EE-612:
Lecture 33:
Heterojunction Bipolar Transistors

Mark Lundstrom
Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA
Fall 2006

NCN

www.nanohub.org

outline

I) Introduction

II) BJT Review

III) The Widegap Emitter

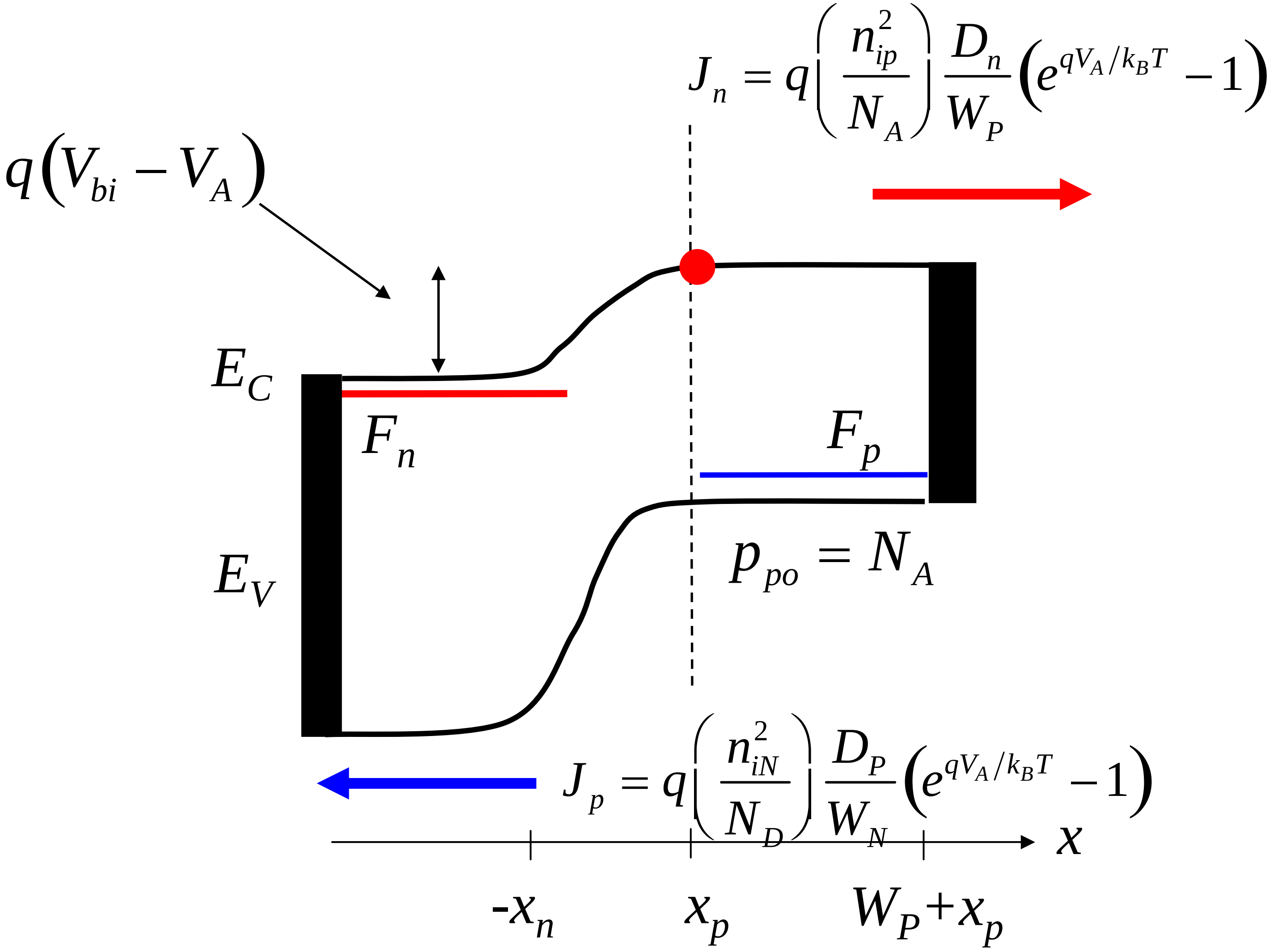
IV) Modern HBTs

V) Summary

Reference:

Mark J. Rodwell, et al., “Submicron Scaling of HBTs,” *IEEE Trans. Electron. Dev.* **48**, p. 2606, 2001.

pn heterojunction with no band spike



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

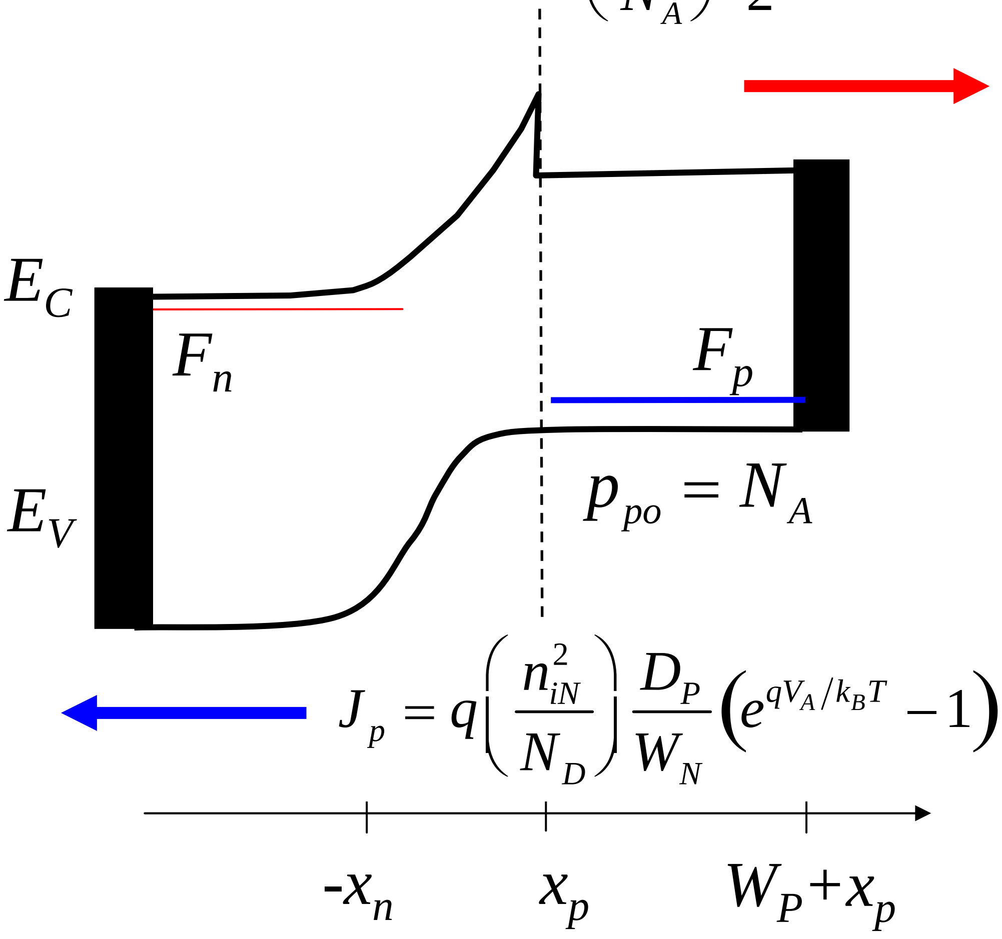
$$q\left(V_{bi}-V_A\right)$$

$$p_{po} = N_A$$

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

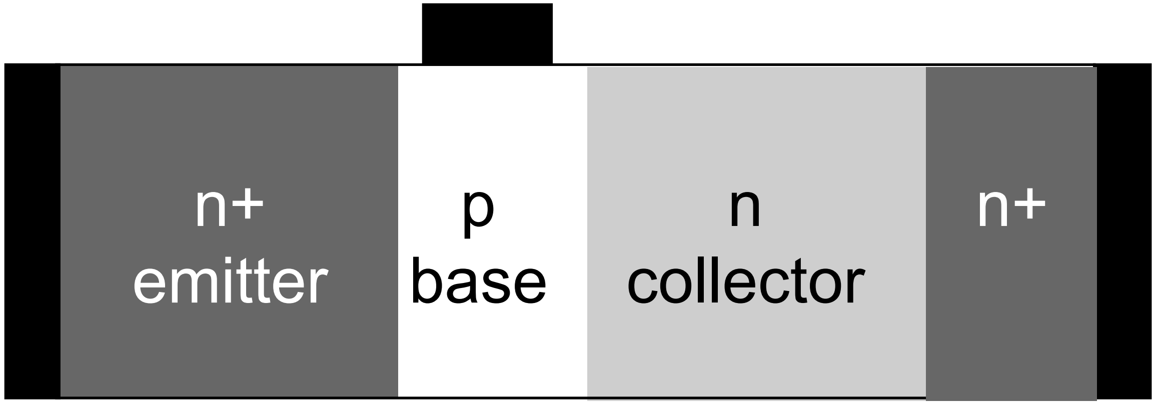
pn heterojunction with CB band spike

$$J_n = q\left(\frac{n_{ip}^2}{N_A}\right)\frac{\upsilon_T}{2}\left(e^{qV_A/k_BT}-1\right)\times e^{-\Delta E_C/k_BT}$$

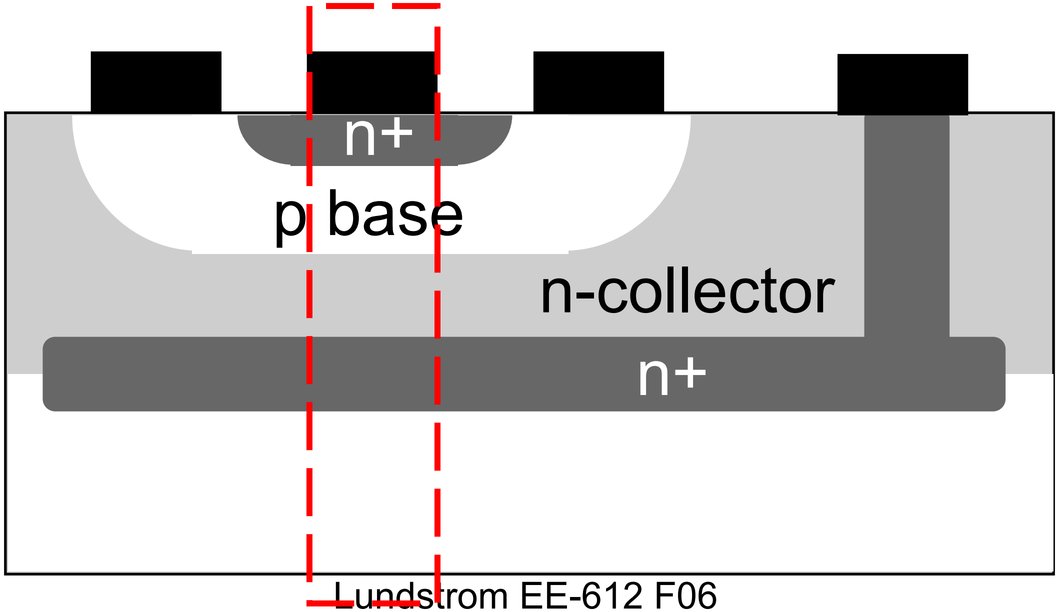


$$J_p = q\left(\frac{n_{iN}^2}{N_D}\right)\frac{D_P}{W_N}\left(e^{qV_A/k_BT}-1\right)$$

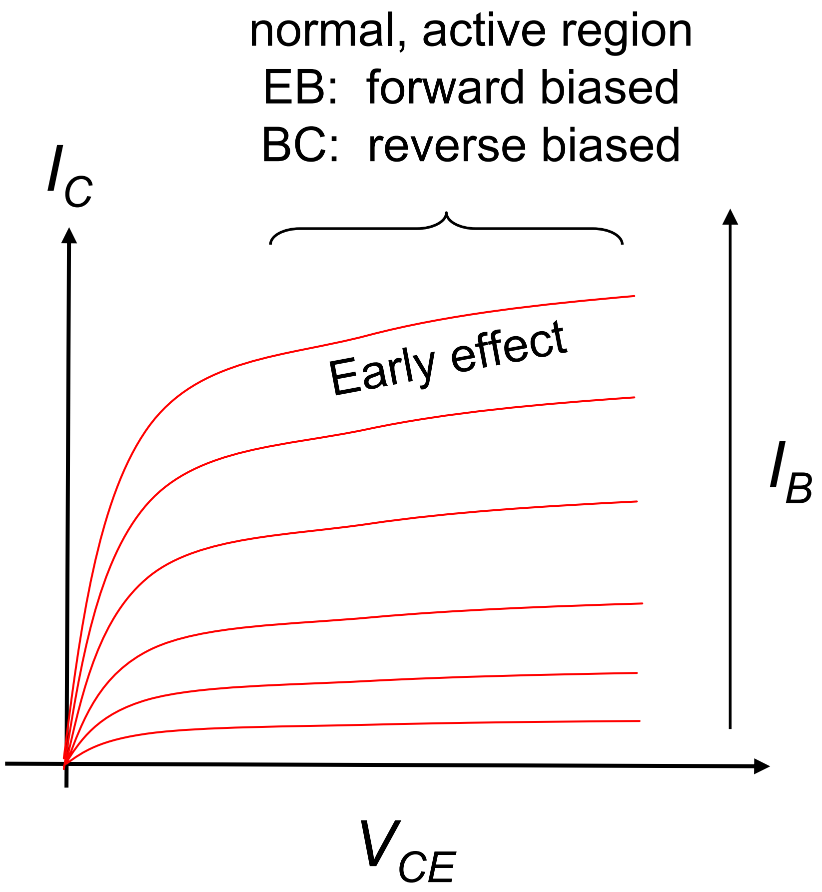
bipolar transistors



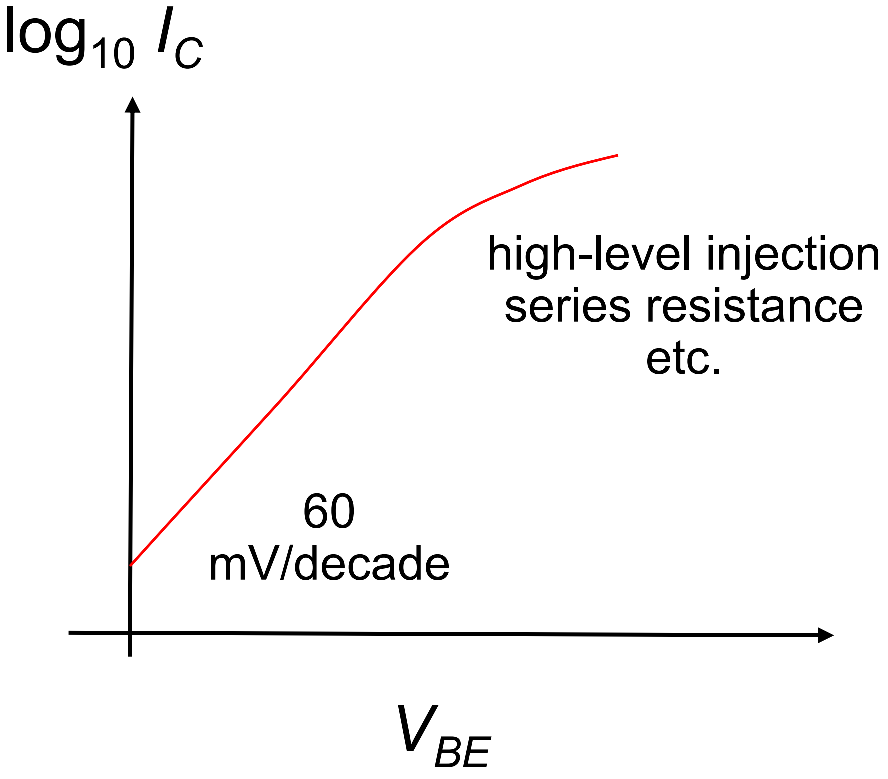
double diffused BJT



bipolar transistors: I-V


normal, active region
EB: forward biased
BC: reverse biased

Early effect

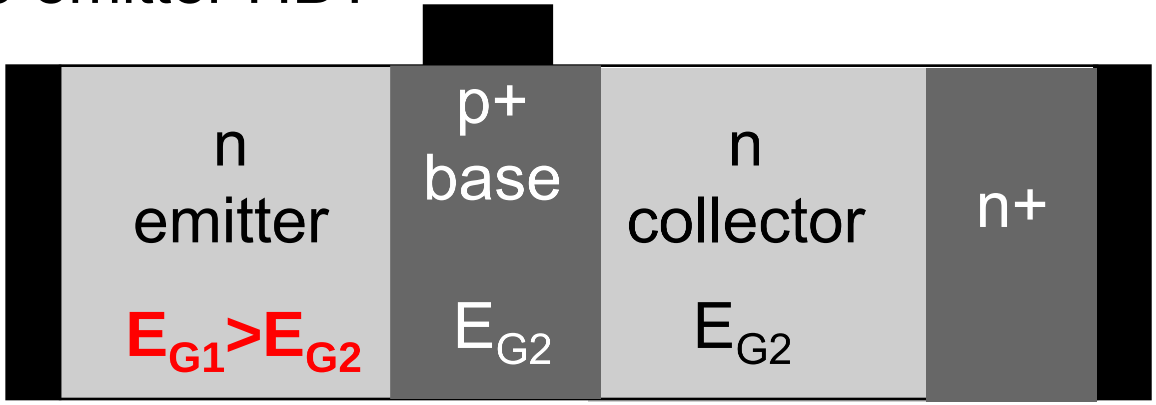

high-level injection
series resistance
etc.

60
mV/decade

$$\beta = \frac{I_C}{I_B}$$

heterojunction bipolar transistors

i) wide gap emitter HBT



n emitter

$E_{G1}>E_{G2}$

p+ base

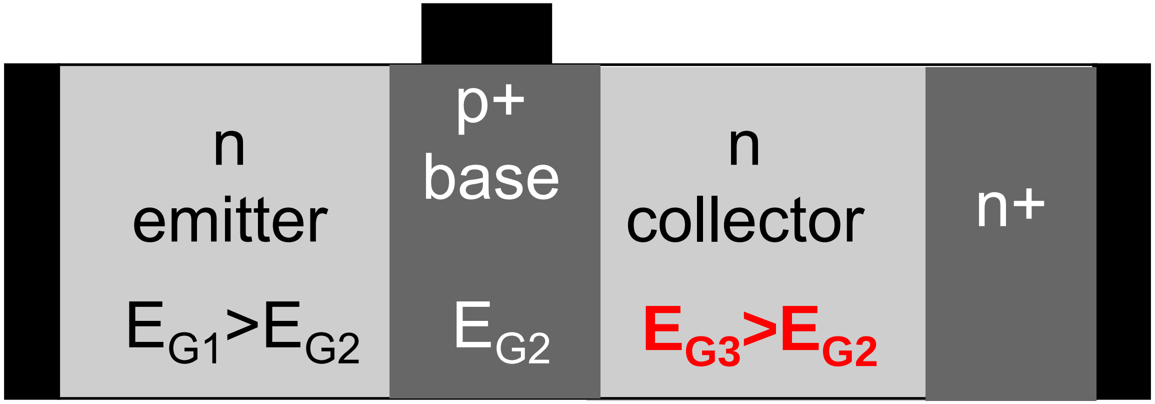
E_{G2}

n collector

E_{G2}

n+

ii) double heterojunction bipolar transistor



n emitter

$E_{G1}>E_{G2}$

p+ base

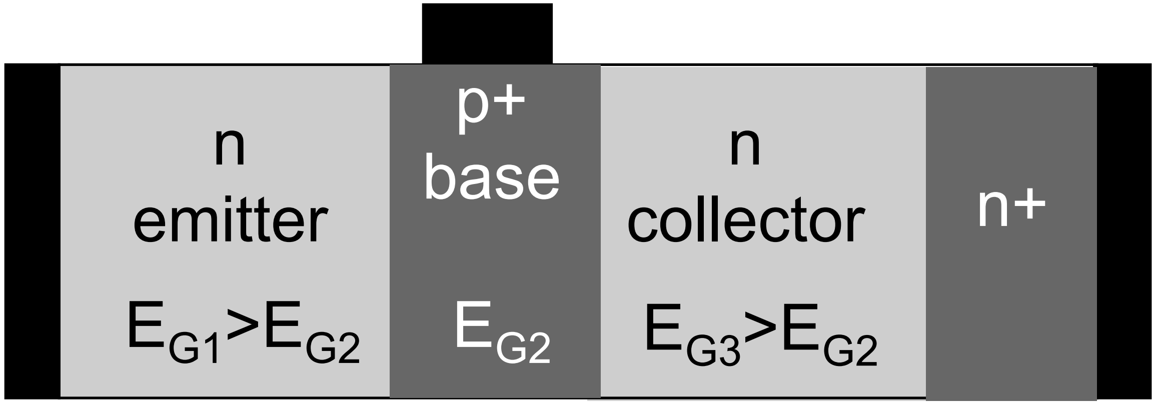
E_{G2}

n collector

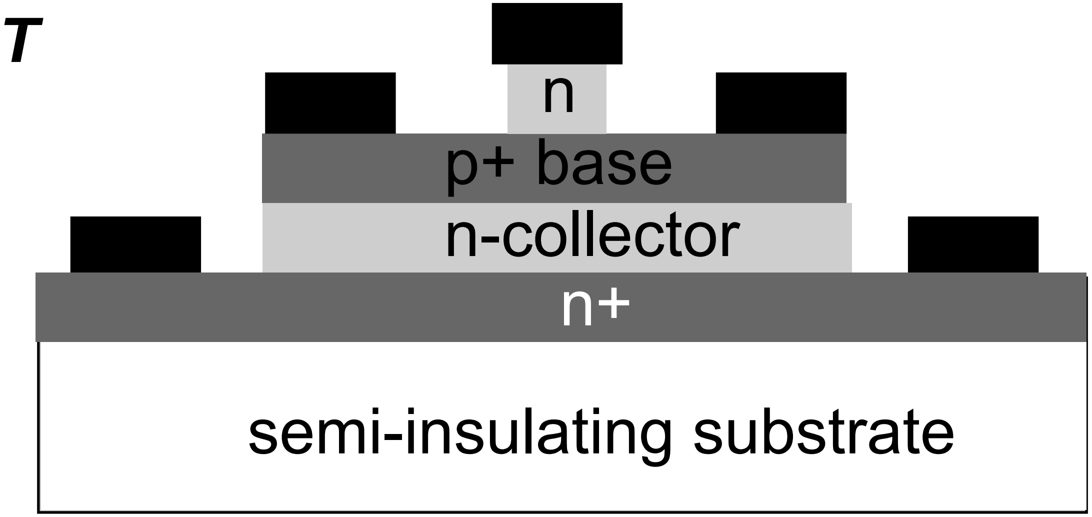
$E_{G3}>E_{G2}$

n+

mesa HBTs



mesa HBT



applications

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)**

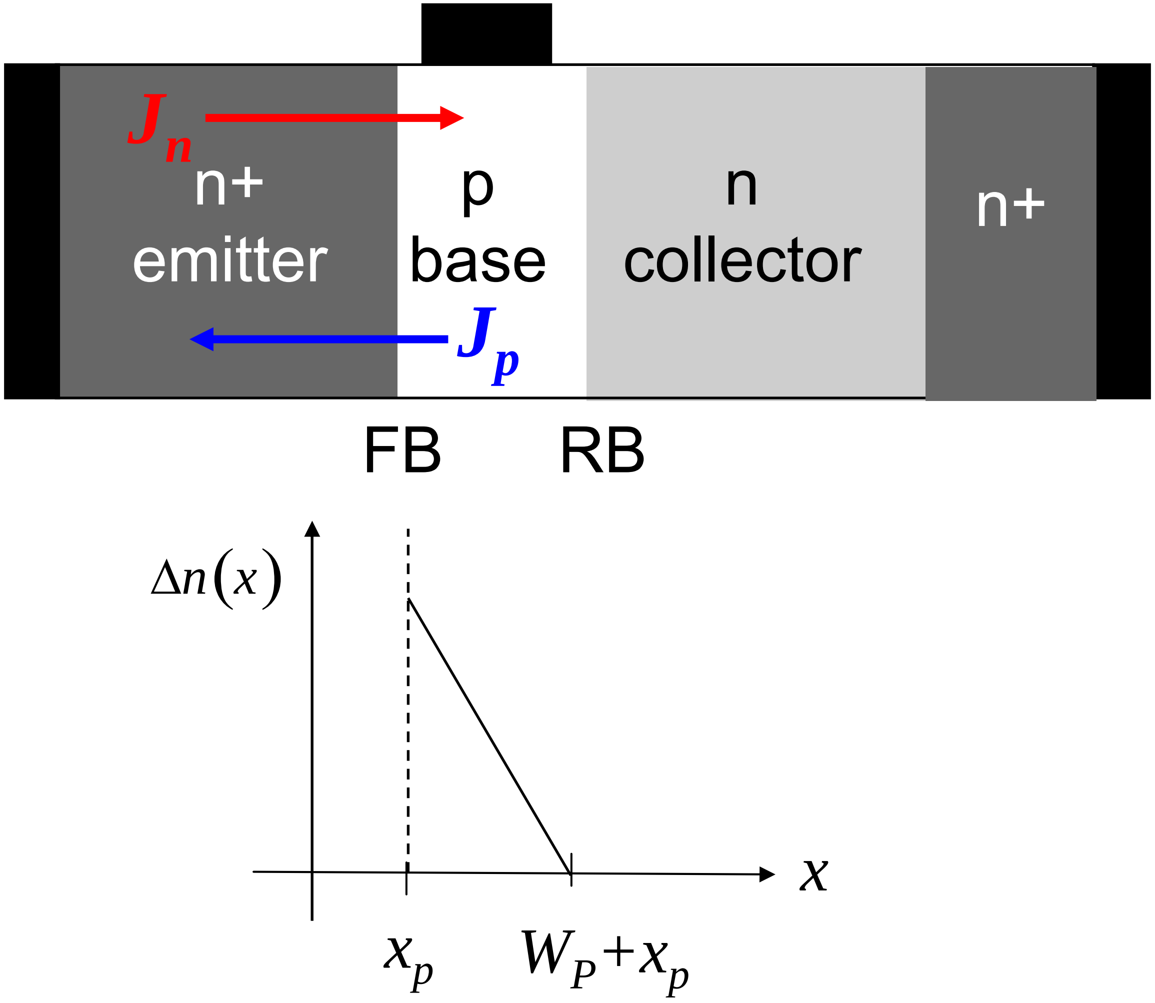
   -front ends for receivers and transmitters

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

outline

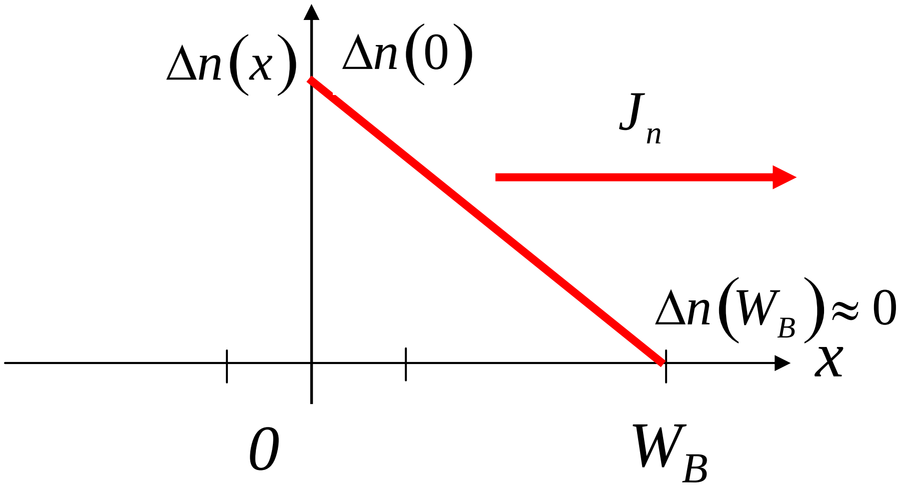
- I) Introduction
- **II) BJT Review**
- III) The Widegap Emitter
- IV) Modern HBTs
- V) Summary

minority carrier injection



See: R.F. Pierret, *Semiconductor Fundamentals*, Addison-Wesley, 1996.

base diffusion current

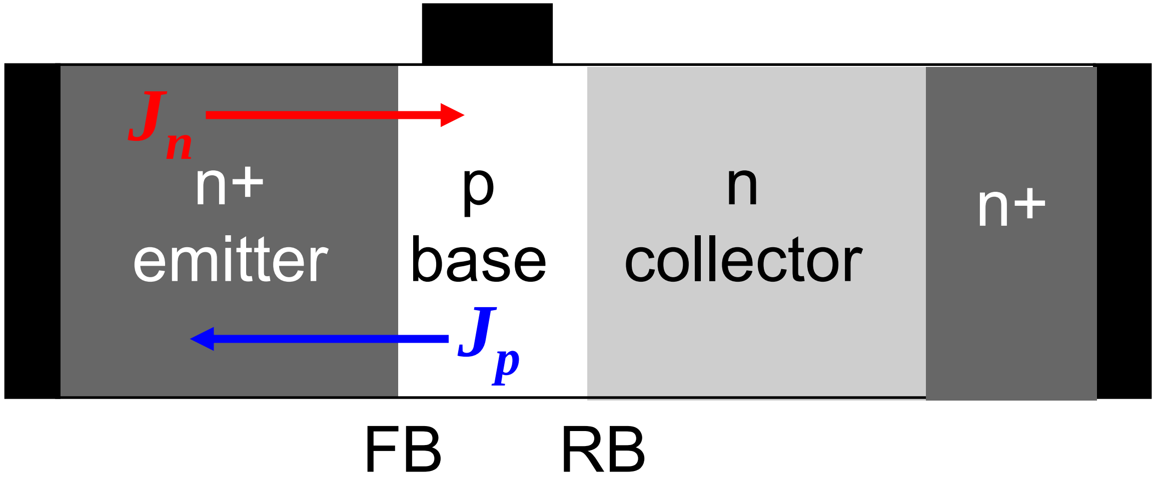


$$J_n = -qD_n \frac{dn(x)}{dx} = qD_n \frac{n(0)}{W_B}$$

$$n(0) = \left(\frac{n_i^2}{N_{AB}}\right) e^{qV_{BE}/k_BT}$$

$$J_n = q\left(\frac{n_i^2}{N_{AB}}\right)\frac{D_n}{W_B} e^{qV_{BE}/k_BT}$$

beta

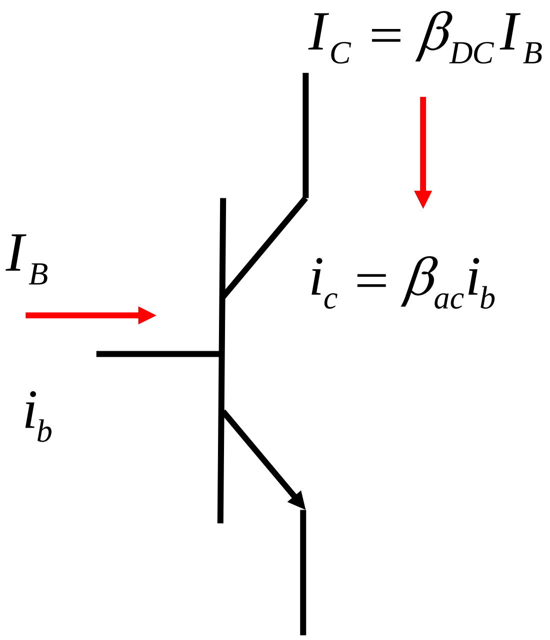


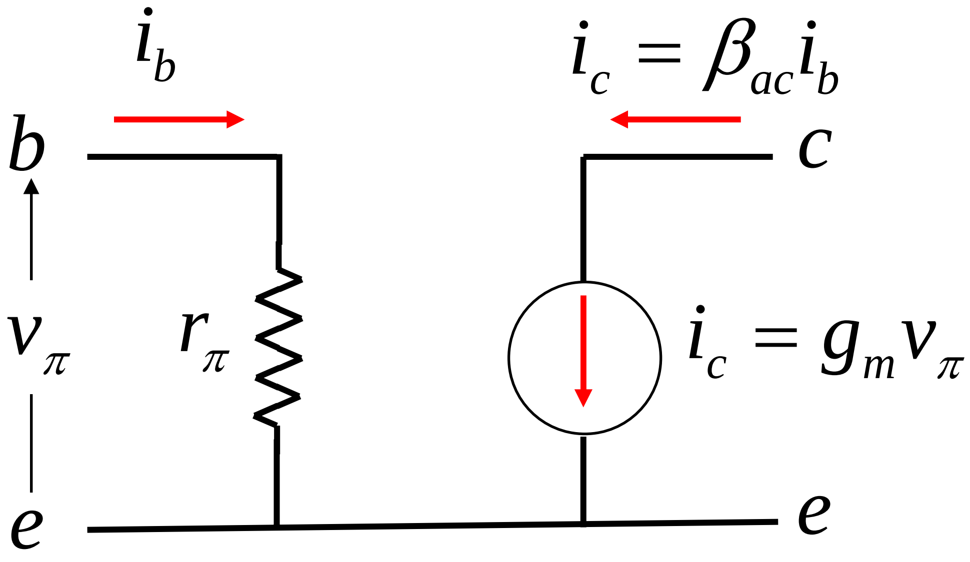
$$J_n = q\left(\frac{n_i^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{qV_{BE}/k_BT}$$

$$J_p = q\left(\frac{n_i^2}{N_{DE}}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$\boxed{\beta = \frac{I_C}{I_B} = \frac{J_n}{J_p} = \frac{N_{DE}}{N_{AE}}\frac{D_n}{D_p}\frac{W_E}{W_B}}$$

ac model



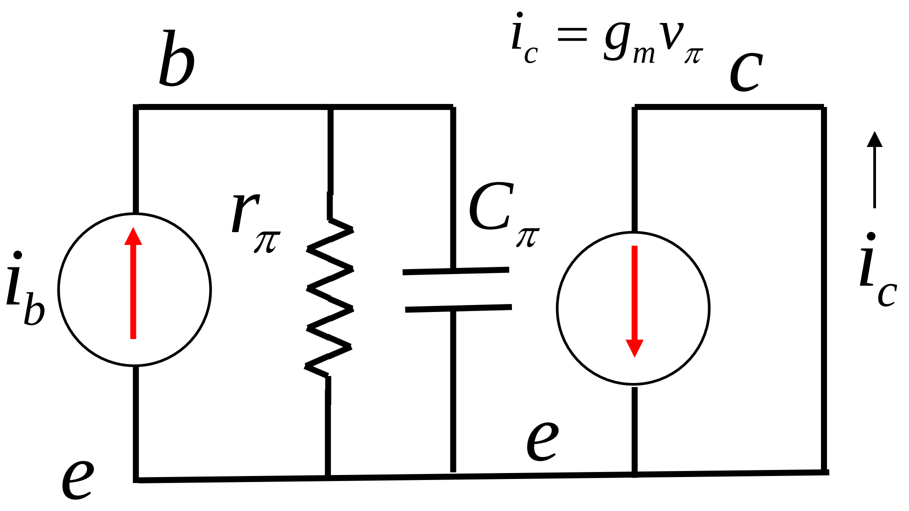


$$I_C = qA_E\left(\frac{n_i^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{qV_{BE}/k_BT}$$

$$g_m = I_C/\left(k_BT/q\right)$$

$$r_\pi = \beta/g_m$$

freq. response



$$i_c = g_m v_\pi = g_m \frac{i_b}{1/r_\pi + j\omega C_\pi}$$

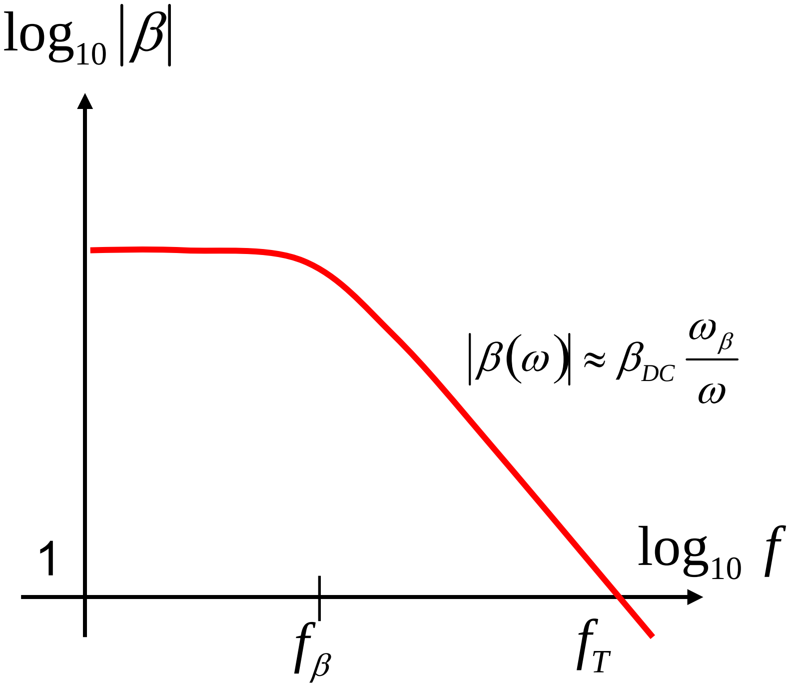
$$\beta(\omega) = \frac{\beta_{DC}}{1 + j\,\omega/\omega_\beta}$$

$$\omega_\beta = 1/r_\pi C_\pi$$

$$|\beta(\omega)| = \frac{\beta_{DC}}{\sqrt{1 + (\omega/\omega_\beta)^2}}$$

f_T

$$|\beta(\omega)| = \frac{\beta_{DC}}{\sqrt{1+(\omega/\omega_\beta)^2}}$$



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

$$|\beta(\omega_T)| = 1 = \beta_{DC}\frac{\omega_\beta}{\omega_T}$$

$$\omega_T = \beta\omega_\beta = \frac{\beta}{r_\pi C_\pi} = \frac{g_m}{C_\pi}$$

$$(\omega_\beta = 1/r_\pi C_\pi)$$

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

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

high frequency metrics

$$\tau = \frac{C_\pi}{g_m} = \frac{\Delta Q_B / \Delta V_{BE}}{\Delta I_C / \Delta V_{BE}} = \frac{\Delta Q_B}{\Delta I_C} \equiv \tau_b \qquad \left(\tau_b = \frac{W_B^2}{2D_n} \right) \qquad \left(\tau_c = \frac{W_c}{2\upsilon_{eff}} \right)$$

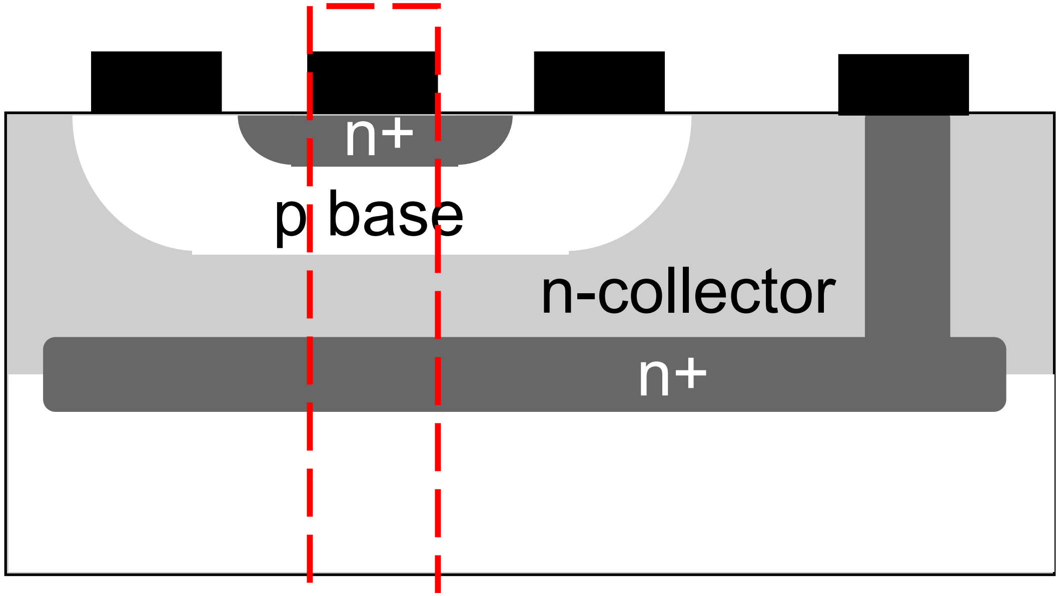
(current-gain cutoff frequency, f_T)

$$\tau = \frac{1}{2\pi f_T} = \tau_b + \tau_c + \frac{k_B T/q}{I_C}\left(C_{je} + C_{cb}\right) + \left(R_{ex} + R_c\right) C_{cb}$$

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

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

BJT design



$$\beta = \frac{N_{DE}}{N_{AE}}\frac{D_n}{D_p}\frac{W_E}{W_B}$$

1) thin base for high speed

2) heavily doped base to prevent punch through, reduce Early effect, and lower R_{ex}

3) even more heavily doped emitter for gain (increase C_{je})

outline

I) Introduction

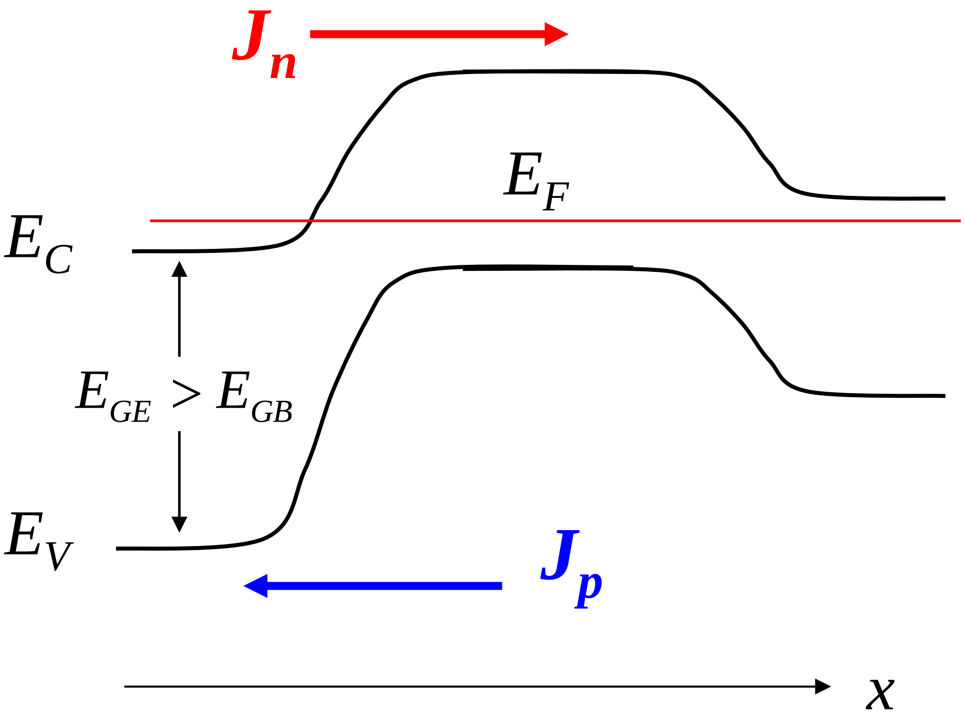
II) BJT Review

III) The Widegap Emitter

IV) Modern HBTs

V) Summary

beta



$$J_n = q\left(\frac{n_{iB}^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{qV_{BE}/k_BT}$$

$$J_p = q\left(\frac{n_{iE}^2}{N_{DE}}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

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

$$n_i = \sqrt{N_C N_V}e^{-E_G/2k_BT}$$

$$\beta \approx \frac{N_{DE}}{N_{AE}}\frac{D_n}{D_p}\frac{W_E}{W_B}e^{\Delta E_G/k_BT}$$

inverted base doping

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

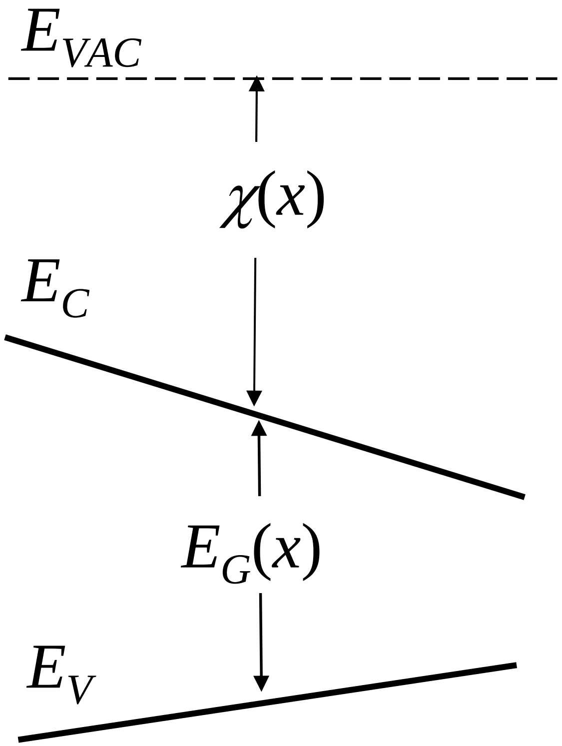
1) thin base for high speed

2) very heavily doped base to prevent punch through, reduce Early effect, and to lower R_{ex}

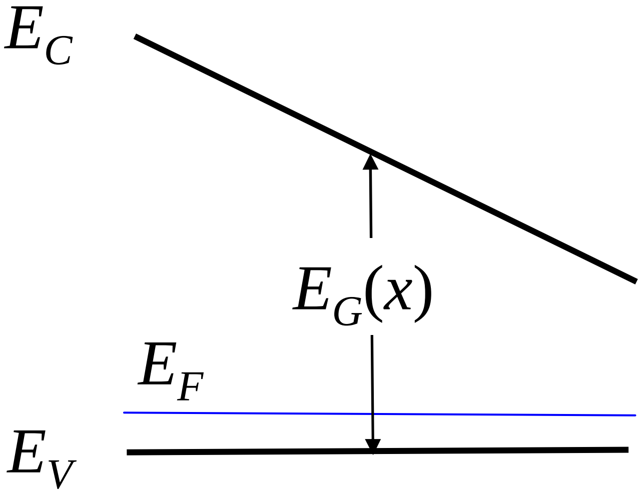
3) moderately doped emitter (lower C_{je})

"inverted base doping" $N_{AB} >> N_{DE}$

graded bases

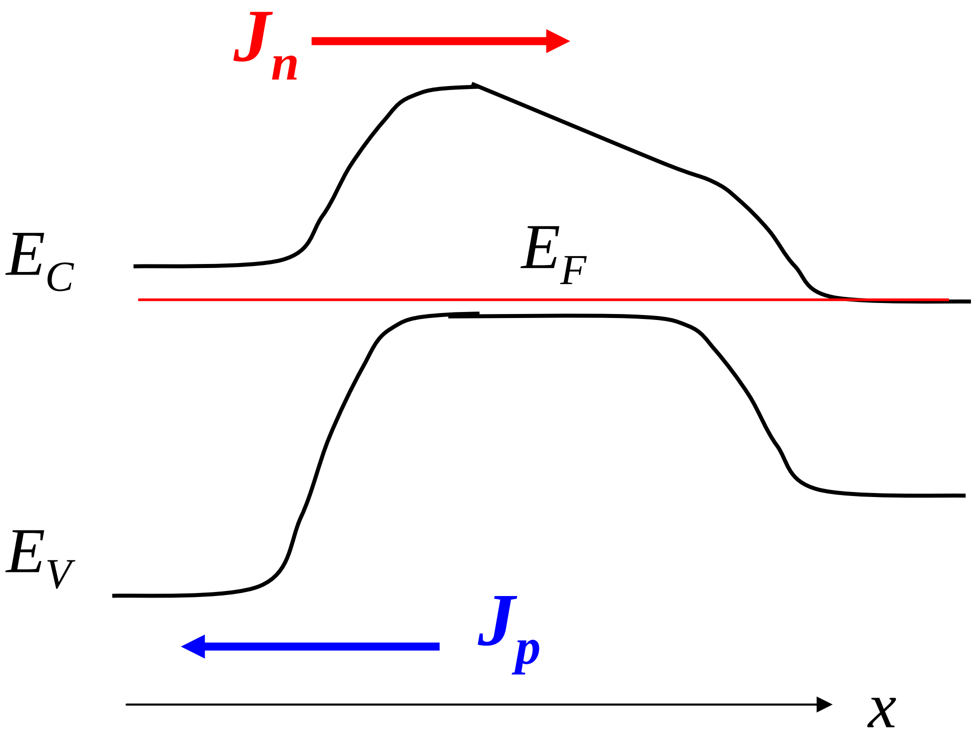


intrinsic
compositionally graded



uniformly p-doped
compositionally graded

graded base HBTs



$$J_n = q\left(\frac{\bar{n}_{iB}^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{qV_{BE}/k_BT}$$

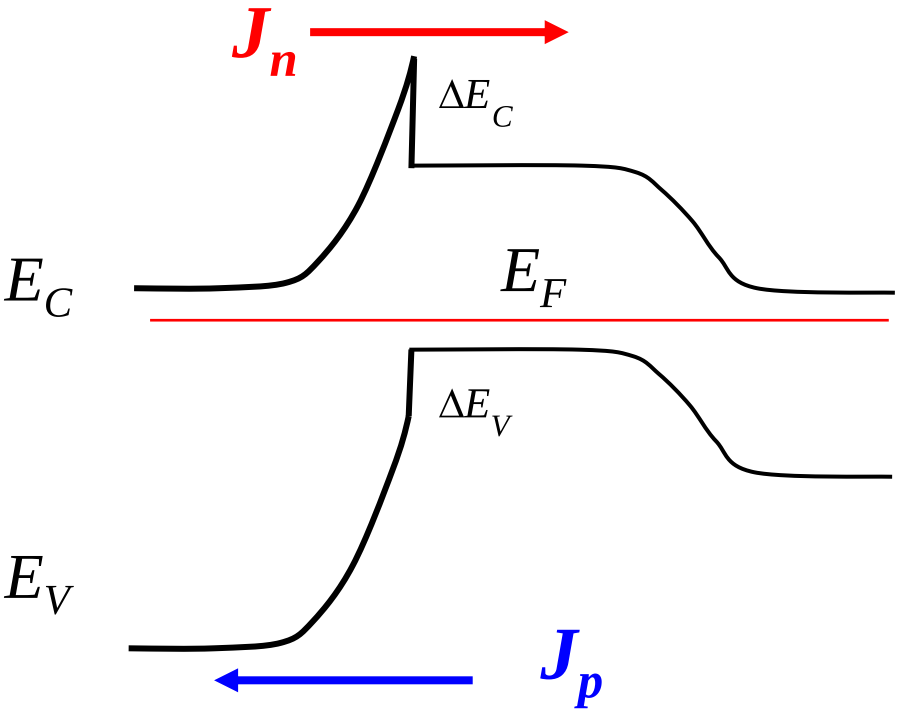
$$J_p = q\left(\frac{n_{iE}^2}{N_{DE}}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$\beta = \frac{N_{DE}}{N_{AE}}\frac{D_n}{D_p}\frac{W_E}{W_B}\frac{\bar{n}_{iB}^2}{n_{iE}^2}$$

$$\tau_b = \frac{W_B}{\mu_n \mathcal{E}_{eff}}$$

$$\mathcal{E}_{eff} = \frac{\Delta E_G/q}{W_B}$$

abrupt junction HBTs



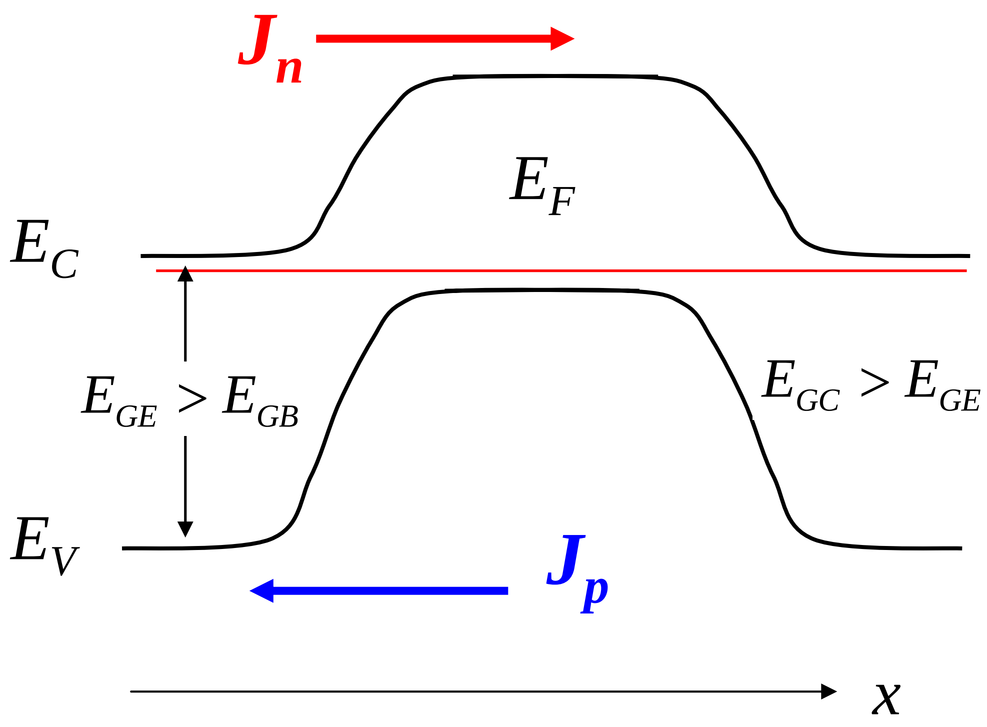
$$J_n = q\left(\frac{n_{iB}^2}{N_{AB}}\right)\upsilon_{Rp}e^{-\Delta E_C/k_BT}e^{qV_{BE}/k_BT}$$

$$J_p = q\left(\frac{n_{iE}^2}{N_{DE}}\right)\frac{D_p}{W_E}e^{qV_{BE}/k_BT}$$

$$\beta = \frac{N_{DE}}{N_{AE}}\frac{\upsilon_{Rp}}{\left(D_p/W_E\right)}\frac{n_{iB}^2}{n_{iE}^2}e^{-\Delta E_C/k_BT}$$

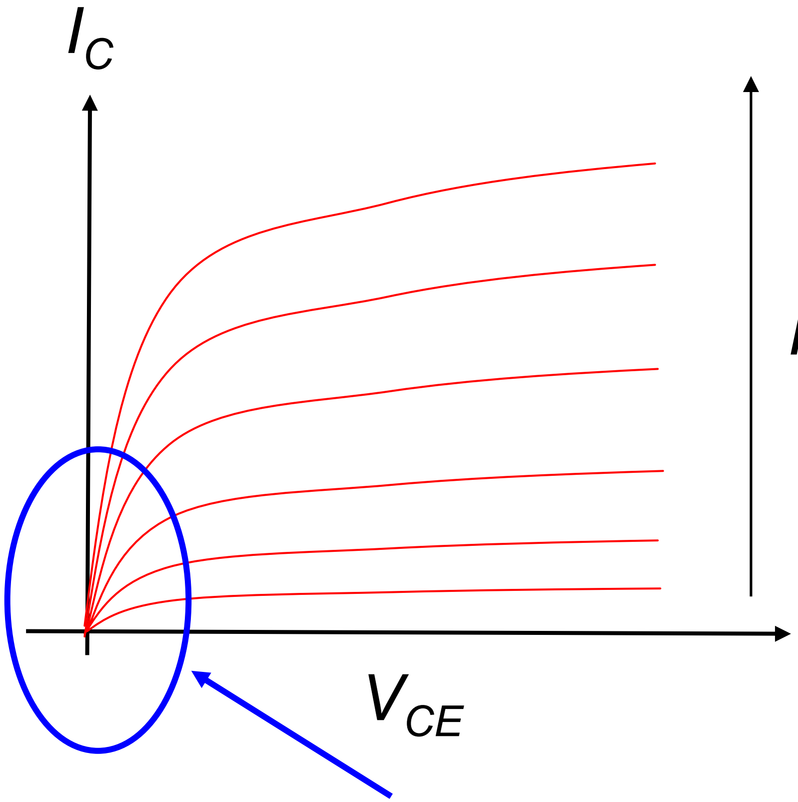
$$\beta = \frac{N_{DE}}{N_{AE}}\frac{\upsilon_{Rp}}{\left(D_p/W_E\right)}e^{\Delta E_V/k_BT}$$

double HBJT

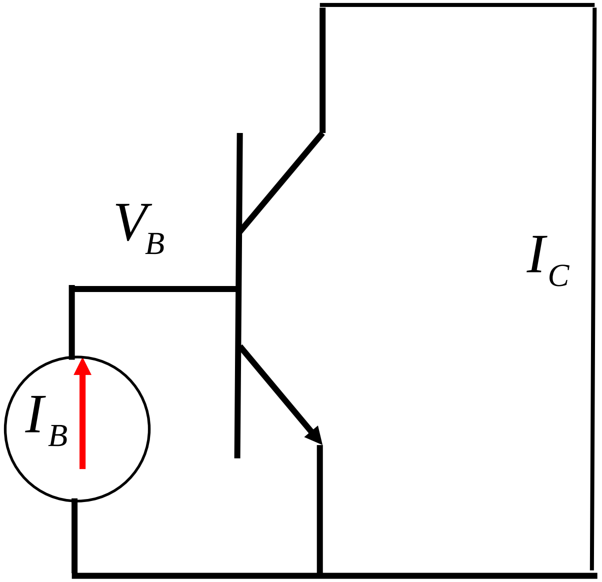


- symmetrical operation
- no charge storage when the b-c junction is forward biased
- reduced collector offset voltage
- higher collector breakdown voltage

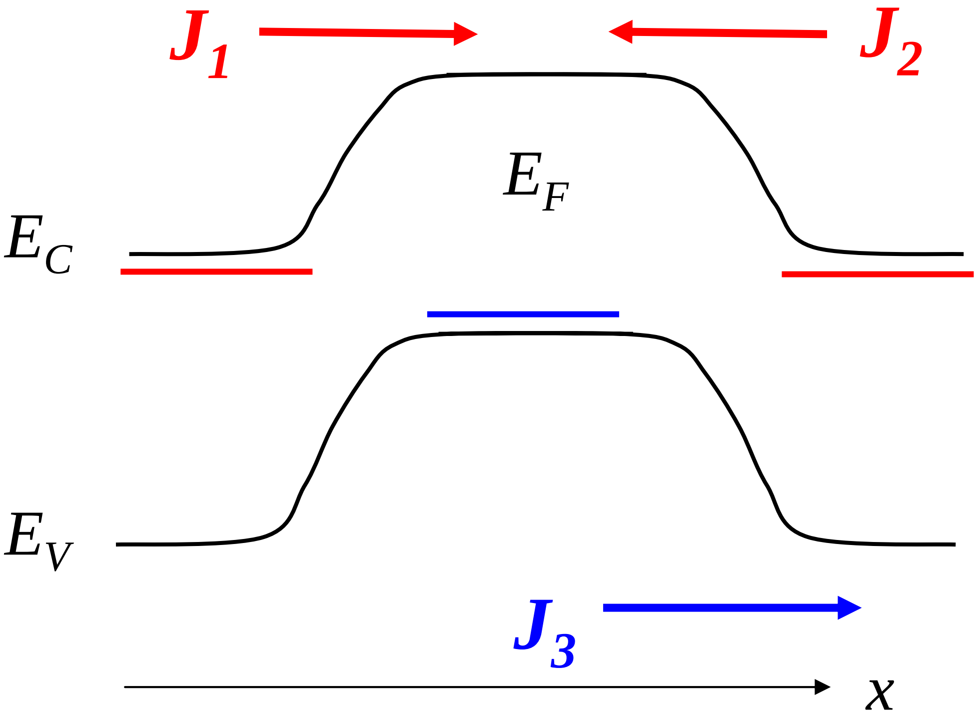
offset voltage



does I_C = 0 at V_{CE} = 0?



offset voltage



$$J_1 = q\left(\frac{n_{iB}^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{q(V_B - V_E)/k_B T}$$

$$J_2 = q\left(\frac{n_{iB}^2}{N_{AB}}\right)\frac{D_n}{W_B}e^{q(V_B - V_C)/k_B T}$$

$$J_3 = q\left(\frac{n_{iC}^2}{N_{DC}}\right)\frac{D_p}{W_C}e^{q(V_B - V_C)/k_B T}$$

$$J_C = J_1 - J_2 - J_3$$

set $J_C = 0$, assume $V_E = 0$, solve for $V_C = V_{OS}$

offset voltage result

$$V_{OS} = \frac{k_B T}{q} \ln\left(1 + 1/\gamma_R\right)$$

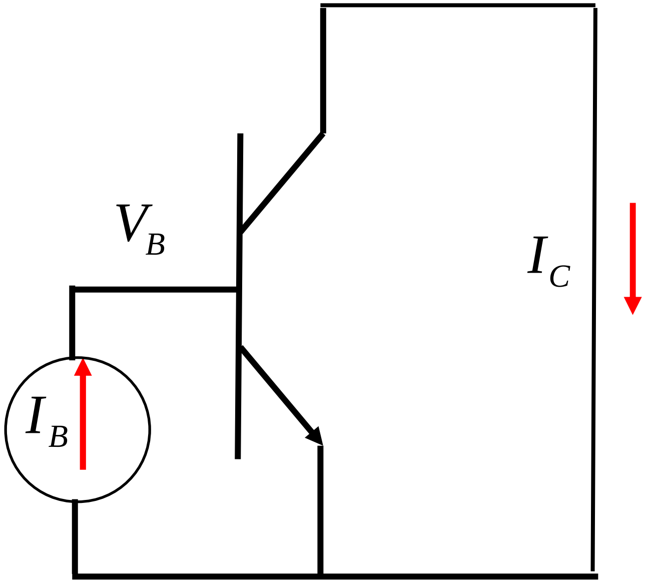
$$\gamma_R = \frac{J_2}{J_3} = \frac{\left(n_{iB}^2 / N_{AB}\right)\left(D_n / W_B\right)}{\left(n_{iC}^2 / N_{DC}\right)\left(D_p / W_C\right)}$$

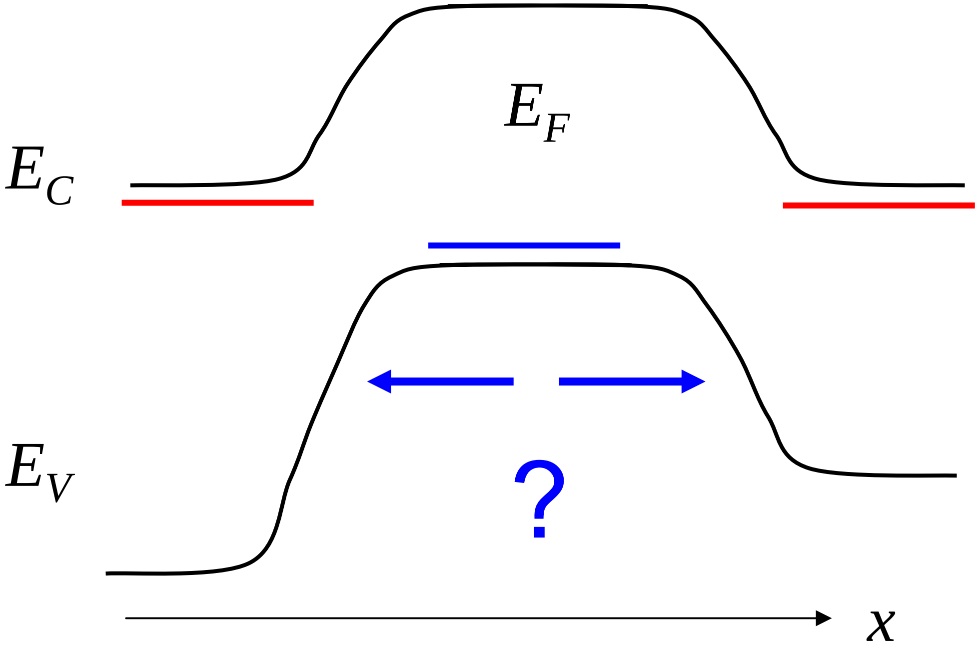
(reverse emitter injection efficiency)

Want a large γ_R. Wide bandgap collector helps.

Exercise: show how V_{OS} depends on ΔE_C and junction area differences.

offset voltage reason





outline

I) Introduction

II) BJT Review

III) The Widegap Emitter

IV) Modern HBTs

V) Summary

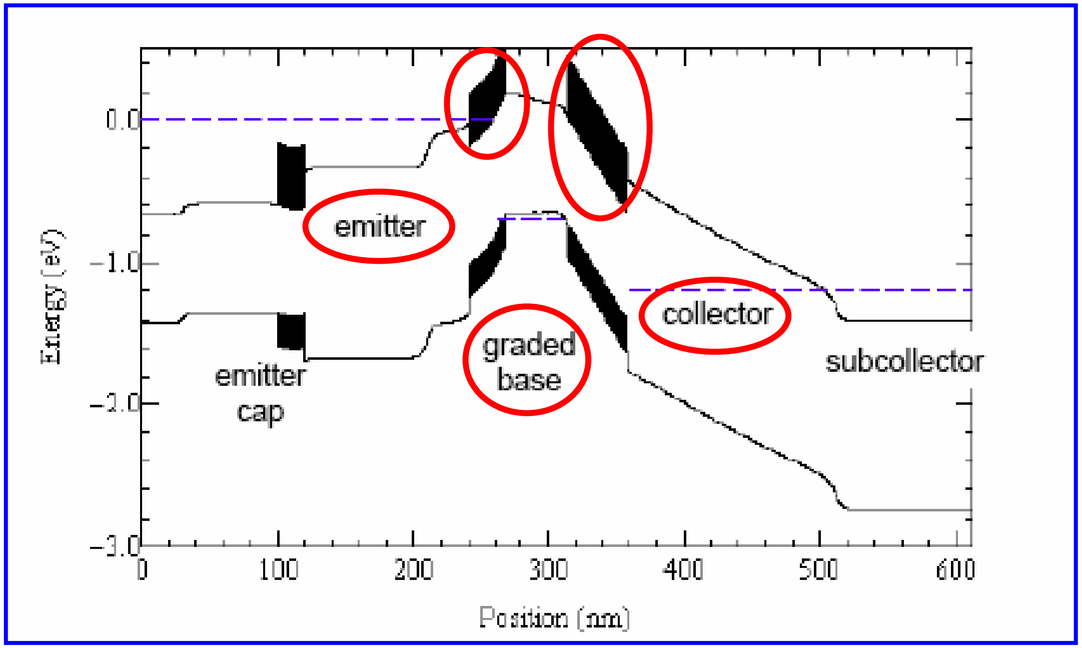
modern HBTs

The following slides are courtesy of Professor Mark Rodwell, UCSB

epitaxial layer design

DHBT: Graded InAlAs emitter and InGaAs base

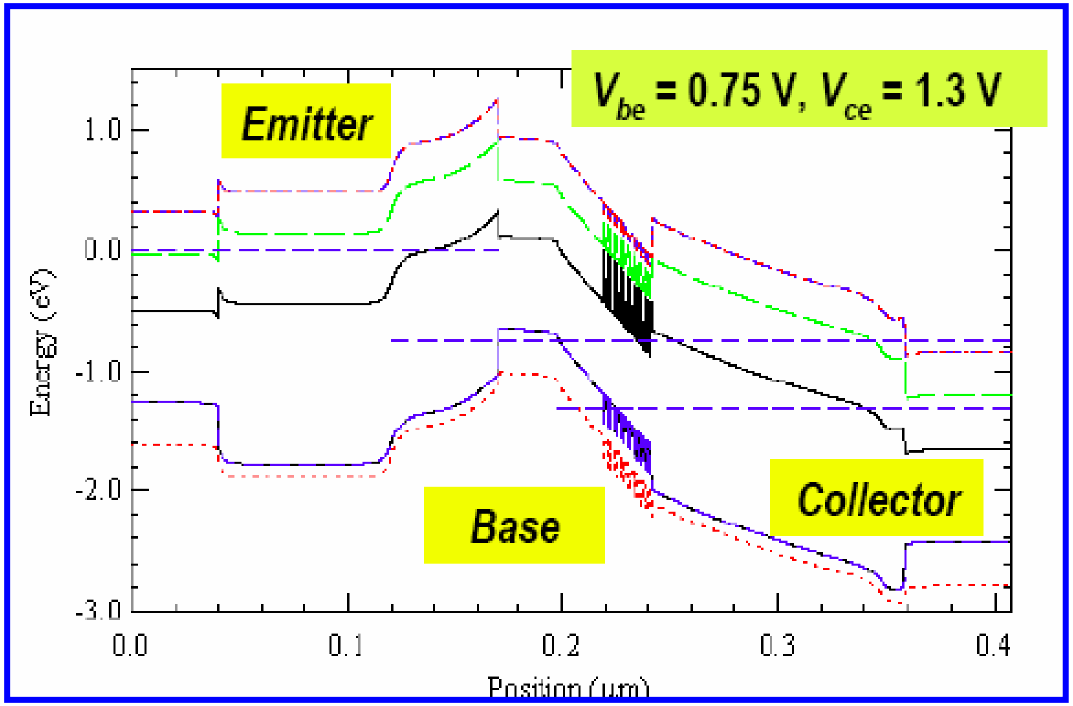
InAlAs emitter
InAlAs/InGaAs CSL grade
bandgap-graded InGaAs base
InAlAs/InGaAs CSL grade
InP collector



epitaxial layer design (ii)

DHBT: Abrupt InP emitter, InGaAs base, InAlGaAs C/B grades

InGaAs 3E19 Si 400 Å
InP 3E19 Si 800 Å
InP 8E17 Si 100 Å
InP 3E17 Si 300 Å
InGaAs 8E19 → 5E19 C 300 Å
Setback 3E16 Si 200 Å
Grade 3E16 Si 240 Å
InP 3E18 Si 30 Å
InP 3E16 Si **1030** Å
InP 1.5E19 Si 500 Å
InGaAs 2E19 Si **125** Å
InP 3E19 Si **3000** Å
SI-InP substrate

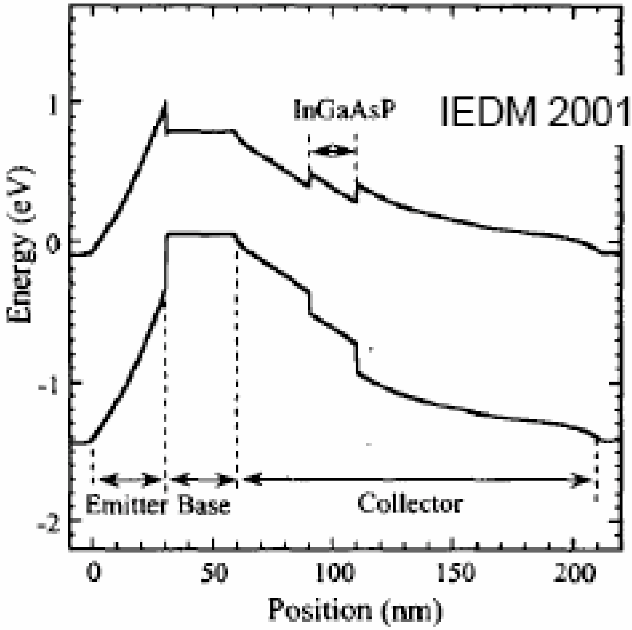


epitaxial layer design (iii)

InGaAs/InGaAsP/InP grade

InP/InGaAs DHBTs with 341-GHz f_T at high current density of over 800 kA/cm^2

Minoru Ida, Kenji Kurishima, Noriyuki Watanabe, and Takatomo Enoki



IEDM 2001

-suitable for MOCVD growth
- excellent results

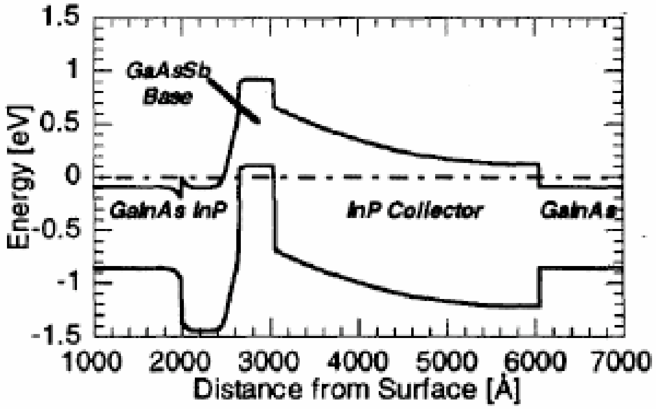
InP/GaAsSb/InP DHBT

11th International Conference on Indium Phosphide and Related Materials
16-20 May 1999 Davos, Switzerland

TuA1-3

InP/GaAsSb/InP DOUBLE HETEROJUNCTION BIPOLAR TRANSISTORS WITH HIGH CUT-OFF FREQUENCIES AND BREAKDOWN VOLTAGES

N. Matine, M. W. Dvorak, X. G. Xu, S. P. Watkins, and C. R. Bolognesi



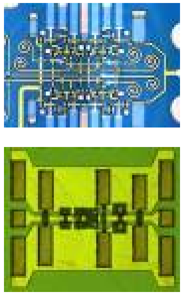
- does not need B/C grading
- E/B band alignment through
  GaAsSb alloy ratio (strain)
  or InAlAs emitter
- somewhat poorer transport parameters
  to date for GaAsSb base

performance

Device Performance:~ 400 GHz f_τ and ~500 GHz f_{max}

Has enabled 150 GHz digital clock rate (static dividers)

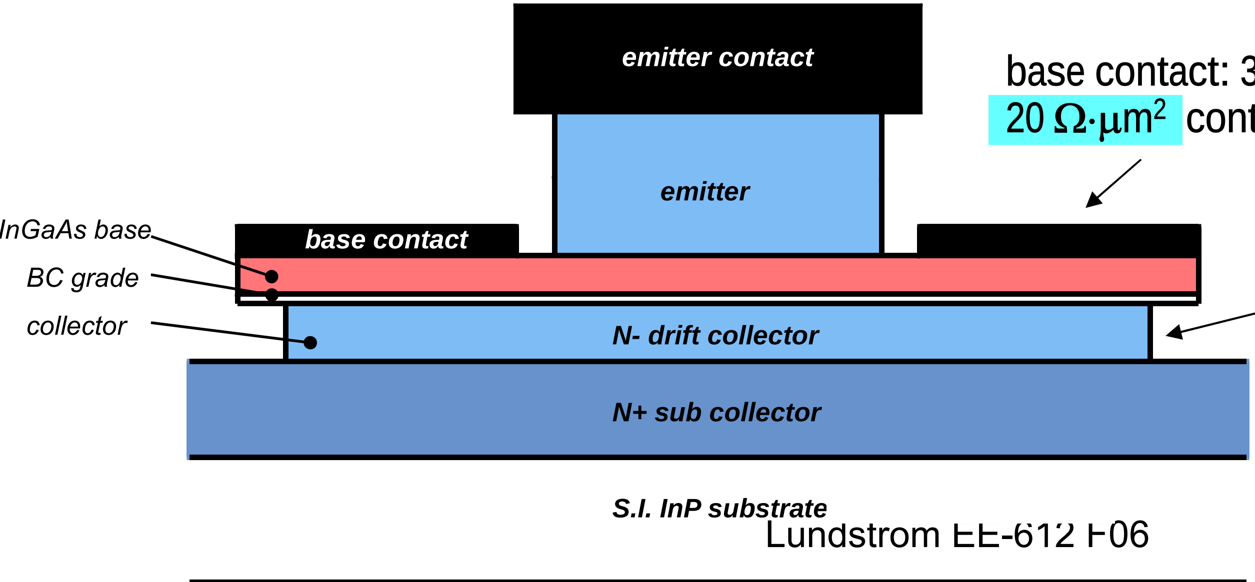
Should enable 300 GHz power amplifiers (175 GHz realized with 300 GHz fmax)



emitter: 500 nm width, $15\ \Omega\cdot\mu m^2$ contact resistivity

base contact: 300 nm width,
$20\ \Omega\cdot\mu m^2$ contact resistivity

collector: 150 nm thick,
5.1 V breakdown (BVCEO)
$5\ mA/\mu m^2$ current density
$10\ mW/\mu m^2$ power density @ 2V
$15\ K/(mW/\mu m^2)$ thermal resistance



modern HBTs

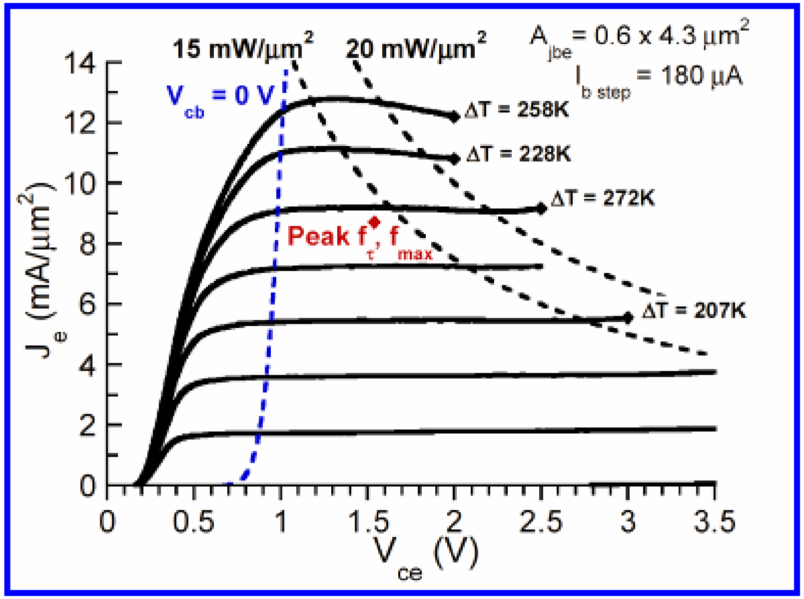
Key scaling challenges:

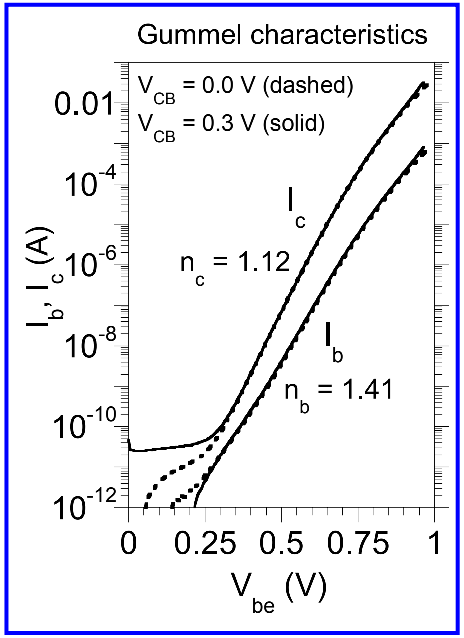
- *emitter & base contact resistivity*
- *current density→ device heating*
- *collector-base junction width scaling*

& Yield !

InP DHBT results

InP DHBT: 600 nm lithog., 120 nm thick coll., 30 nm thick base





$\beta \approx 40$, $V_{BR,CEO} = 3.9$ V.

Emitter contact Rcont < 10 Ω×μm²

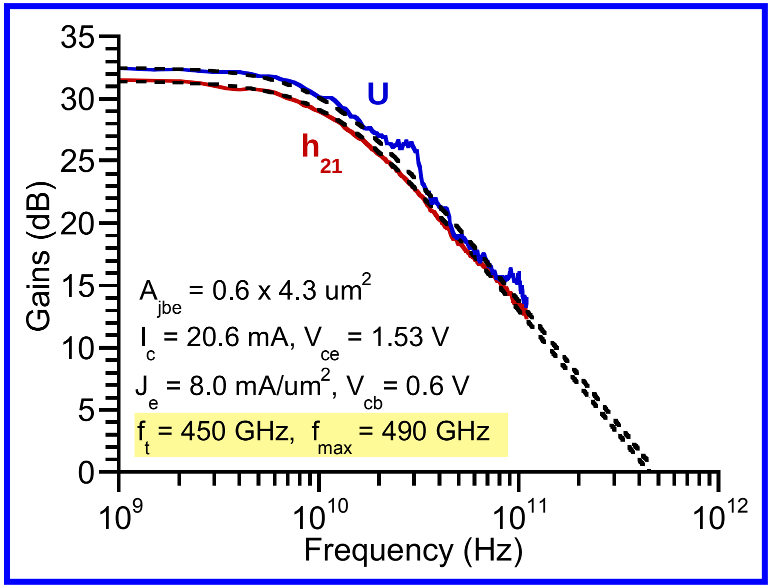
Base : Rsheet = 610 W/sq, Rcont = 4.6 Ω×μm²

Collector : R_{sheet} = 12.1 Ω/sq, Rcont = 8.4 Ω×μm²

Courtesy Mark Rodwell, UCSB

high-frequentcy performance

InP DHBT: 600 nm lithog., 120 nm thick coll., 30 nm thick base



Courtesy Mark Rodwell, UCSB

outline

I) Introduction

II) BJT Review

III) The Widegap Emitter

IV) Modern HBTs

V) Summary

summary

1) The use of a wide bandgap emitter has two benefits:

  - -allows heavy base doping
  - -allows moderate emitter doping

2) The use of a wide bandgap collector has benefits:

  - -symmetrical device
  - -reduced charge storage in saturation
  - -reduced collector offset voltage
  - -higher collector breakdown voltage

3) Bandgap engineering has potential benefits:

  - -heterojunction launching ramps
  - -compositionally graded bases
  - -elimination of band spikes

4) HBTs have the potential for THz cutoff frequencies

References

The idea of the wide bandgap emitter dates to the 1950's, but the modern story begins with:

Herbert Kroemer, "Heterostructure bipolar transistors and integrated circuits," Proc. *IEEE ,* **70**, pp. 13-25, 1982.

For an update on current practice, see:

Mark J. Rodwell, et al., "Submicron Scaling of HBTs," *IEEE Trans. Electron. Dev.* **48**, pp. 2606-2624, 2001.