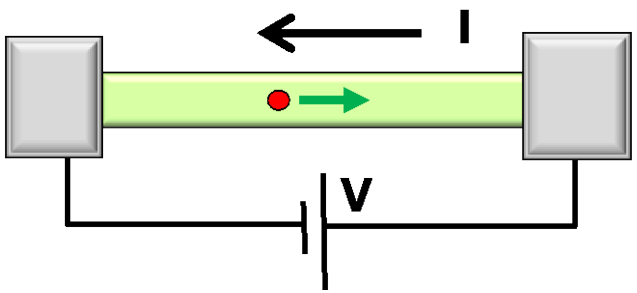
$$\beta_{poly,ballistic} \rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{\upsilon_s}$$

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



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

Section 27
Heterojunction Bipolar Transistor



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

charge density velocity area

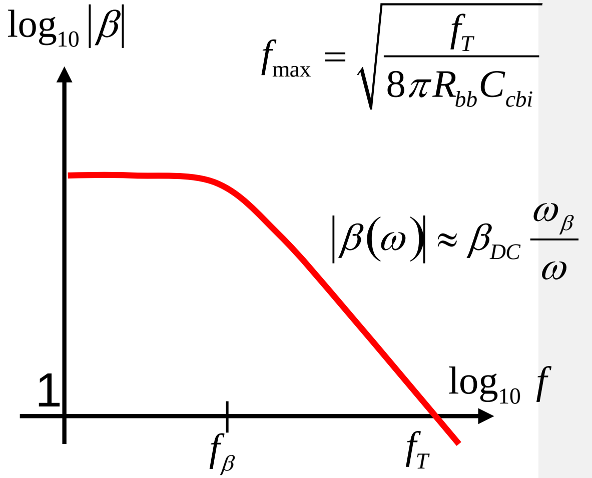
1
2
3
4
5
6
7
8

- 27.1 Applications, Concept, Innovation, Nobel Prize
- 27.2 Heterojunction Equilibrium Solution
- 27.3 Types of heterojunctions
- 27.4 Abrupt junction HBTs
- 27.5 Graded junction HBTs
- 27.6 Graded base HBTs
- 27.7 Double heterojunction HBTs
- 27.8 Modern Designs

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

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

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



Mark Lundstrom, “Heterostructure Fundamentals,” Purdue University, 1995.
Herbert Kroemer, “Heterostructure bipolar transistors and integrated circuits,” Proc. *IEEE* , **70**, pp. 13-25, 1982.

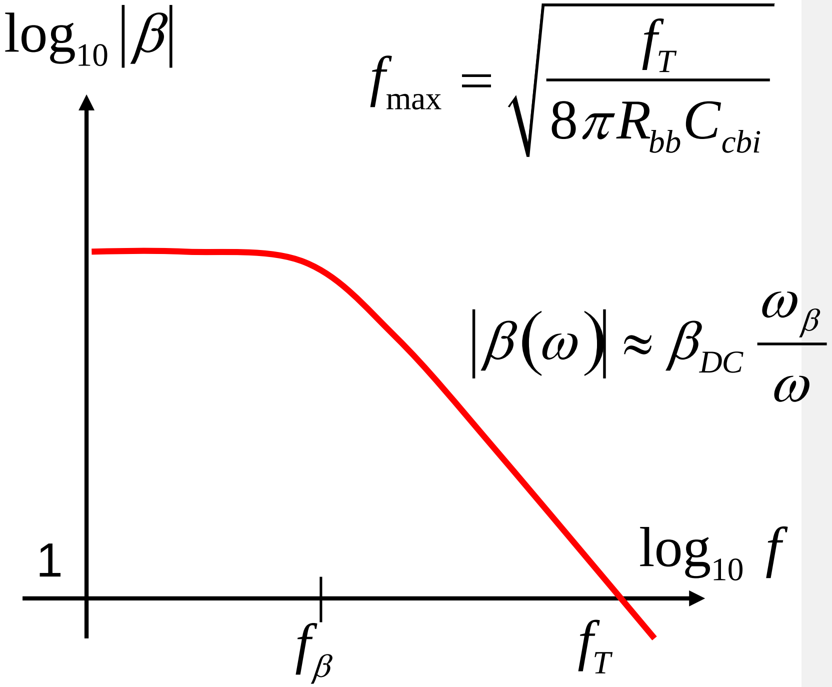
High Frequency Applications

$$\beta_{DC} = \frac{I_C}{I_B} \qquad \beta_{poly,ballistic} \rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{\upsilon_s}$$

1) **Optical fiber communications**
   -40Gb/s…….160Gb/s

2) **Wideband, high-resolution DA/AD converters and digital frequency synthesizers**
   -military radar and communications

3) **Monolithic, millimeter-wave IC's (MMIC's)**
   -front ends for receivers and transmitters



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

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

future need for transistors with 1 THz power-gain cutoff freq.

How to make a better Transistor?

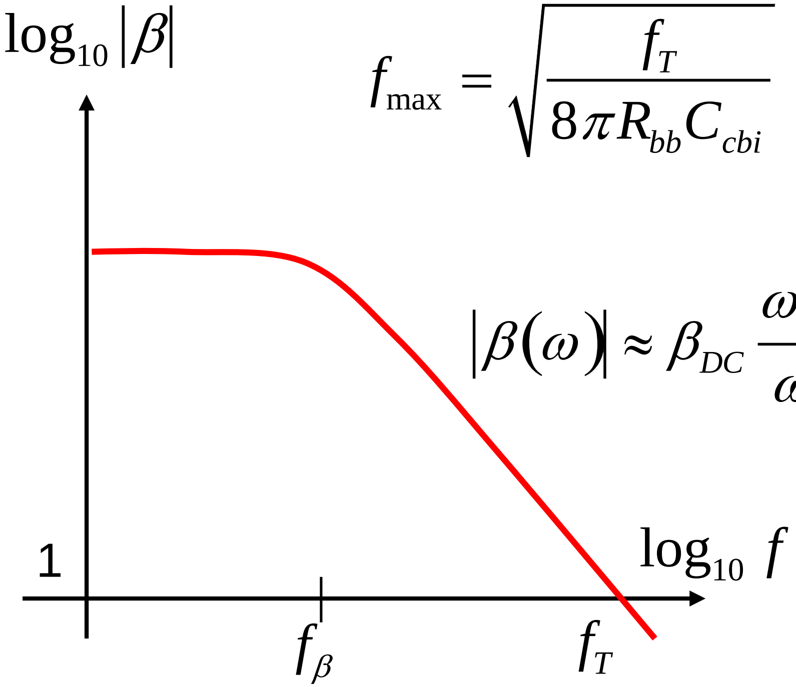
$$\beta_{poly,ballistic} \rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{\upsilon_s}$$

Graded Base transport

Polysilicon Emitter

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

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



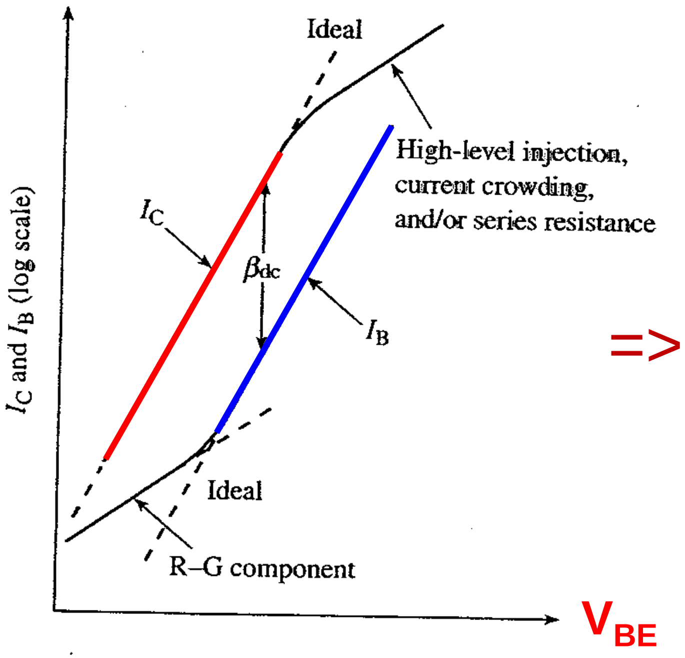
$$|\beta(\omega)| \approx \beta_{DC} \frac{\omega_\beta}{\omega}$$

Heterojunction bipolar transistor

$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B} N_{V,B} e^{-E_{g,B}\beta}}{N_{C,E} N_{V,E} e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E} - E_{g,B}\right)\beta}$$

Emitter bandgap > Base Bandgap

Gummel Plot

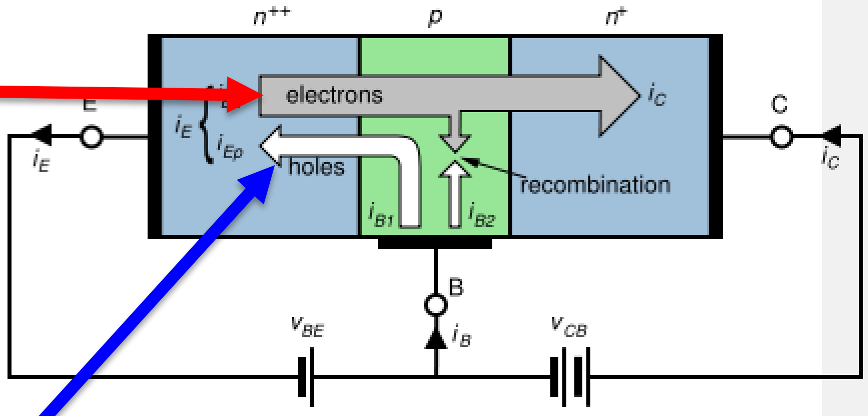


$$\frac{I_C}{A} \approx -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)$$

Minority electrons in base

Goal: Increase I_C

=> Increase n_i decrease E_G



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

Minority holes in base

Goal: Decrease I_B

=> Decrease n_i increase E_G

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

$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E} - E_{g,B}\right)\beta}$$

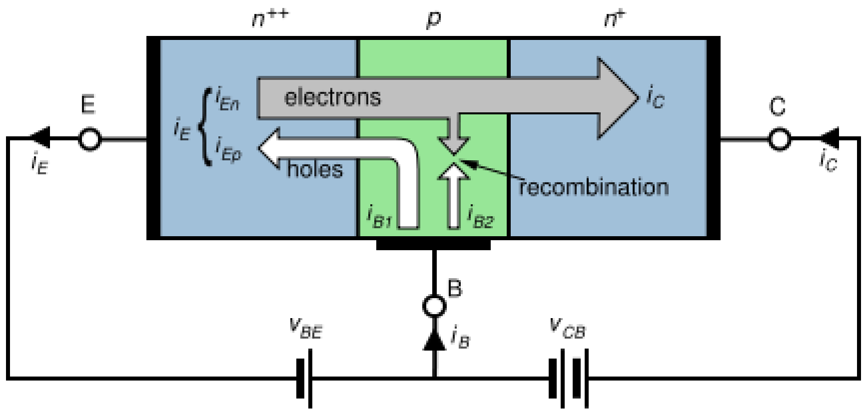
Emitter bandgap > Base Bandgap

Some History

Schokley realized that HBT is possible,

Herbert Kroemer
provided the foundation of the field
and worked out the details
Proc. IEEE, 70, pp 13-25, 1982.

Kroemer
Nobel Prize (2000)



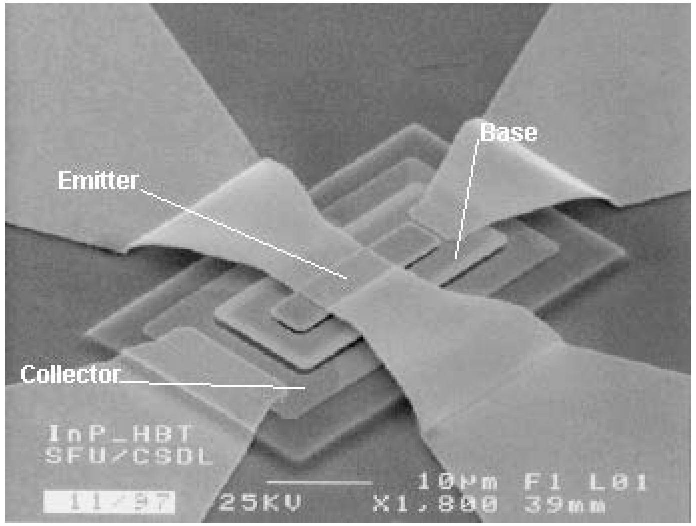
$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B} N_{V,B} e^{-E_{g,B}\beta}}{N_{C,E} N_{V,E} e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E} - E_{g,B}\right)\beta}$$

Schokley realized that HBT is possible,

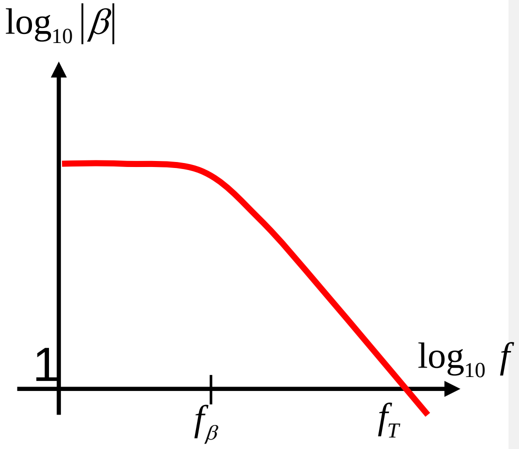
Herbert Kroemer
provided the foundation of the field
and worked out the details
Proc. IEEE, 70, pp 13-25, 1982.

Kroemer
Nobel Prize (2000)

A heterojunction bipolar transistor



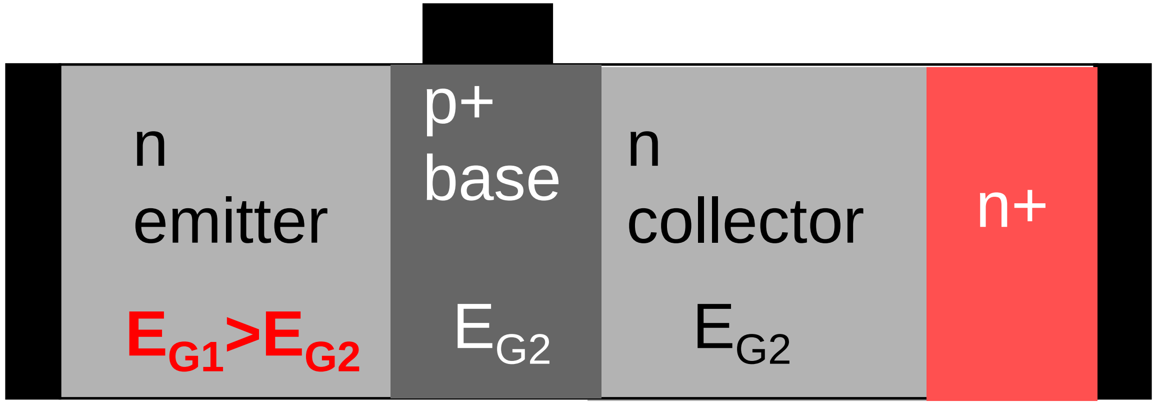
$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}} \approx e^{(E_{g,E}-E_{g,B})\beta}$$



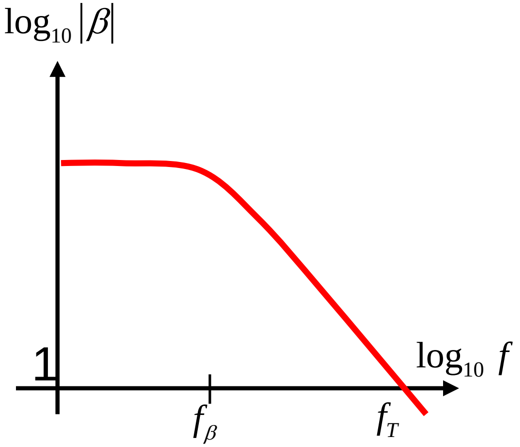
Today:
Think of all the cell phones and wifi routers…
Communication networks…
Satellite communications

Heterojunction Bipolar Transistors

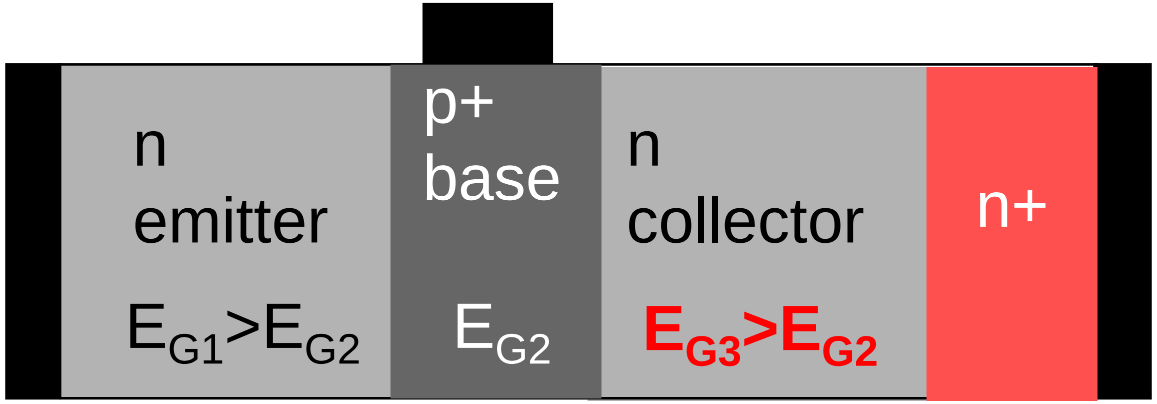
i) Wide gap Emitter HBT



$$\frac{n_{i,B}^2}{n_{i,E}^2}=\frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}}\approx e^{\left(E_{g,E}-E_{g,B}\right)\beta}$$

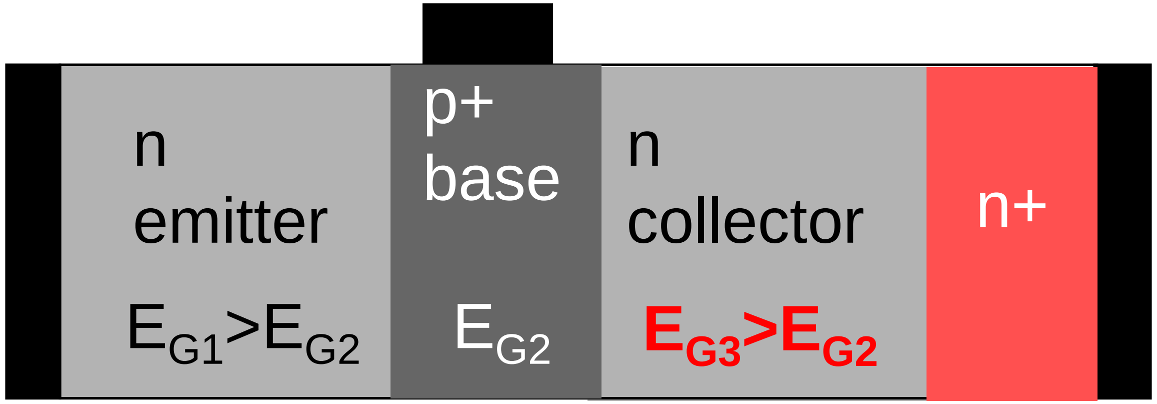


ii) **Double** Heterojunction Bipolar Transistor

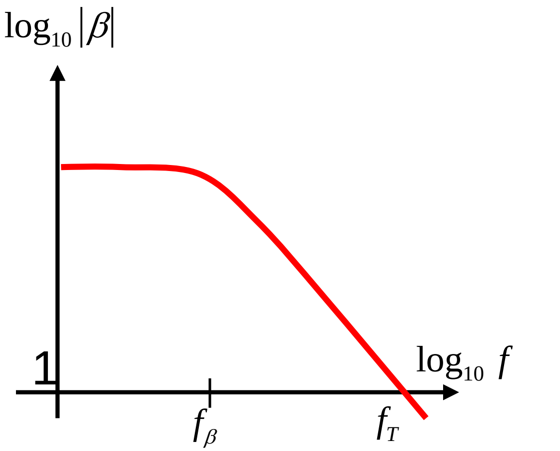


Larger bandgap material in collector => do not loose control under high current

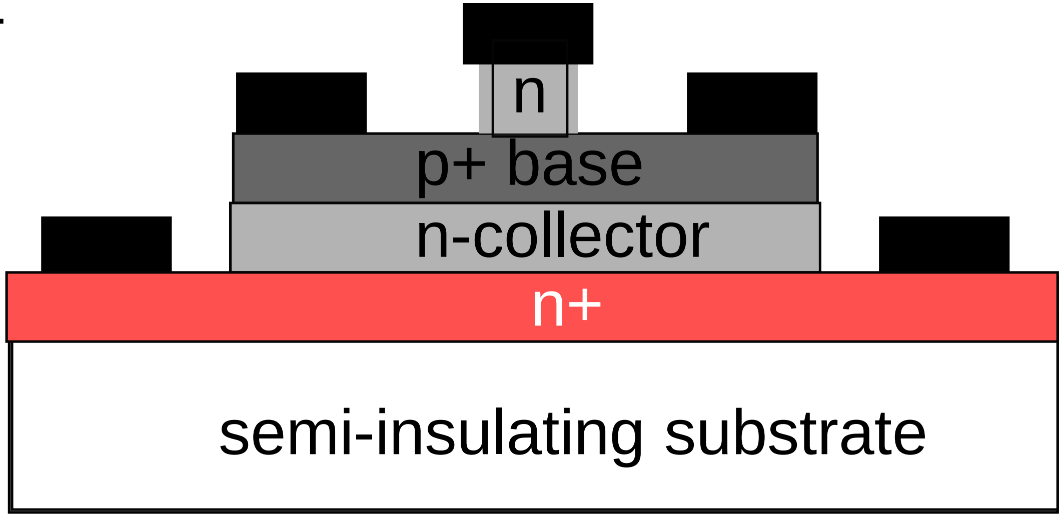
Mesa HBTs



$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E}-E_{g,B}\right)\beta}$$



Mesa HBT



Intentional traps,
Fermi level pinned
Low conductance
Low capacitance
High speed

Bandgaps and Lattice Matching

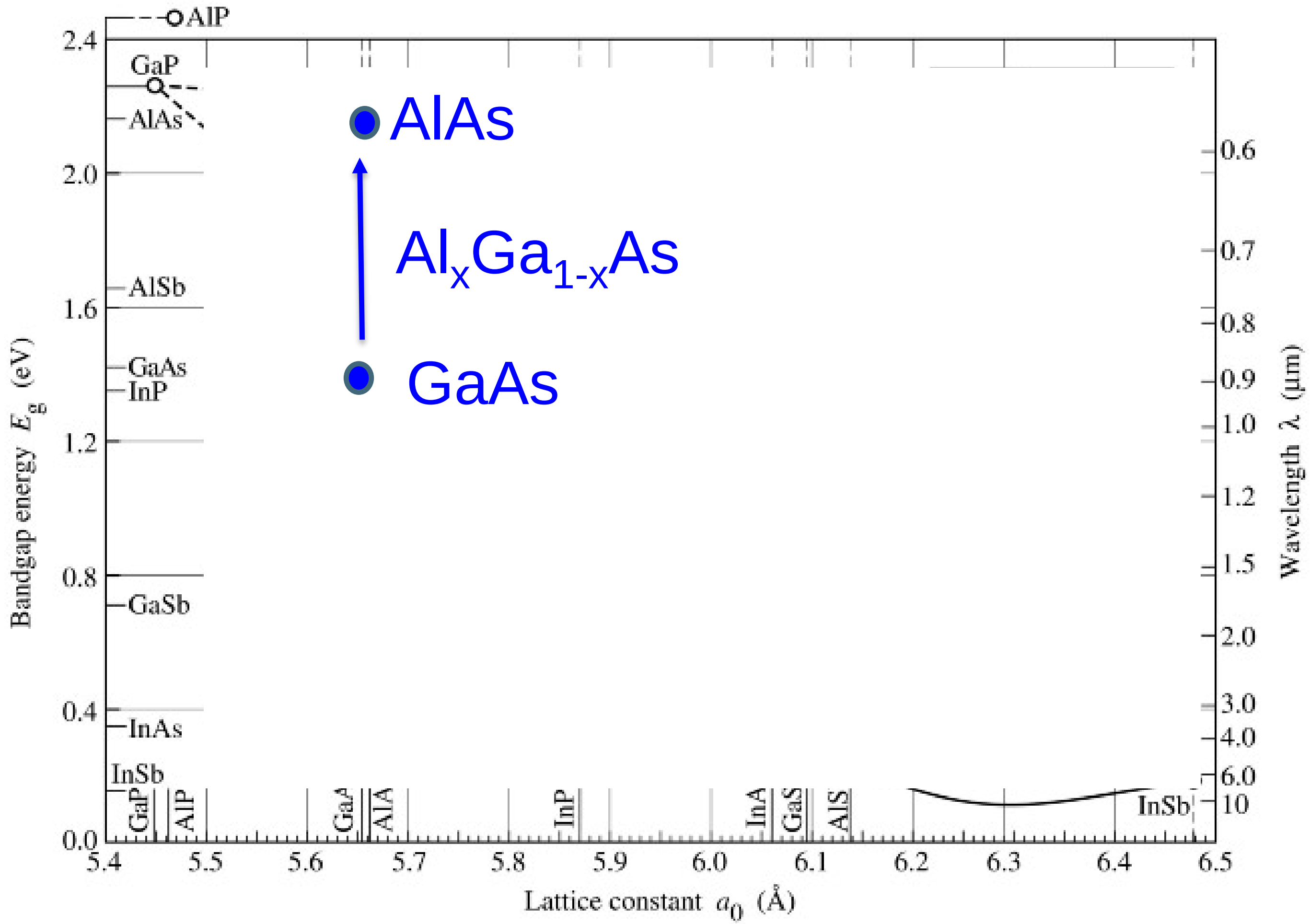


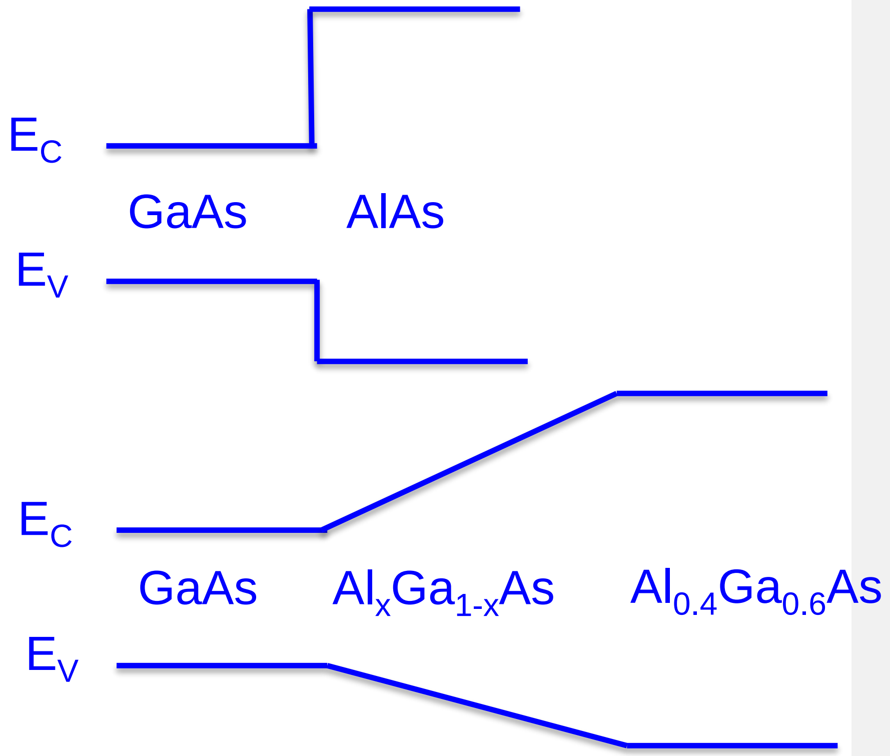
Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B} N_{V,B} e^{-E_{g,B}\beta}}{N_{C,E} N_{V,E} e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E} - E_{g,B}\right)\beta}$$

GaAs/AlGaAs

GaAs has “small” E_G

AlGaAs is barrier / high E_G



Bandgaps and Lattice Matching

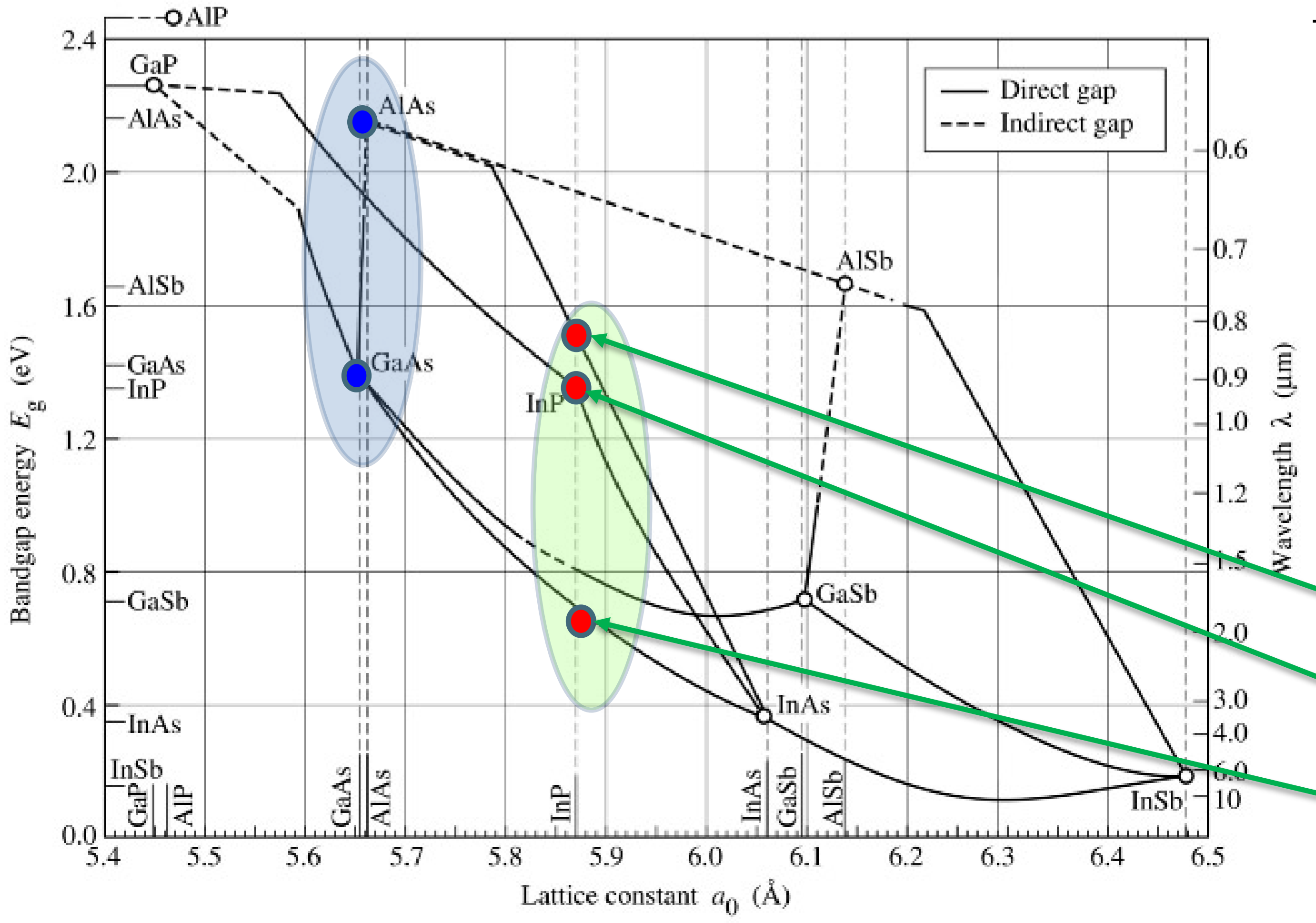


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B} N_{V,B} e^{-E_{g,B}\beta}}{N_{C,E} N_{V,E} e^{-E_{g,E}\beta}} \approx e^{\left(E_{g,E} - E_{g,B}\right)\beta}$$

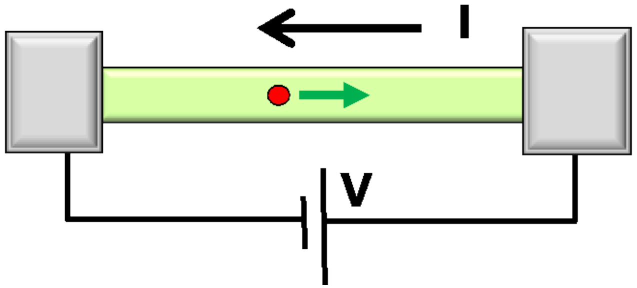
GaAs/AlGaAs

- GaAs has “small” E_G
- AlGaAs is barrier / high E_G

InP/InGaAs/InAlAs

- InAlAs is barrier / high E_G
- InP is substrate / high E_G
- InGaAs is “small” E_G

Section 27
Heterojunction Bipolar Transistor



I = G x V

= q x n x v x A

charge density velocity area

$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}} \approx e^{(E_{g,E}-E_{g,B})\beta}$$

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

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

1
2
3
4
5
6
7
8

- 27.1 Applications, Concept, Innovation, Nobel Prize
- 27.2 Heterojunction Equilibrium Solution
- 27.3 Types of heterojunctions
- 27.4 Abrupt junction HBTs
- 27.5 Graded junction HBTs
- 27.6 Graded base HBTs
- 27.7 Double heterojunction HBTs
- 27.8 Modern Designs

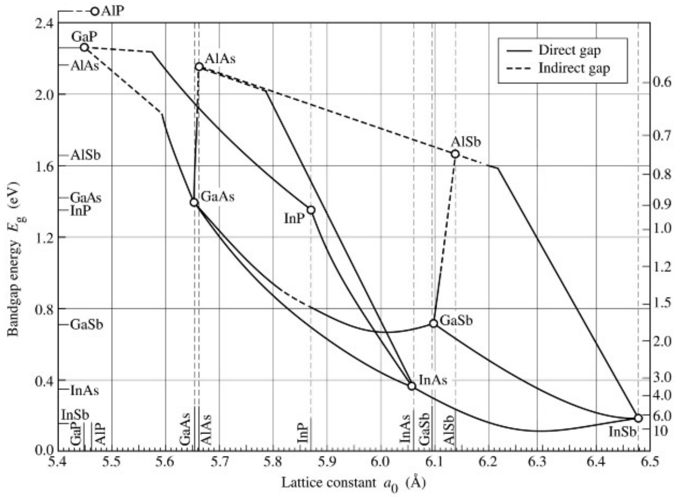
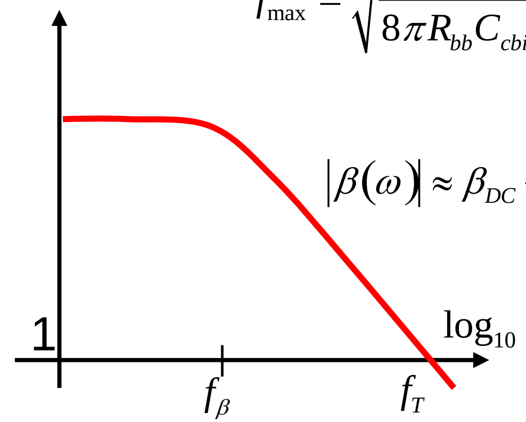


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

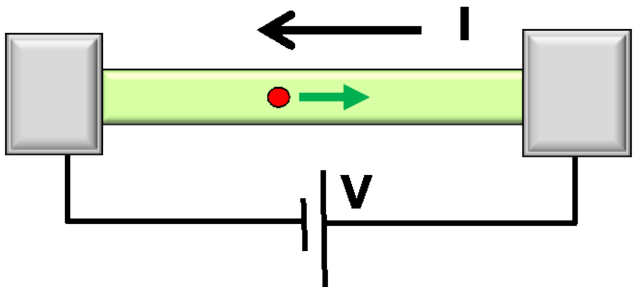
$$f_{max} = \sqrt{\frac{f_T}{8\pi R_{bb}C_{cbi}}}$$



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

Mark Lundstrom, "Heterostructure Fundamentals," Purdue University, 1995.
Herbert Kroemer, "Heterostructure bipolar transistors and integrated circuits," Proc. *IEEE* , **70**, pp. 13-25, 1982.

Section 27
Heterojunction Bipolar Transistor



I = G x V

= q x n x v x A

charge density velocity area

$$\frac{n_{i,B}^2}{n_{i,E}^2} = \frac{N_{C,B}N_{V,B}e^{-E_{g,B}\beta}}{N_{C,E}N_{V,E}e^{-E_{g,E}\beta}} \approx e^{(E_{g,E}-E_{g,B})\beta}$$

- 27.1 Applications, Concept, Innovation, Nobel Prize
- 27.2 Heterojunction Equilibrium Solution
- 27.3 Types of heterojunctions
- 27.4 Abrupt junction HBTs
- 27.5 Graded junction HBTs
- 27.6 Graded base HBTs
- 27.7 Double heterojunction HBTs
- 27.8 Modern Designs

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

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

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

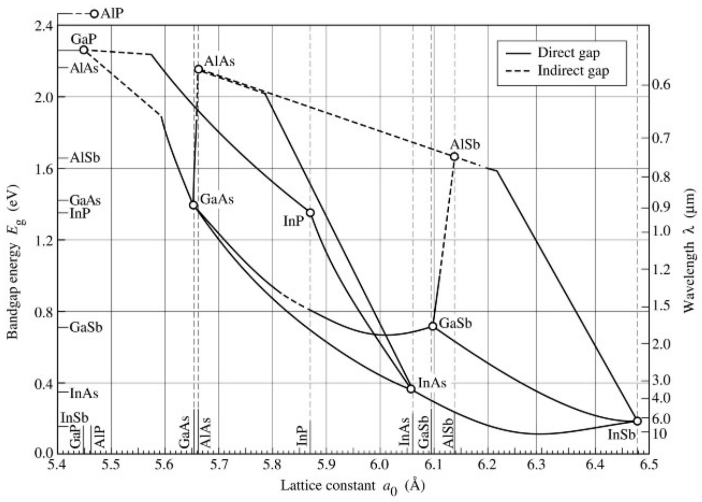
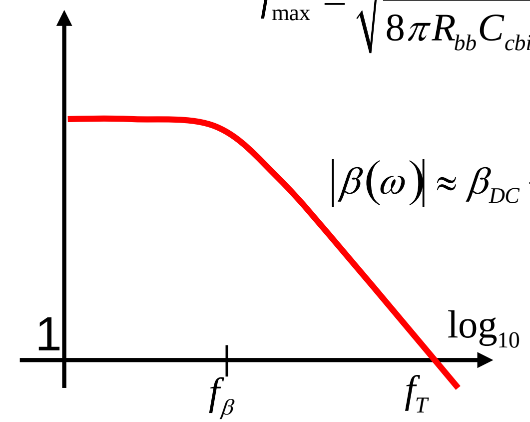


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

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



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

Mark Lundstrom, “Heterostructure Fundamentals,” Purdue University, 1995.
Herbert Kroemer, “Heterostructure bipolar transistors and integrated circuits,” Proc. *IEEE* , **70**, pp. 13-25, 1982.