

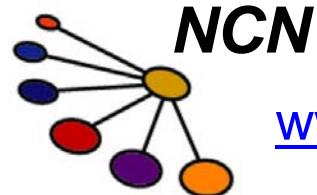
EE-612:

Lecture 27:

Heterojunction

Bipolar Transistors

Mark Lundstrom
Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA
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www.nanohub.org

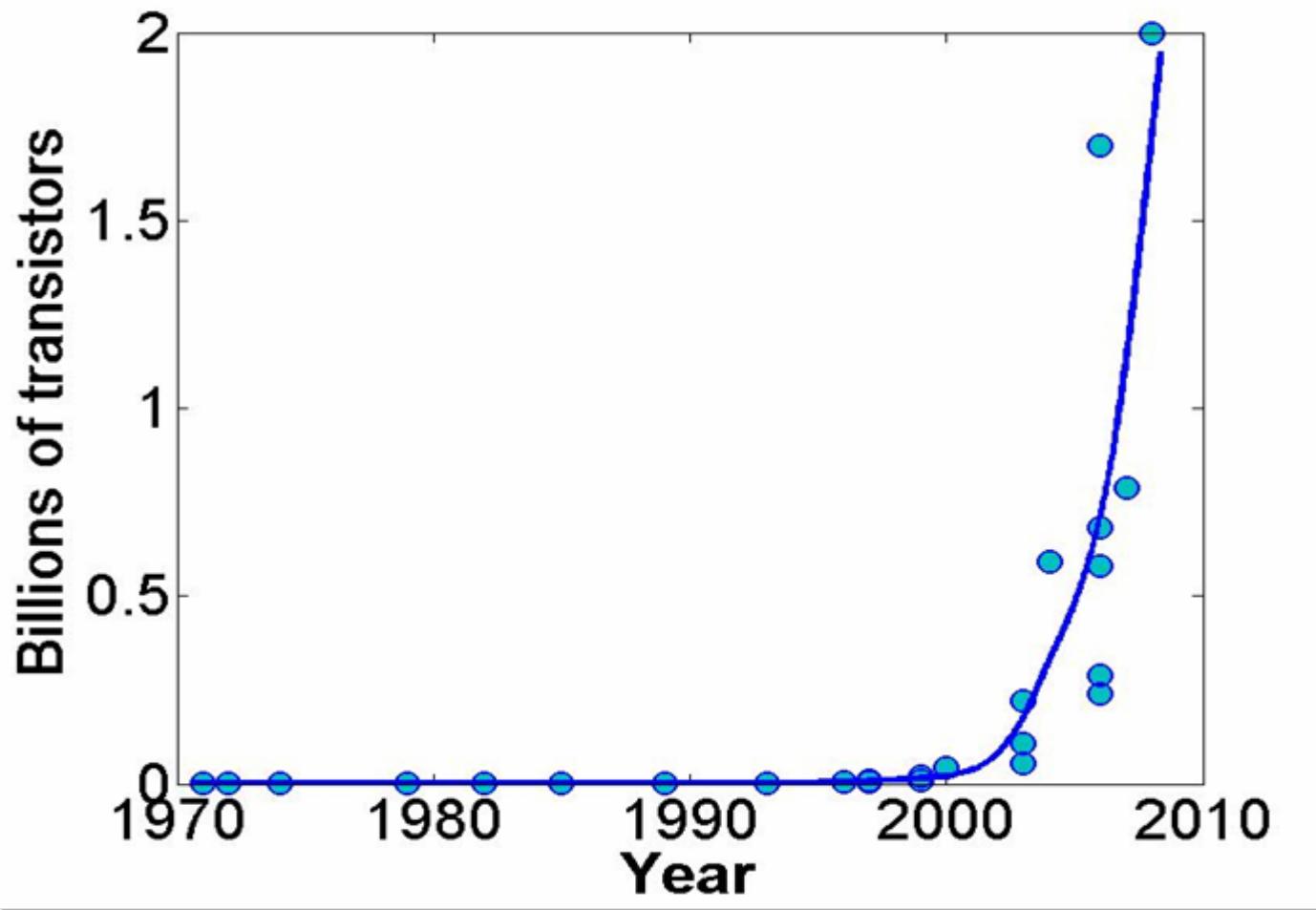
Lundstrom EE-612 F08

PURDUE
UNIVERSITY

in the news this morning

Intel Unveils 32-Nanometer Chip. The Oregonian (12/10, Rogoway) reported on Intel's unveiling of its "new 32-nanometer chip," which "will have more computing power and better energy management than Intel's current 45-nanometer chips, extending the battery life of laptop computers and handheld devices." And, "importantly for Intel, smaller chips cost less to make, meaning the company's profits margins will improve along with its technology." The company's "latest chip technology was largely created at [its] Hillsboro research factory, known as D1D, where about 600 engineers worked to build the chip on a scale many times narrower than a human hair." Meanwhile, "other companies are also hard at work on their own 32-nanometer chips." AMD "plans to have its version out sometime in 2010. AMD and IBM have developed early versions of even smaller chips, but Intel has historically led the way in bringing new chips to market."

Moore's Law



EE-612 all(?) about transistors

MOSFET	HFET	GBT
MOST	DHFET	RHET
IGFET	HIGFET	QWBRTT
DMOS	SISFET	TETRAN
HEXFET	PBT	SIT
VMOS	LRTFET	NWFET
TFT	VMT	CNT FET
MISFET	BJT	SB FET
JFET	HBT	BTBT FET
VFET	DGBT	induced base transistor
MESFET	THETA	planar doped barrier transistor
MOSFET	RST	metal base transistor
HEMT	BICFET	Stark-effect transistor
TEGFET	RTBT	delta-doped channel heterojunction FET

Kwok K. Ng, "A Survey of Semiconductor Devices," *IEEE Trans. Electron. Dev.* **43**, pp. 1760-1766, 1996.

outline

I) Introduction

II) PN junctions and heterojunctions

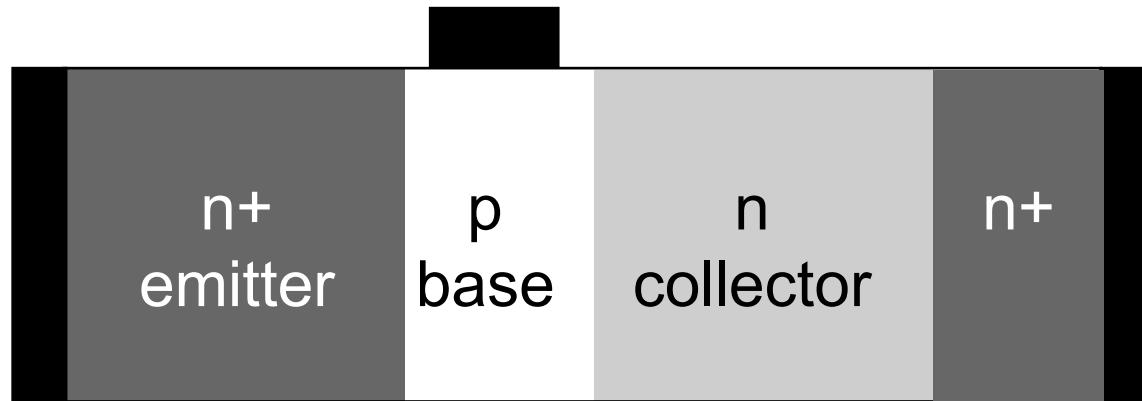
III) BJT review

IV) The widegap Emitter BJT

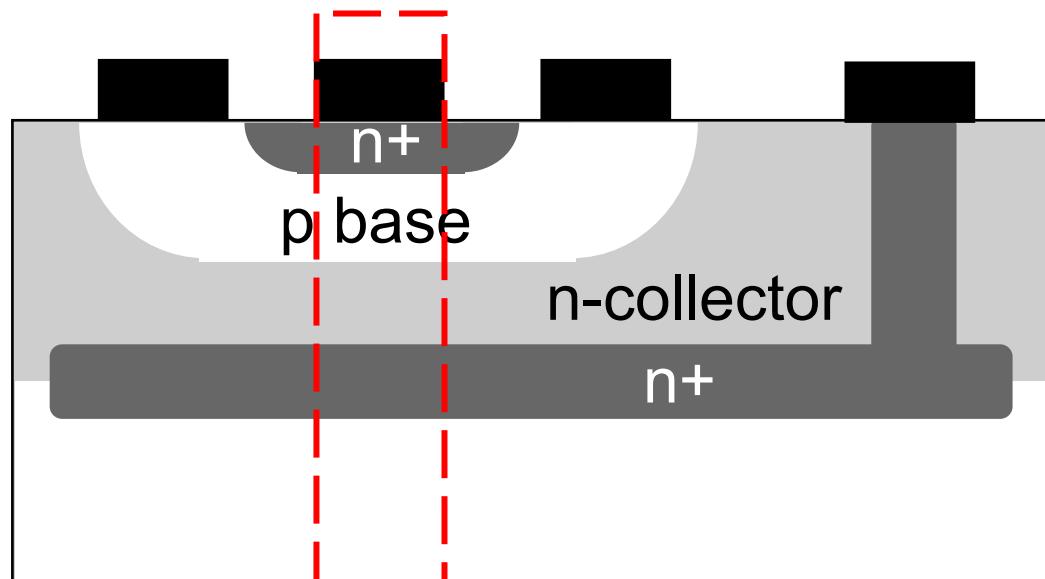
V) Modern HBTs

VI) Summary

bipolar transistors



*double
diffused
BJT*

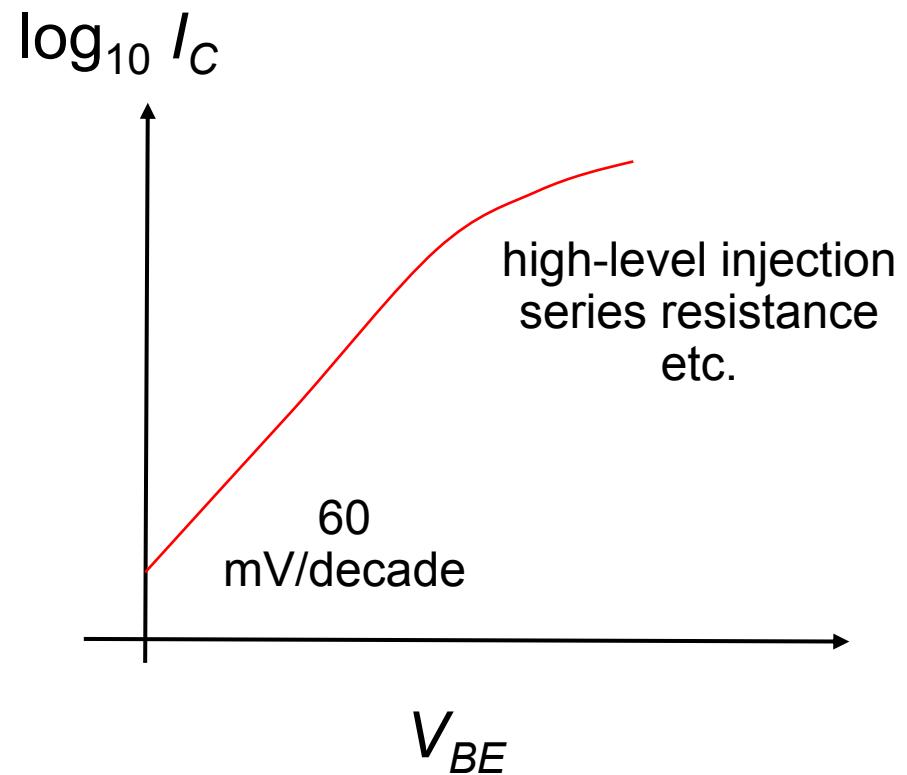
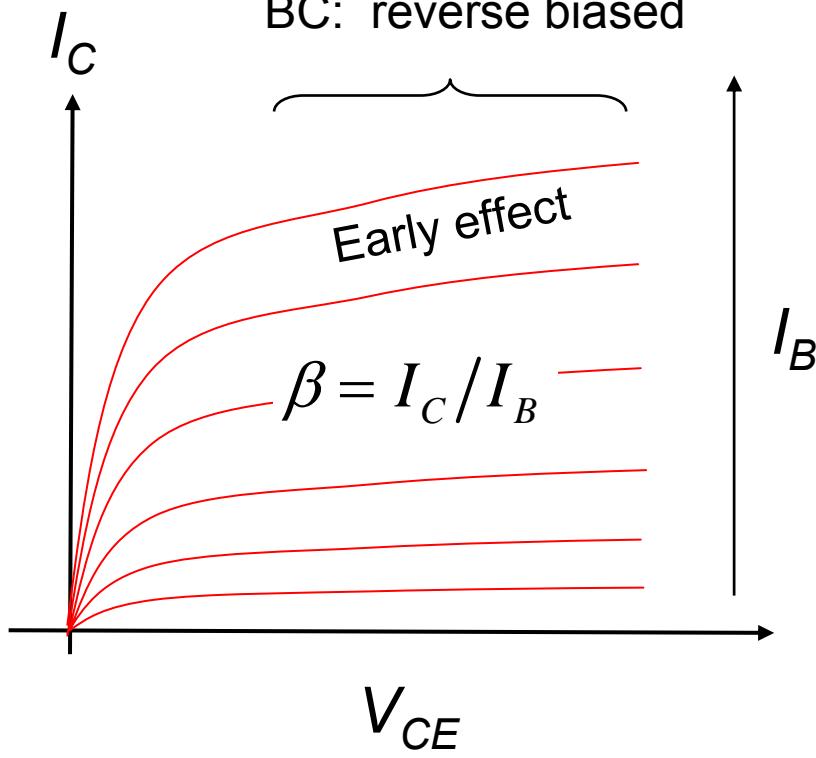


bipolar transistors: I-V

normal, active region

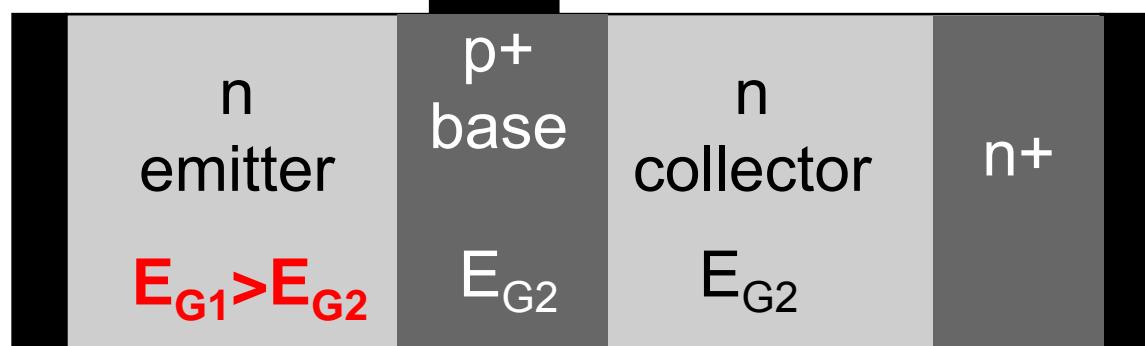
EB: forward biased

BC: reverse biased

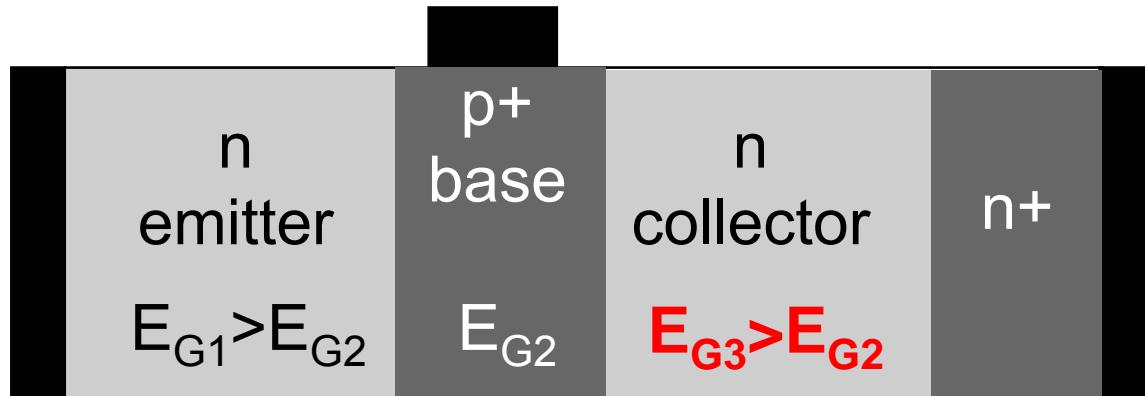


heterojunction bipolar transistors

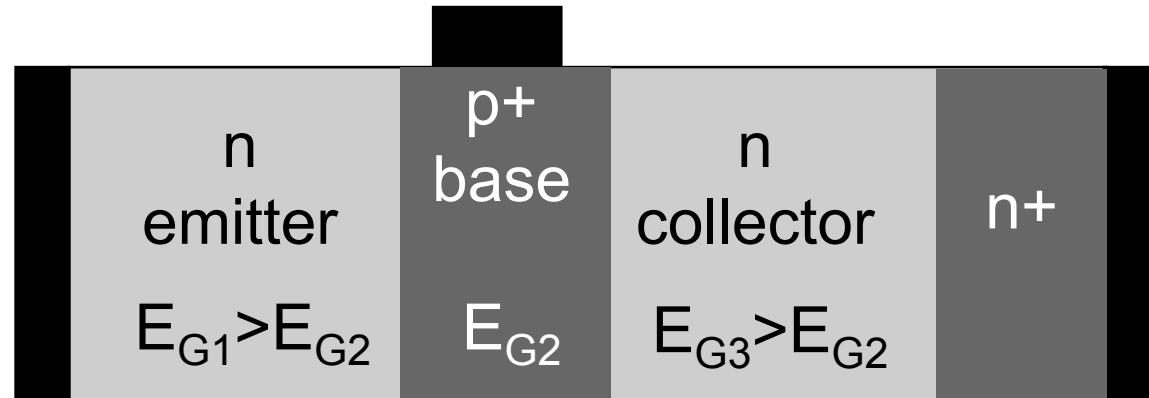
i) wide gap emitter HBT



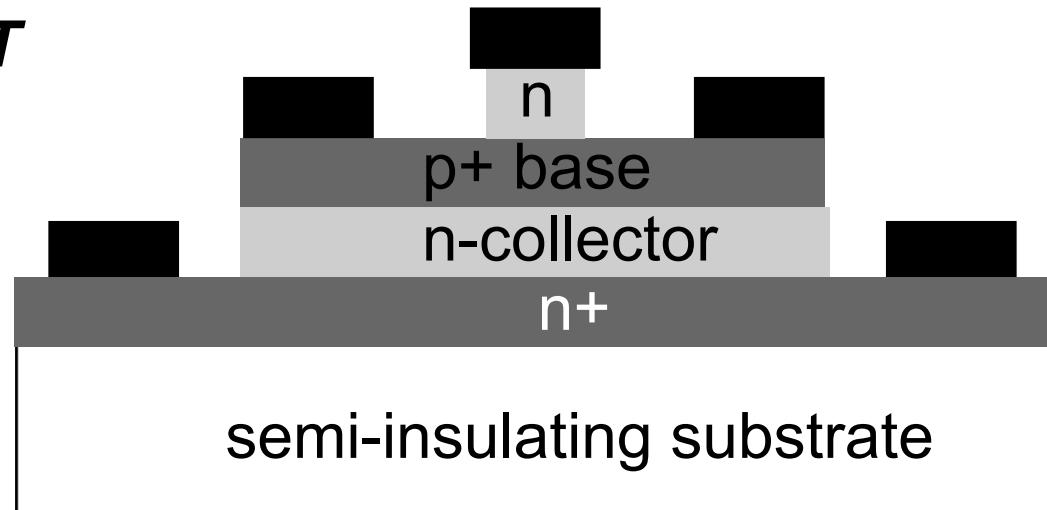
ii) double heterojunction bipolar transistor



mesa HBTs



mesa HBT



HBTs

- 1) Why is a wide band emitter useful?
- 2) What's useful about a double HBT?
- 3) What materials are used, what performance is possible, what are the applications, etc.

applications

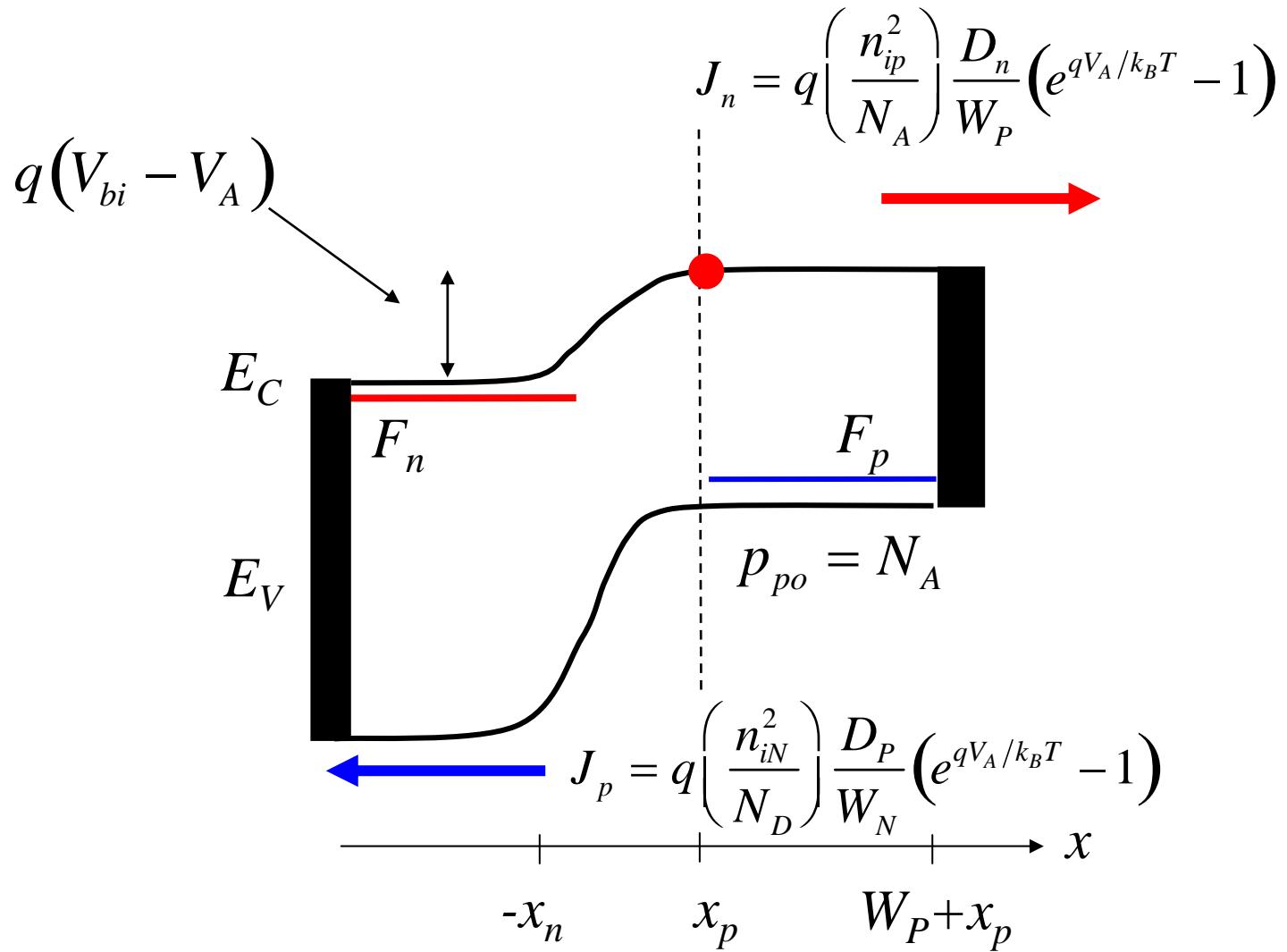
- 1) optical fiber communications**
-40Gb/s.....160Gb/s
- 2) Wideband, high-resolution DA/AD converters
and digital frequency synthesizers**
-military radar and communications
- 3) Monolithic, millimeter-wave IC's (MMIC's)**
-front ends for receivers and transmitters

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

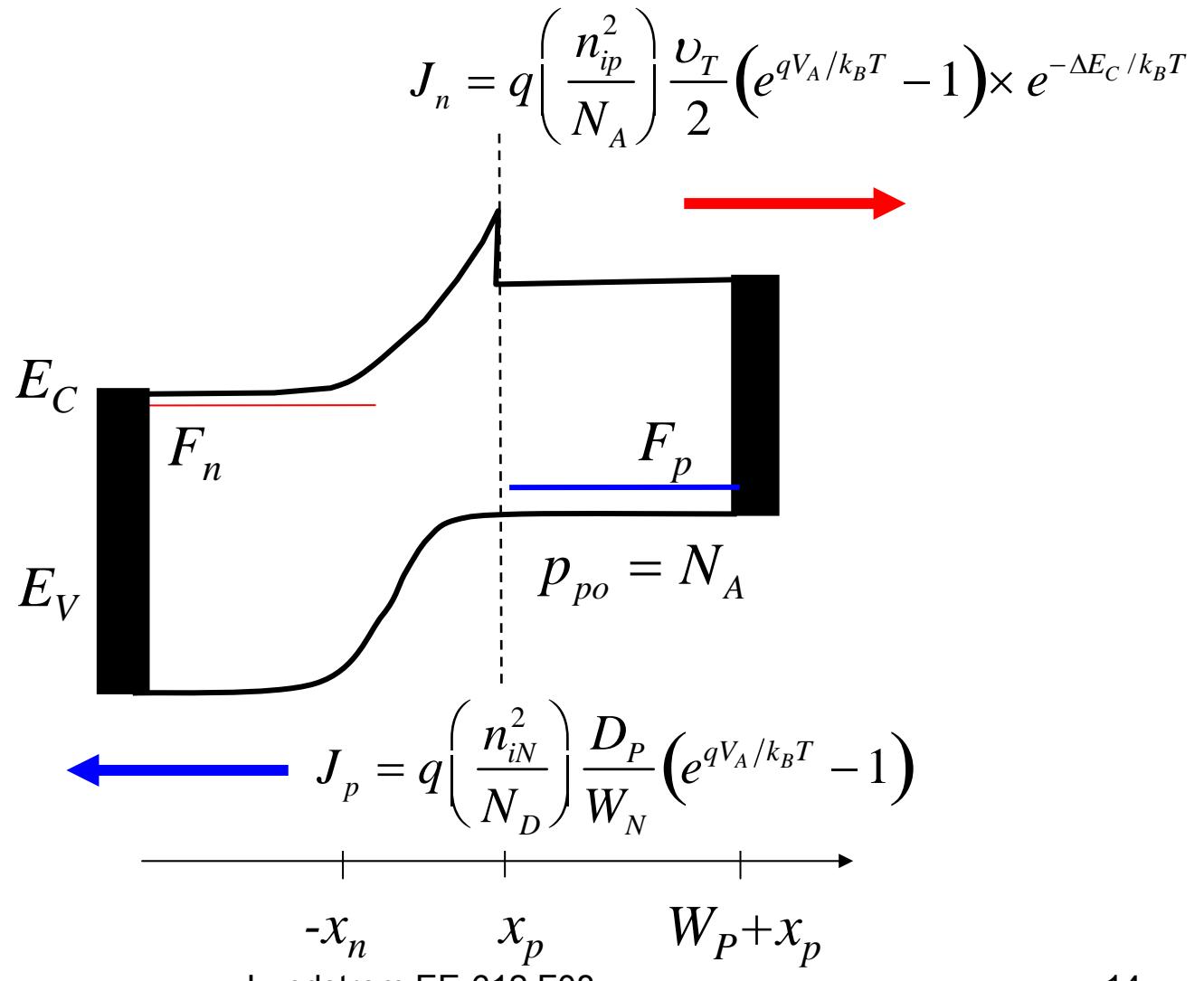
outline

- I) Introduction
- II) PN junctions and heterojunctions**
- III) BJT review
- IV) The widegap emitter BJT
- V) Modern HBTs
- VI) Summary

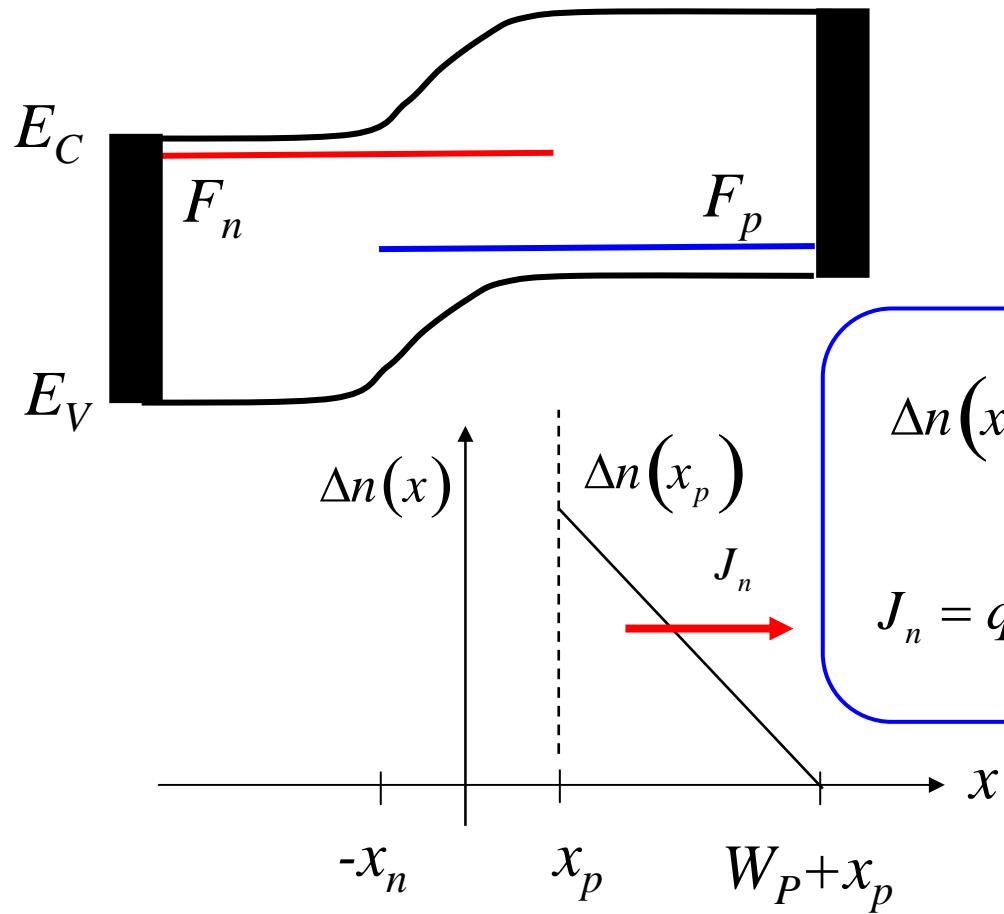
pn heterojunction with no band spike



pn heterojunction with CB band spike



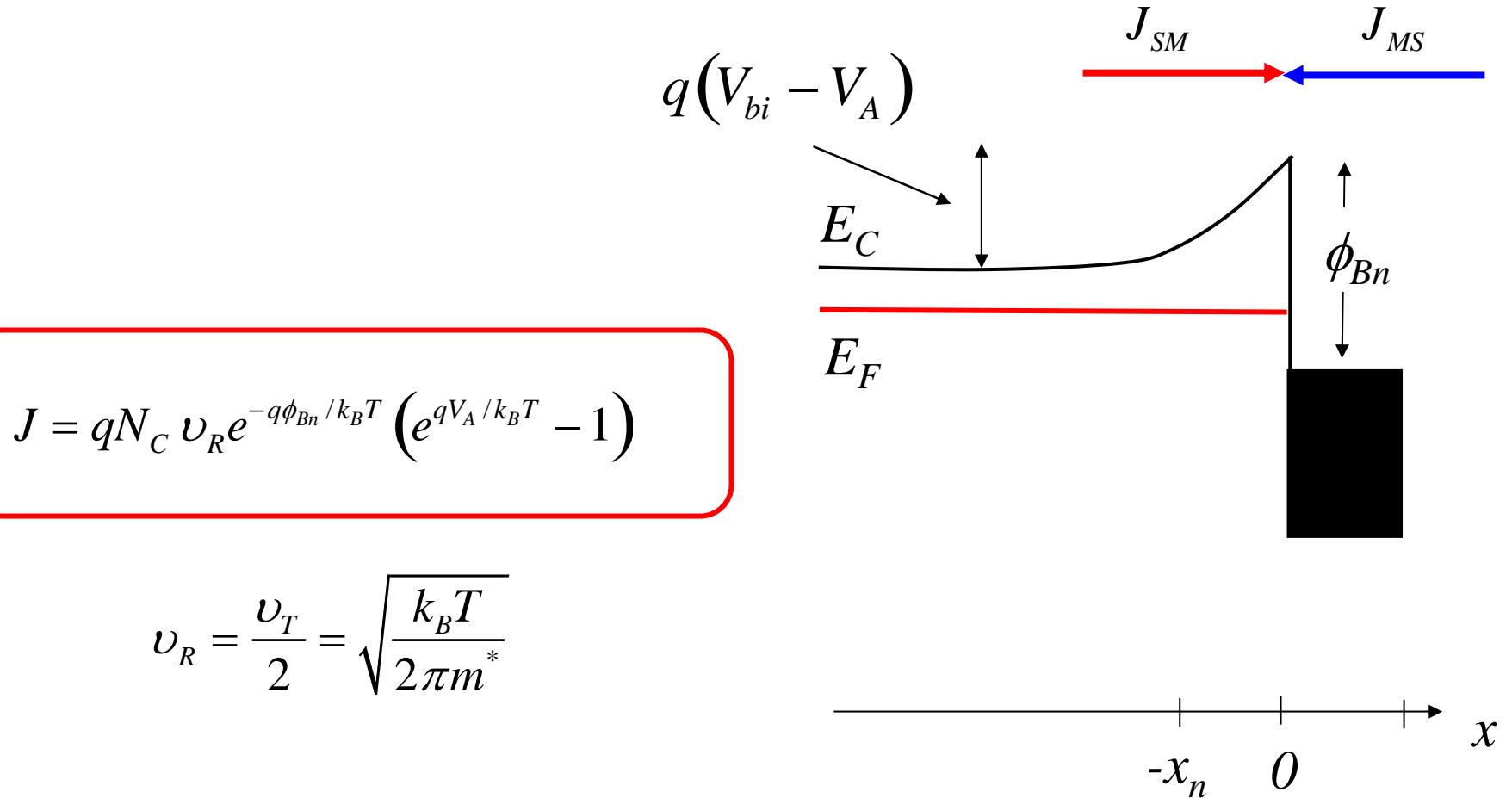
review: law of the junction



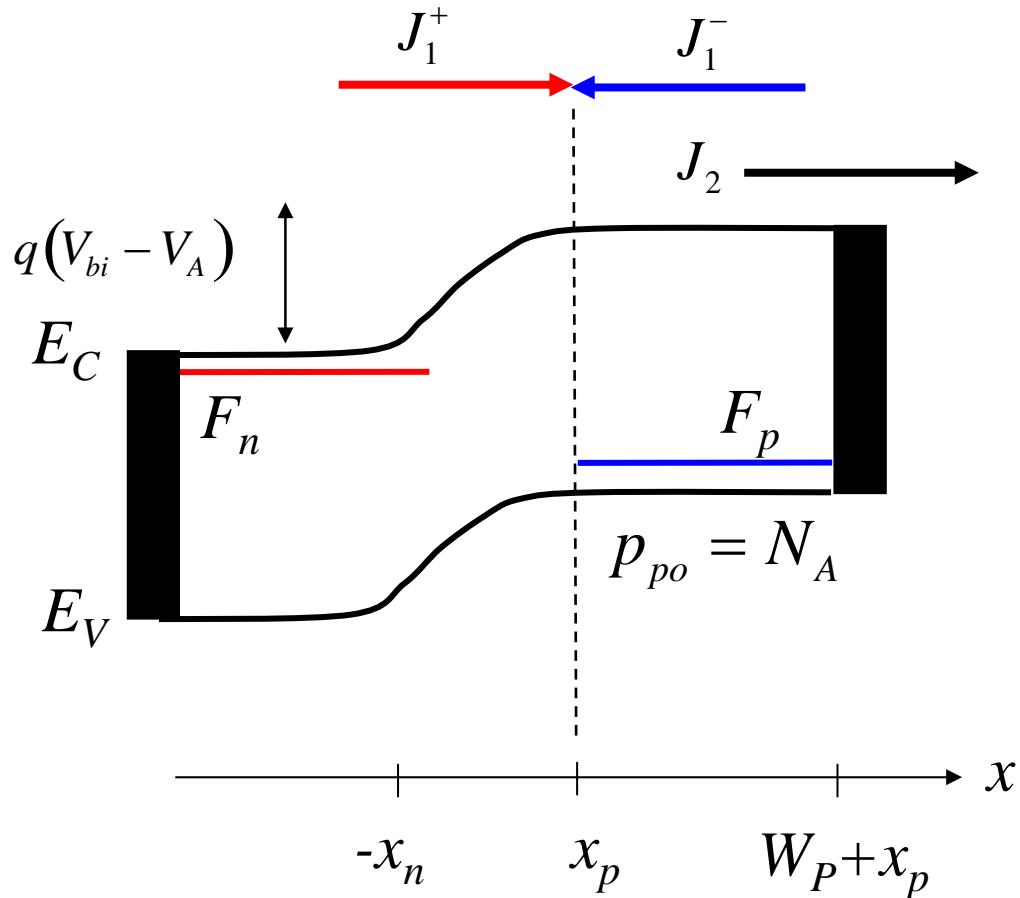
$$\Delta n(x_p) = \frac{n_i^2}{N_A} (e^{qV_A/k_B T} - 1)$$

$$J_n = qD_n \frac{\Delta n(x_p)}{W_p} = q \frac{n_i^2}{N_A} \frac{D_n}{W_p} (e^{qV_A/k_B T} - 1)$$

review: MS junction



generalized law of the junction (homojunctions)



$$J_1^+ = q \frac{N_D}{2} v_T e^{-q(V_{bi} - V_A)/k_B T}$$

$$J_1^- = q \frac{n(x_p)}{2} v_T$$

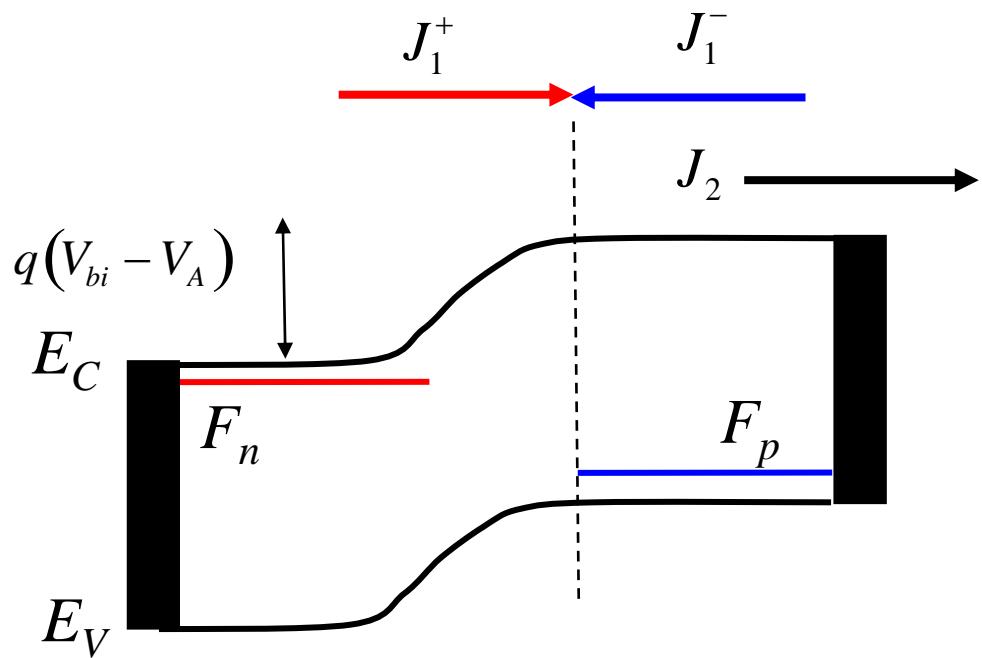
$$J_2 = q D_n \frac{\Delta n(x_p)}{W_P} = q \Delta n(x_p) v_{Dp}$$

$$v_{Dp} = \frac{D_n}{W_P}$$

$$J_n = J_1^+ - J_1^- = J_2$$

“current balancing”

generalized law the pn homojunction



$$\Delta n(x_p) = \left[\frac{1}{1 + v_{Dp}/v_R} \right] \left(\frac{n_i^2}{N_A} \right) \left(e^{qV_A/k_B T} - 1 \right)$$

$$v_{Dp} \ll v_R$$

$$\Delta n(x_p) = \left(\frac{n_i^2}{N_A} \right) \left(e^{qV_A/k_B T} - 1 \right)$$

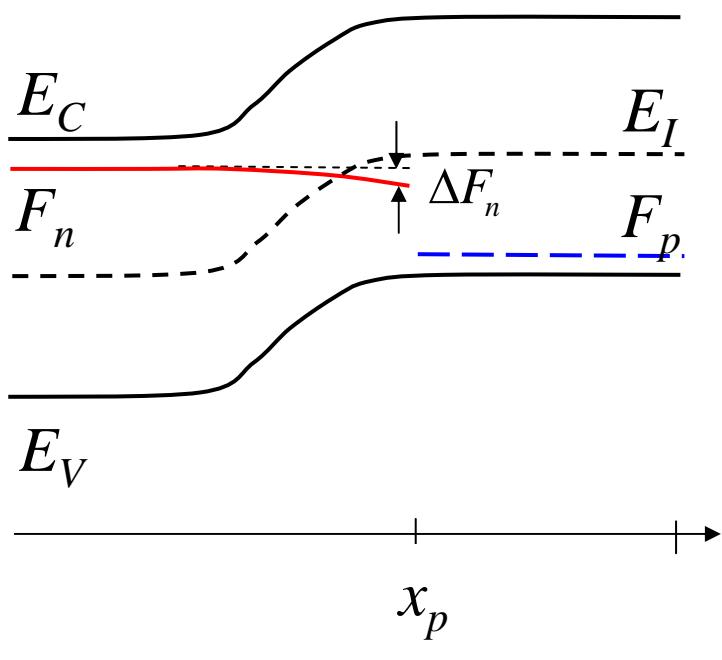
(base diffusion limited)

$$v_{Dp} \gg v_R$$

$$\Delta n(x_p) = \left(\frac{n_i^2}{N_A} \right) \frac{v_R}{v_{Dp}} \left(e^{qV_A/k_B T} - 1 \right)$$

(emission limited)

Fermi level “droop”



$$N_D = n_i e^{(F_n(-\infty) - E_i(-\infty))/k_B T}$$

$$n(x_p) = n_i e^{(F_n(x_p) - E_i(x_p))/k_B T}$$

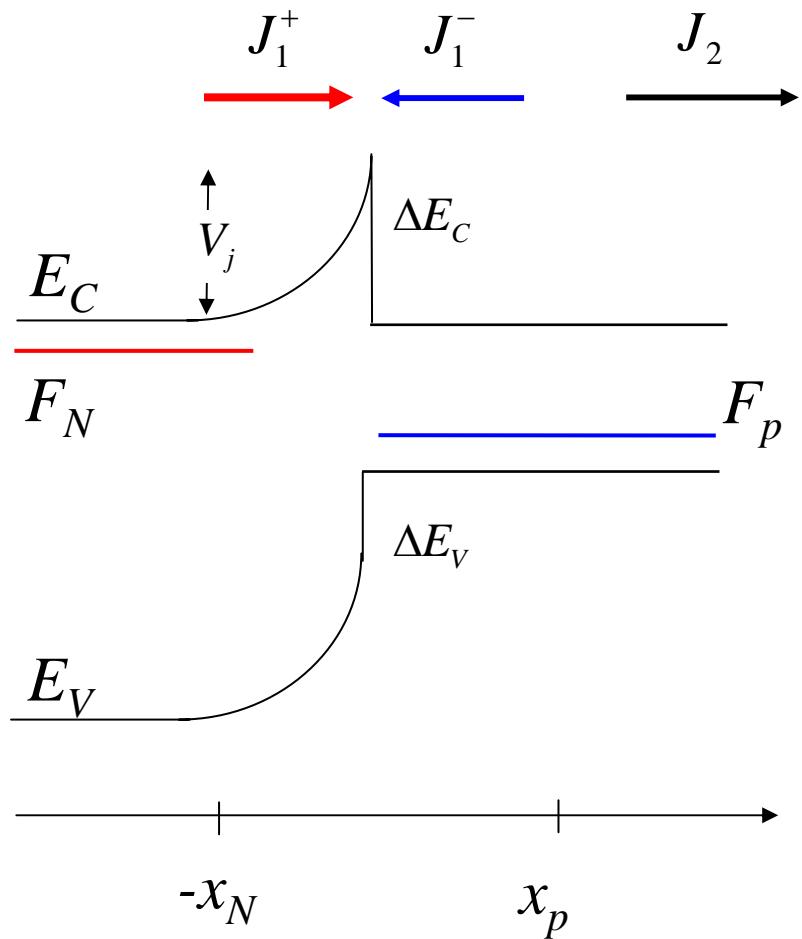
$$\Delta F_n = F_n(-\infty) - F_n(x_p)$$

$$\boxed{\Delta F_n = k_B T \ln(1 + v_{Dp}/v_R)}$$

if $v_{Dp} \ll v_R$

$$\Delta F_n \approx 0$$

heterojunctions



$$J_1^+ = q \frac{N_D}{2} v_{TN} e^{-qV_j/k_B T}$$

$$J_1^- = q \frac{n(x_p)}{2} v_{Tp} e^{-\Delta E_C / k_B T}$$

$$J_2 = q D_n \frac{\Delta n(x_p)}{W_P} = q \Delta n(x_p) v_{Dp}$$

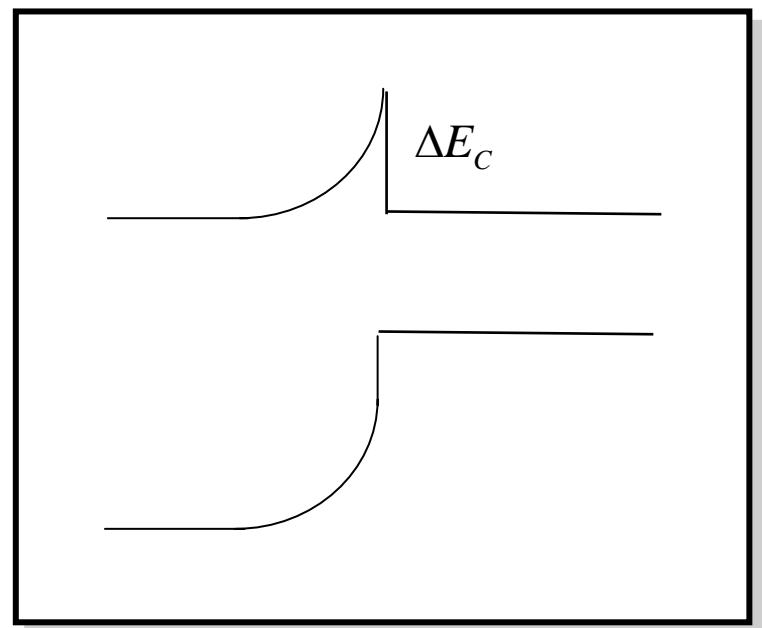
$$J_n = J_1^+ - J_1^- = J_2$$

generalized law for heterojunctions

$$\Delta n(x_p) = \frac{1}{\left[1 + v_{Dp}/v_{ems}\right]} \frac{n_{ip}^2}{N_A} \left(e^{qV_A/k_B T} - 1\right)$$

$$v_{ems} = \frac{v_T}{2} e^{-\Delta E_C / k_B T} \quad v_{Dp} = \frac{D_n}{W_P}$$

$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \frac{1}{\left[1/v_{Dp} + 1/v_{ems} \right]} \left(e^{qV_A/k_B T} - 1 \right)$$



generalized law for heterojunctions (ii)

$$J_n = q \left(\frac{n_{ip}^2}{N_A} \right) \frac{1}{\left[1/v_{Dp} + 1/v_{ems} \right]} \left(e^{qV_A/k_B T} - 1 \right)$$

$$v_{Dp} = \frac{D_n}{W_p} \quad v_{ems} = v_{Rp} e^{-\Delta E_C / k_B T} = \frac{v_T}{2} e^{-\Delta E_C / k_B T}$$

$$\Delta E_C \ll k_B T$$

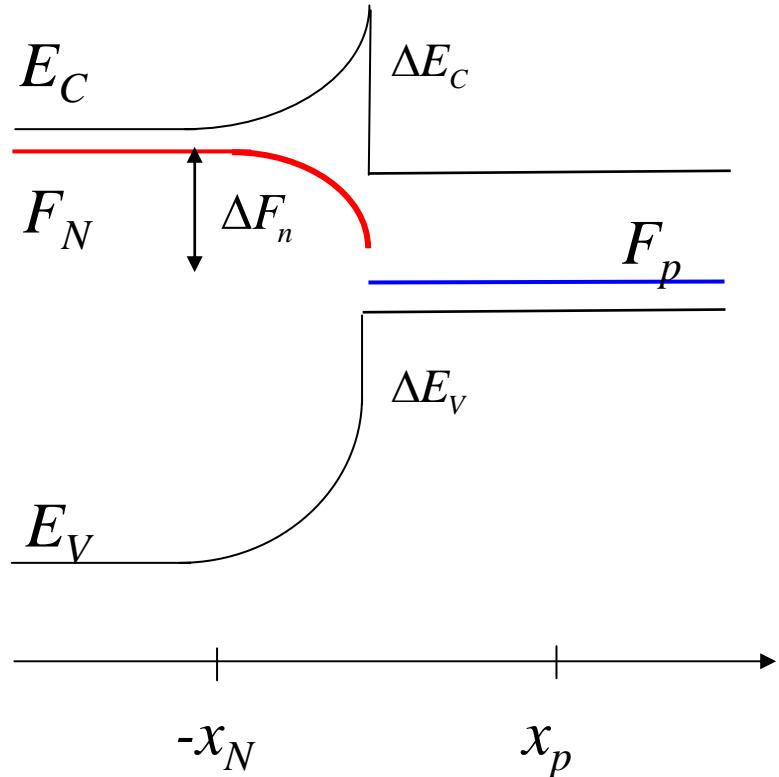
$$\Delta E_C \gg k_B T$$

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

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

band spikes suppress current

Fermi level droop



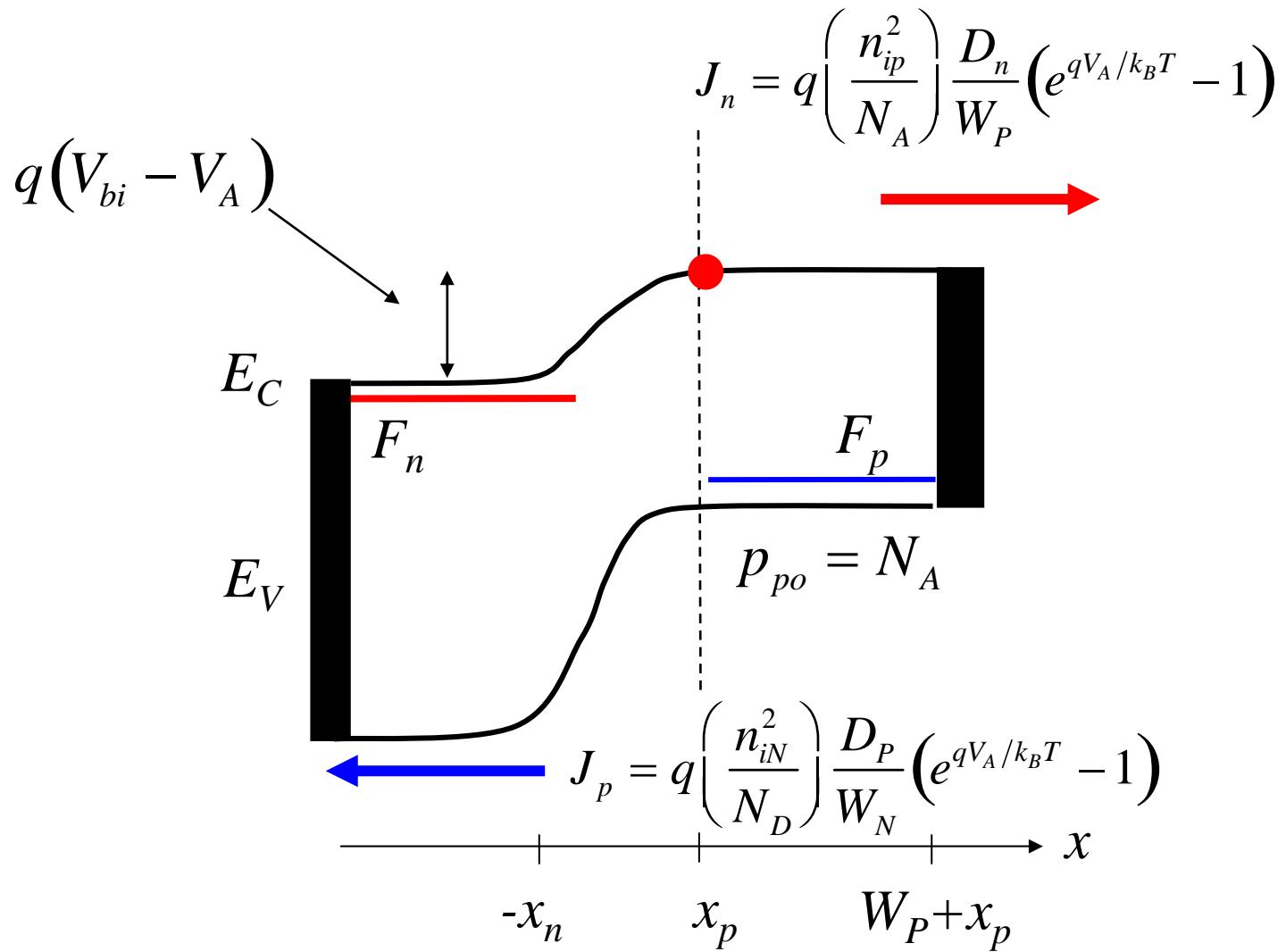
$$\Delta F_n = k_B T \ln\left(1 + v_{Dp} / v_{ems}\right)$$

$$\Delta F_n = k_B T \ln\left[1 + \left(v_{Dp} / v_{Rp}\right) e^{\Delta E_C / k_B T}\right]$$

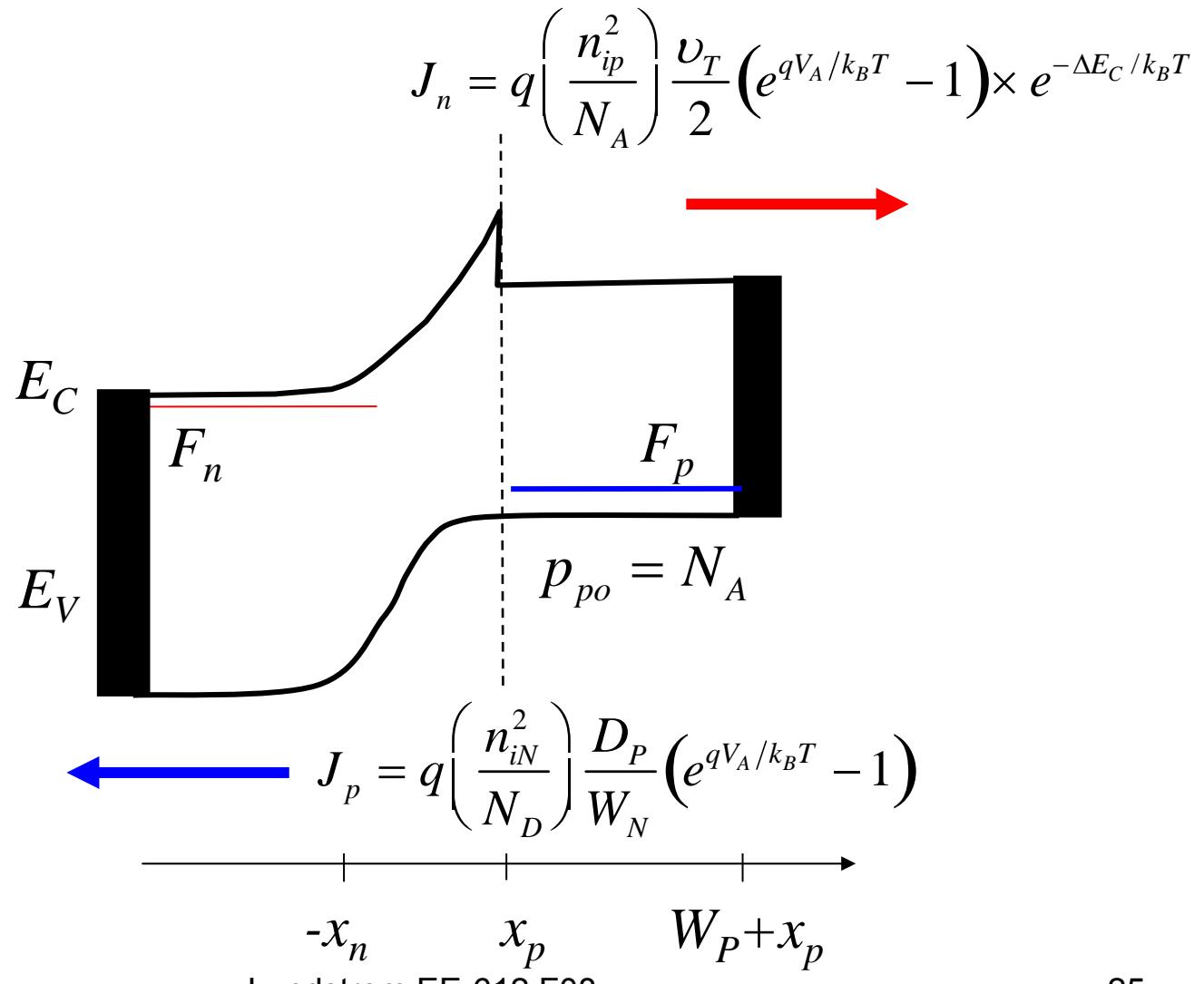
if $\Delta E_C \gg k_B T$

$$\Delta F_n \approx \Delta E_C$$

pn heterojunction with no band spike



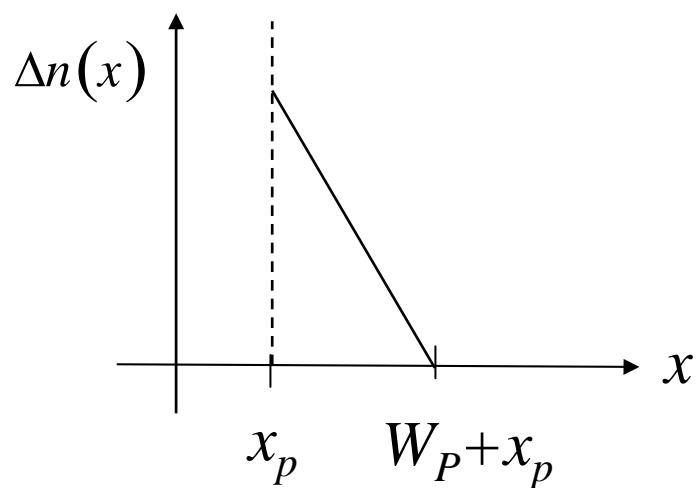
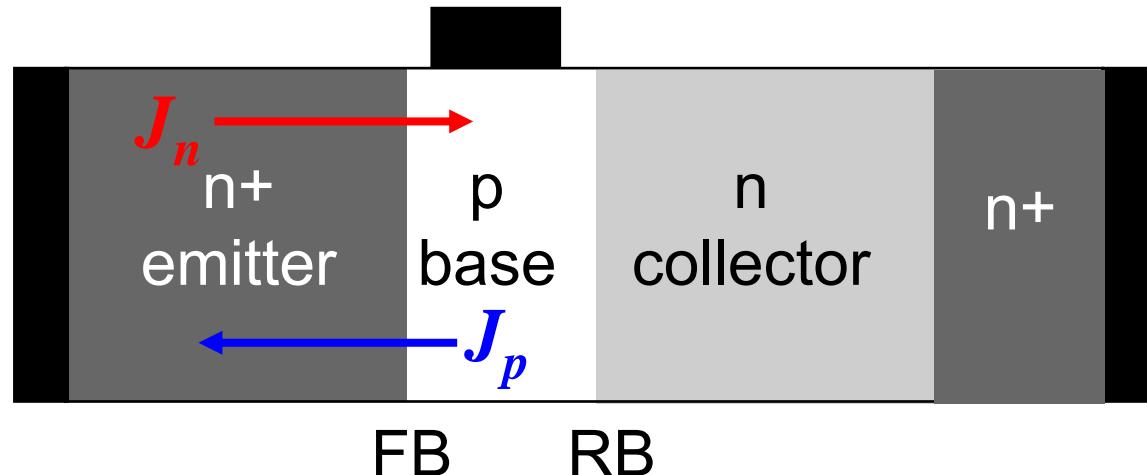
pn heterojunction with CB band spike



outline

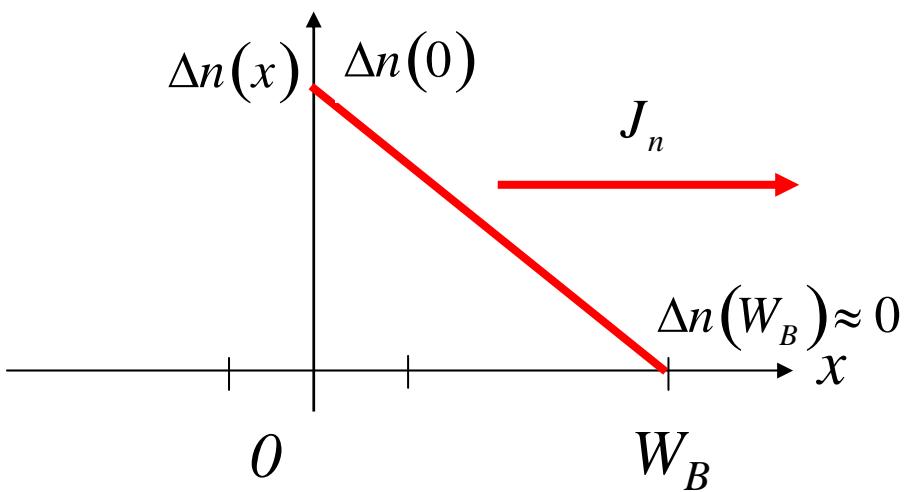
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minority carrier injection



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

base diffusion current

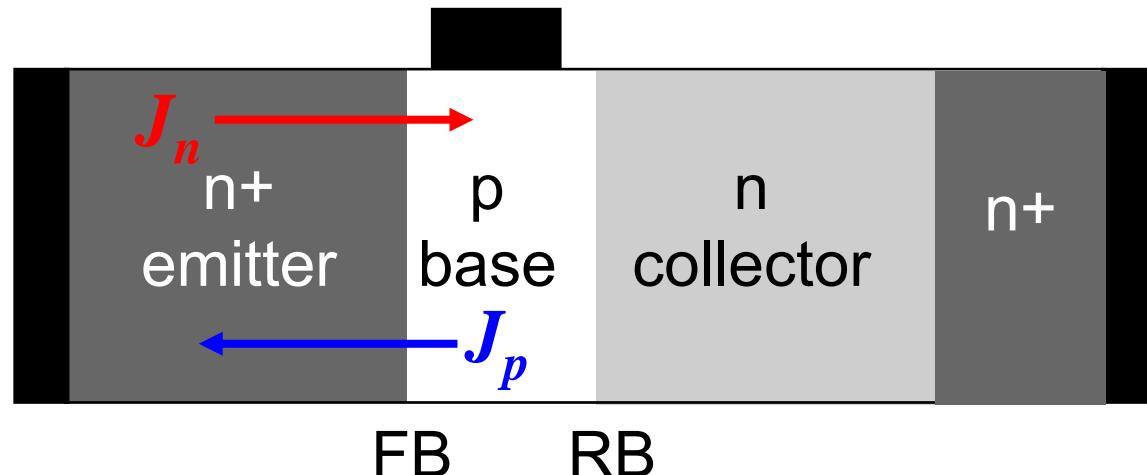


$$J_n = -qD_n \frac{dn(x)}{dx} = qD_n \frac{n(0)}{W_B}$$

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

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

beta

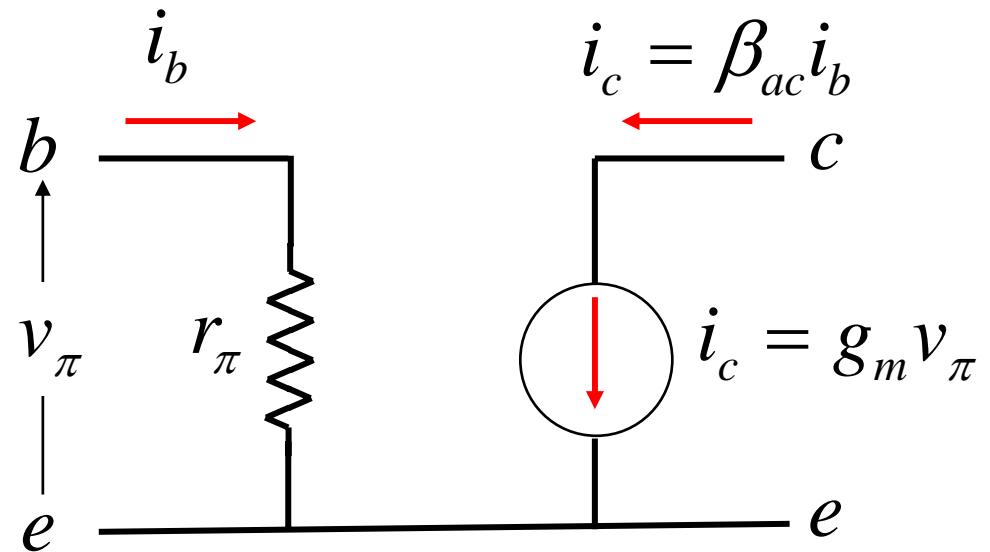
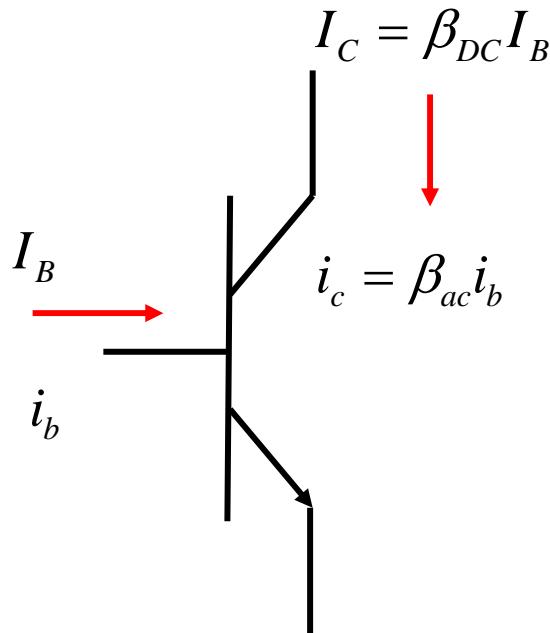


$$J_n = q \left(\frac{n_i^2}{N_{AB}} \right) \frac{D_n}{W_B} e^{qV_{BE}/k_B T}$$

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

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

ac model

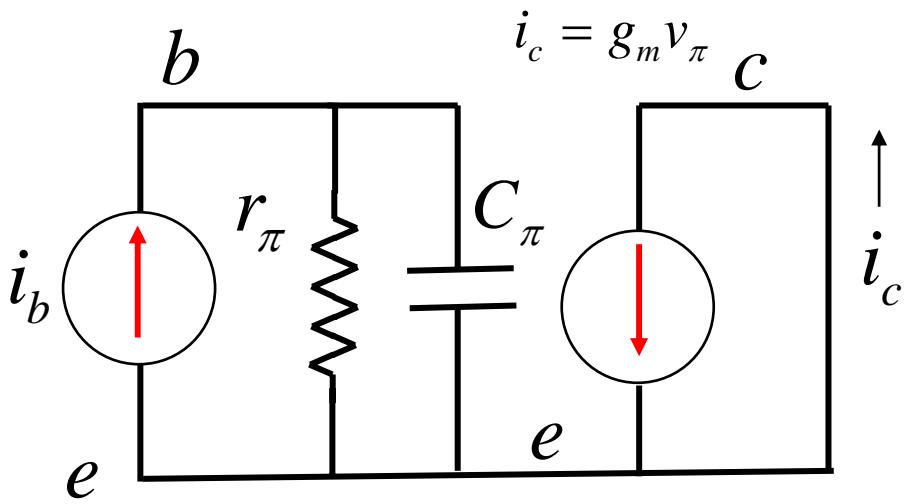


$$I_C = qA_E \left(\frac{n_i^2}{N_{AB}} \right) \frac{D_n}{W_B} e^{qV_{BE}/k_B T}$$

$$g_m = I_C / (k_B T / q)$$

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

freq. response



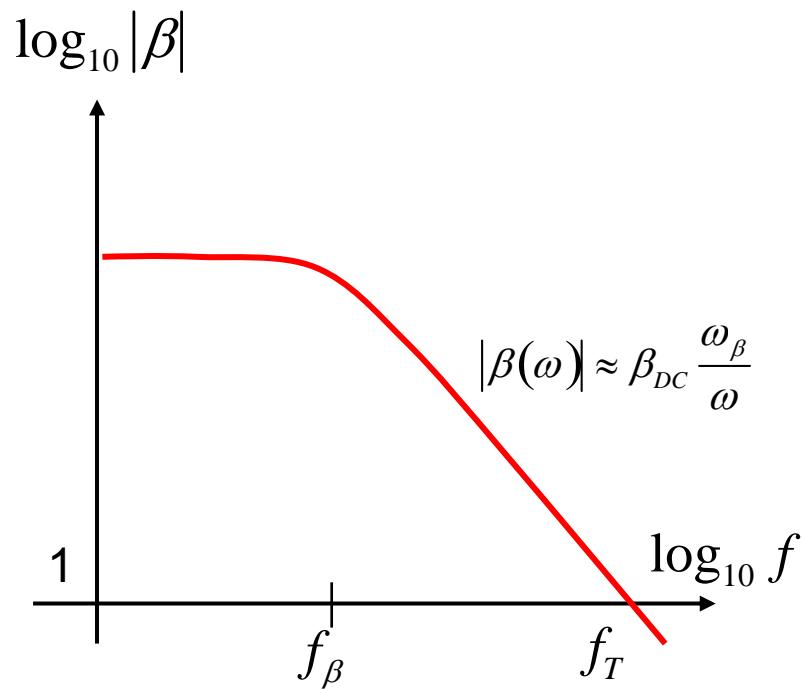
$$i_c = g_m v_\pi = g_m \frac{i_b}{1/r_\pi + j\omega C_\pi}$$

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

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

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

f_T



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

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

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

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

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

high frequency metrics

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

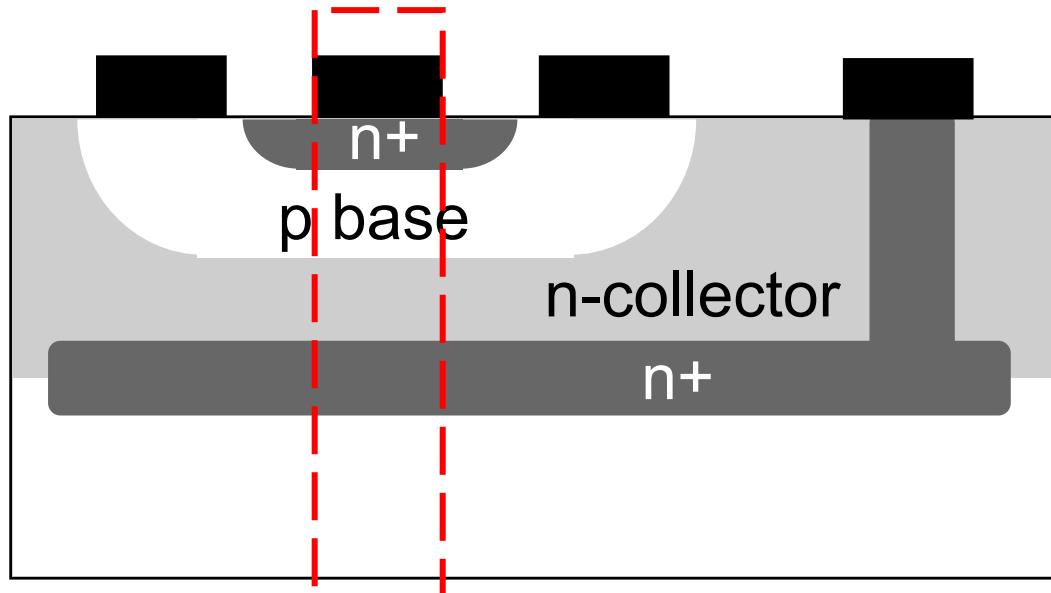
(current-gain cutoff frequency, f_T)

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

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

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

BJT design



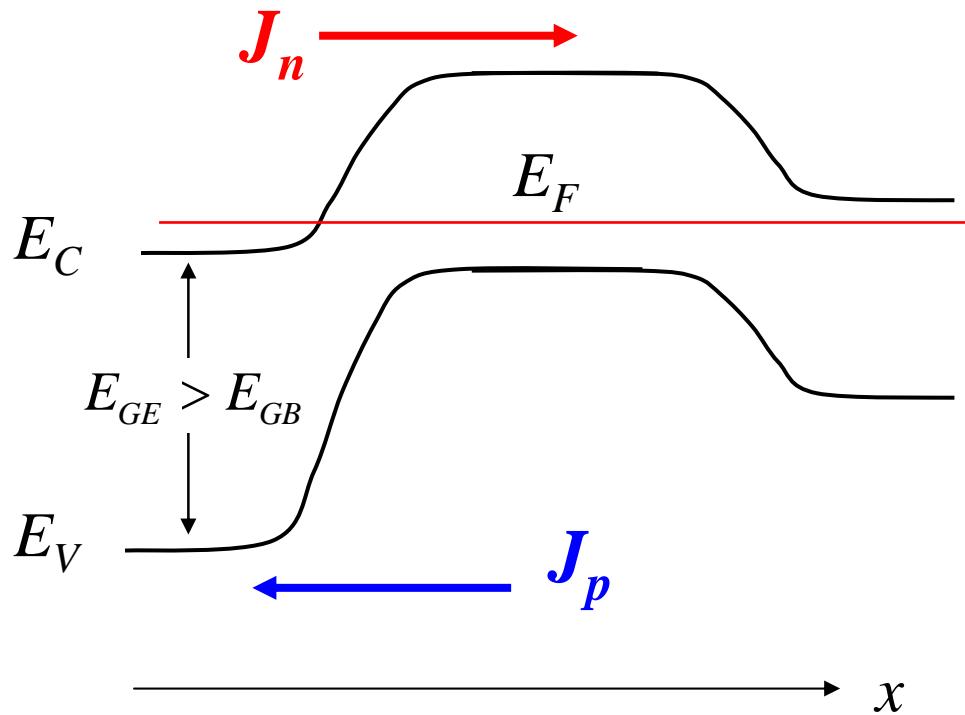
$$\beta = \frac{N_{DE}}{N_{AE}} \frac{D_n}{D_p} \frac{W_E}{W_B}$$

- 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})

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beta



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

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

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

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

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

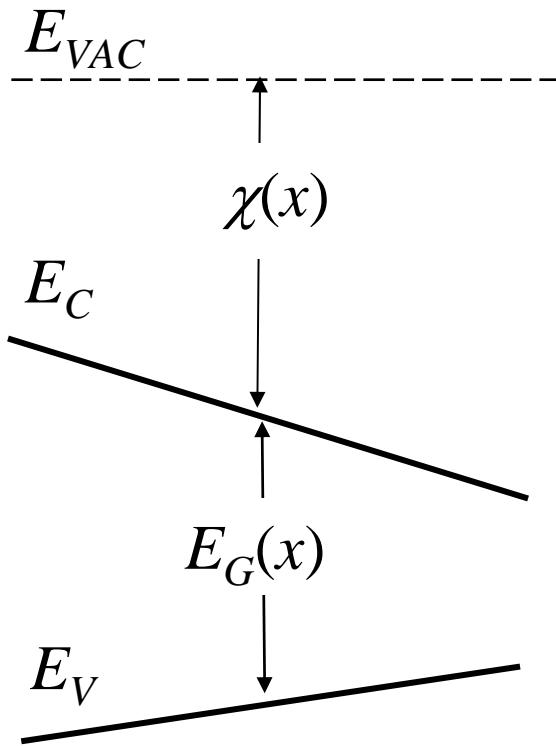
inverted base doping

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

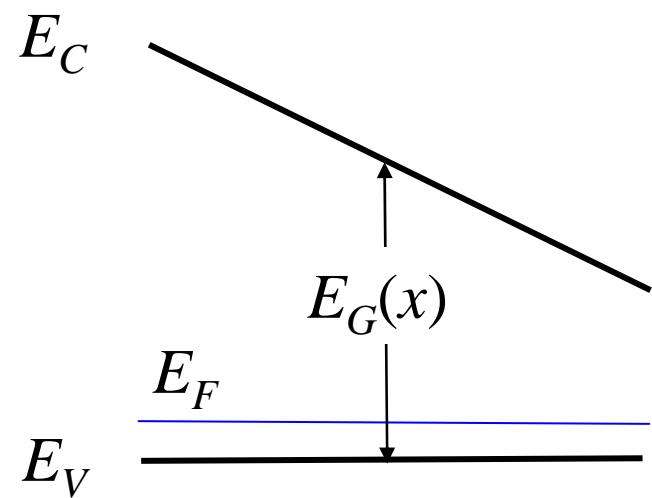
- 1) thin base for high speed
- 2) very heavily doped base to prevent punch through, reduce Early effect, and to lower R_{ex}
- 3) moderately doped emitter (lower C_{je})

“inverted base doping” $N_{AB} \gg N_{DE}$

graded bases

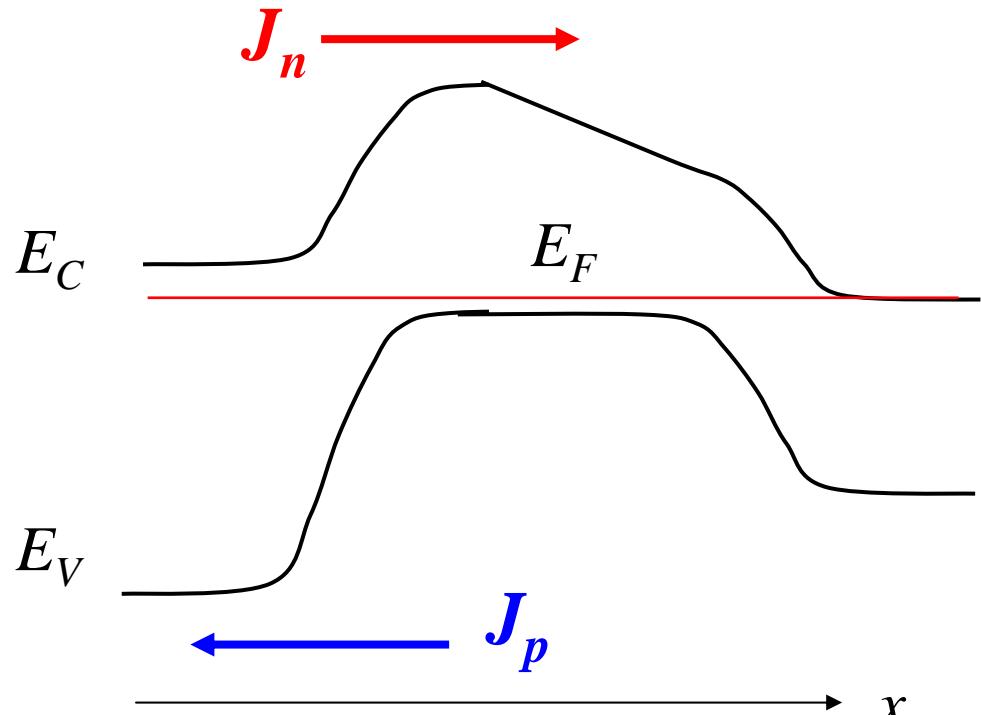


intrinsic
compositionally graded



uniformly p-doped
compositionally graded

graded base HBTs



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

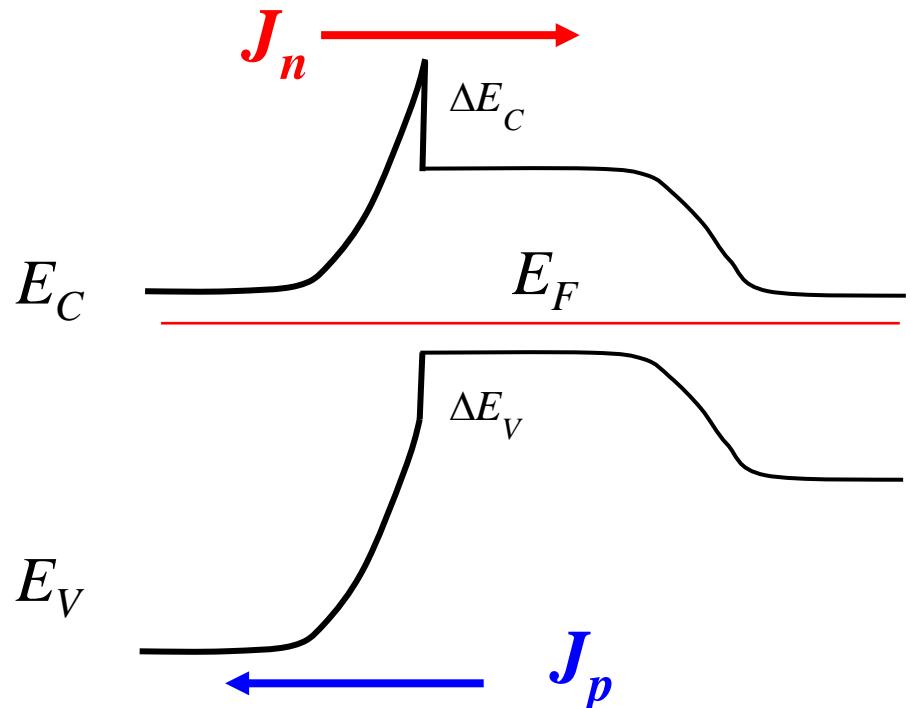
$$J_p = q \left(\frac{n_{iE}^2}{N_{DE}} \right) \frac{D_p}{W_E} e^{qV_{BE}/k_B T}$$

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

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

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

abrupt junction HBTs



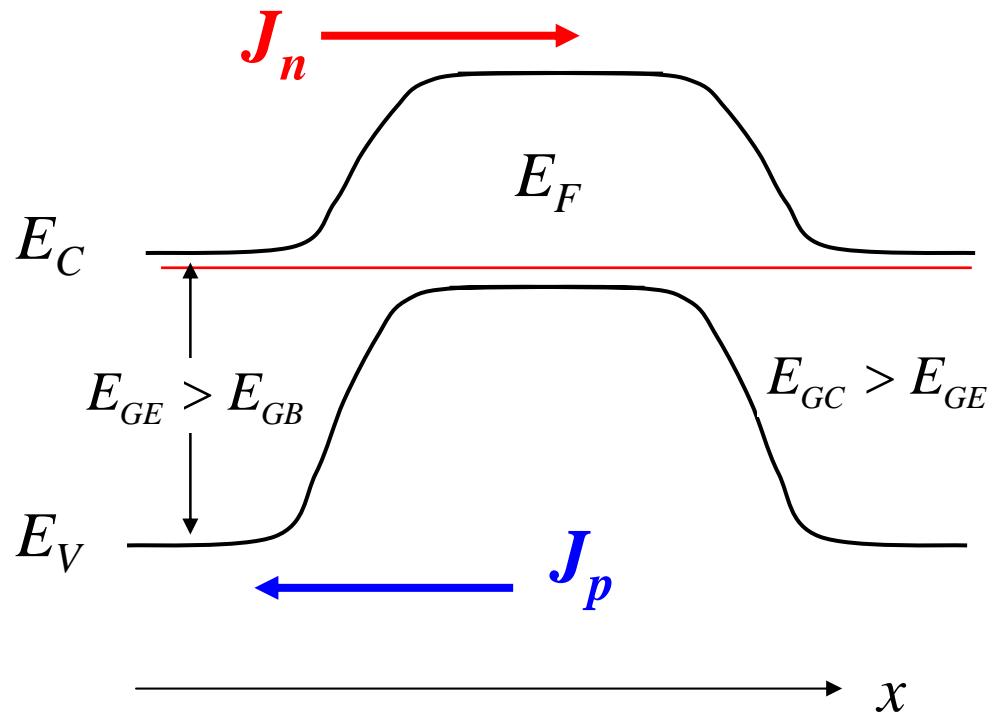
$$J_n = q \left(\frac{n_{iB}^2}{N_{AB}} \right) v_{Rp} e^{-\Delta E_C/k_B T} e^{qV_{BE}/k_B T}$$

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

$$\beta = \frac{N_{DE}}{N_{AE}} \frac{v_{Rp}}{(D_p/W_E)} \frac{n_{iB}^2}{n_{iE}^2} e^{-\Delta E_C/k_B T}$$

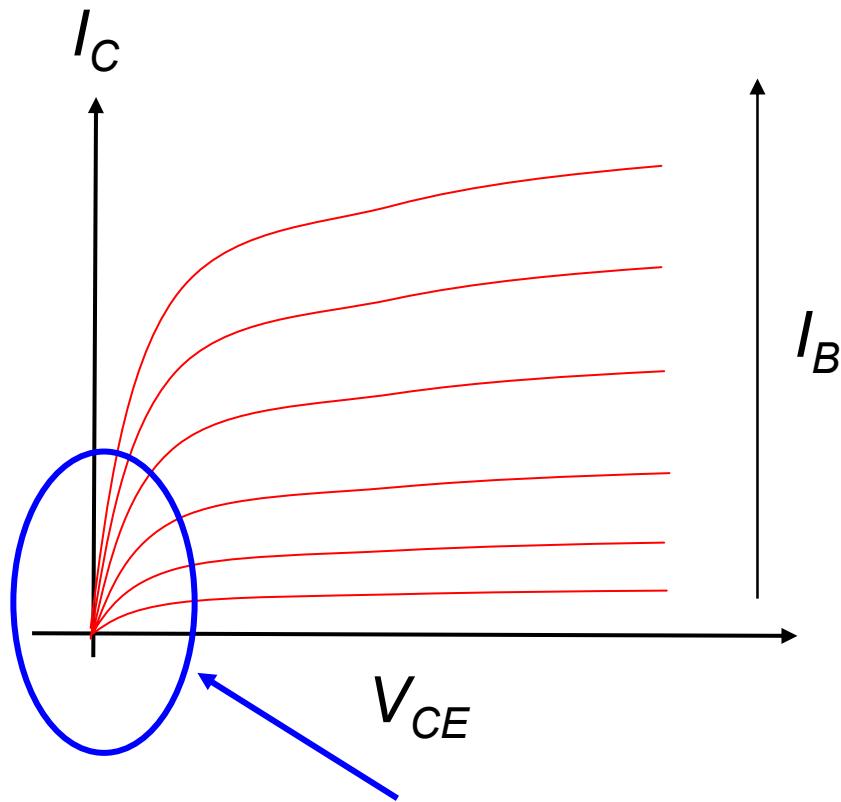
$$\beta = \frac{N_{DE}}{N_{AE}} \frac{v_{Rp}}{(D_p/W_E)} e^{\Delta E_V/k_B T}$$

double HBJT

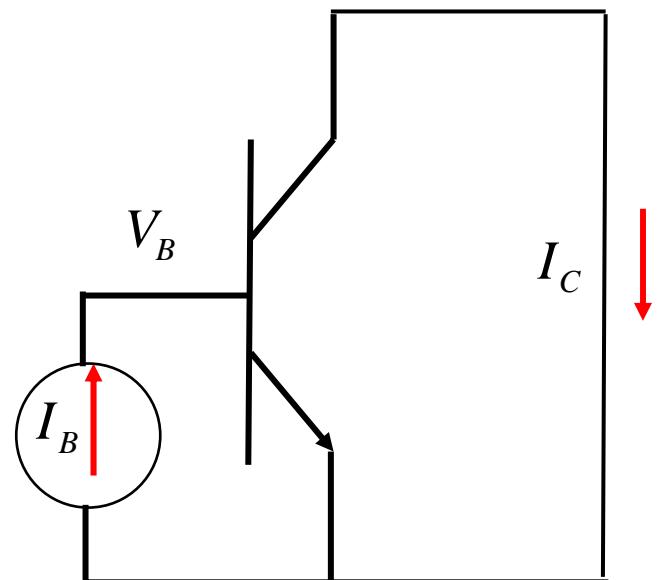


- symmetrical operation
- no charge storage when the b-c junction is forward biased
- reduced collector offset voltage
- higher collector breakdown voltage

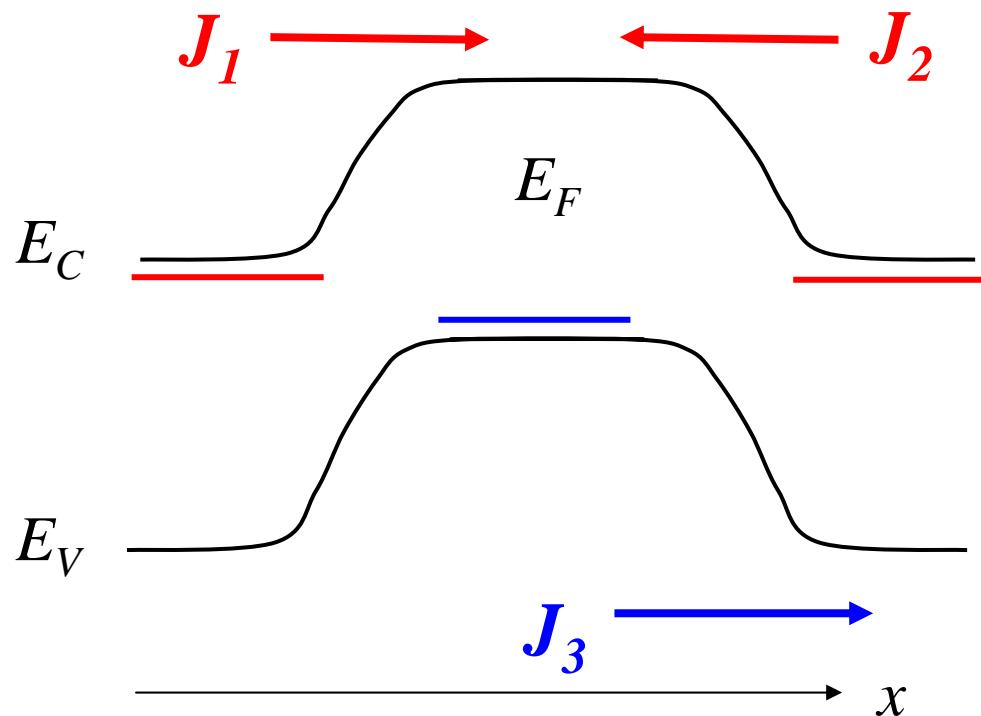
offset voltage



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

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

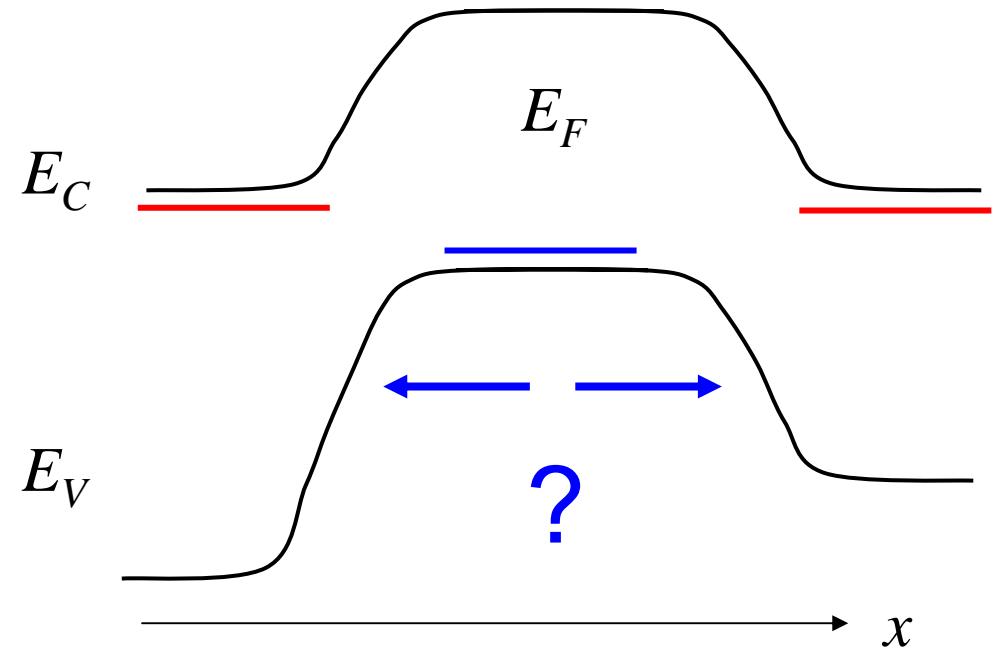
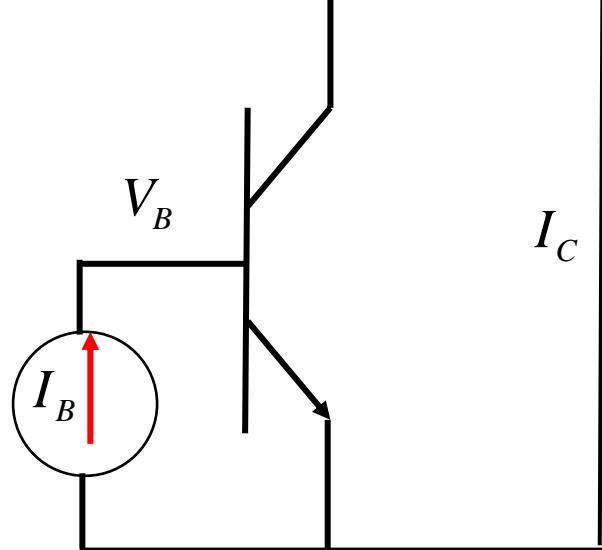
$$\gamma_R = \frac{J_2}{J_3} = \frac{\left(n_{iB}^2/N_{AB}\right)\left(D_n/W_B\right)}{\left(n_{iC}^2/N_{DC}\right)\left(D_p/W_C\right)}$$

(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

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- IV) The widegap emitter BJT
- V) Modern HBTs
- VI) Summary

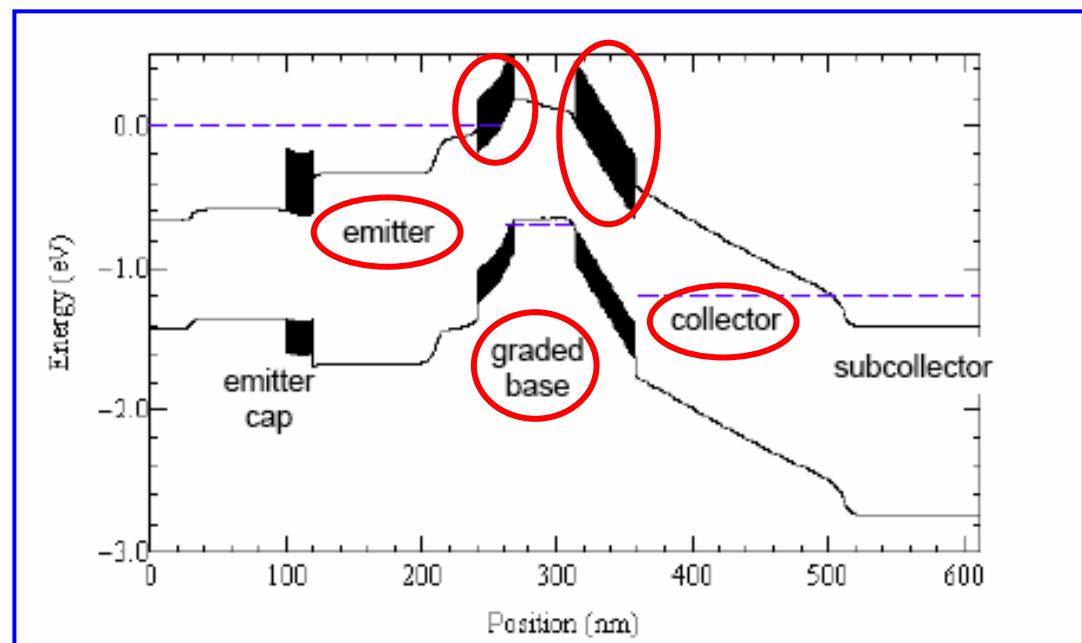
modern HBTs

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

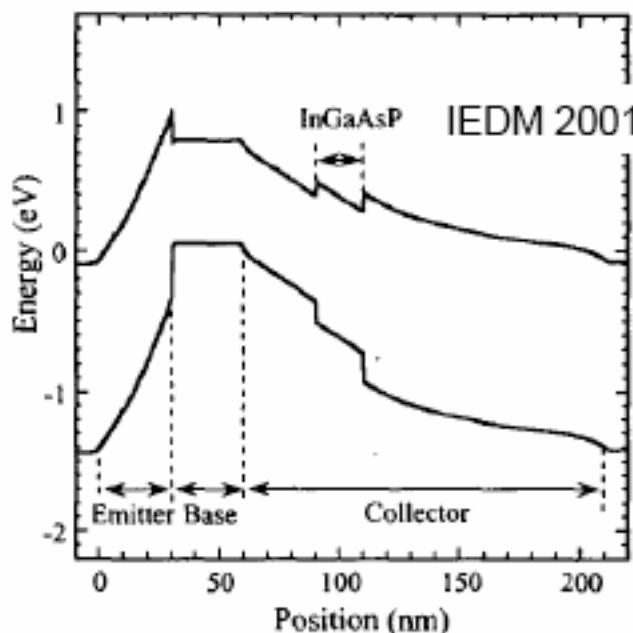


epitaxial layer design (iii)

InGaAs/InGaAsP/InP grade

InP/InGaAs DHBTs with 341-GHz f_T at high current density of over 800 kA/cm²

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



- suitable for MOCVD growth
- excellent results

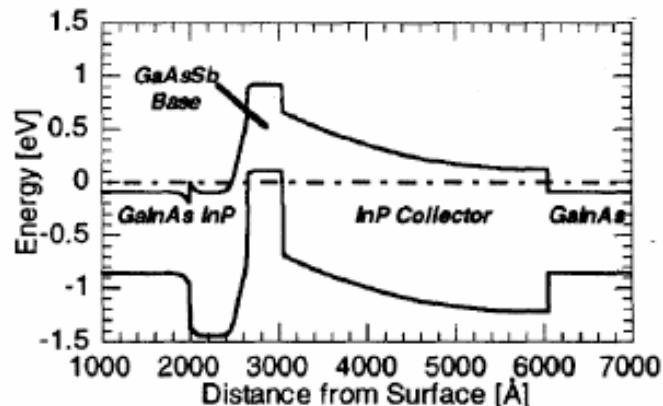
InP/GaAsSb/InP DHBT

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

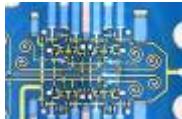
N. Matine, M. W. Dvorak, X. G. Xu, S. P. Watkins, and C. R. Bolognesi



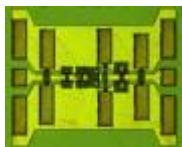
- does not need B/C grading
- E/B band alignment through GaAsSb alloy ratio (strain) or InAlAs emitter
- somewhat poorer transport parameters to date for GaAsSb base

performance

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

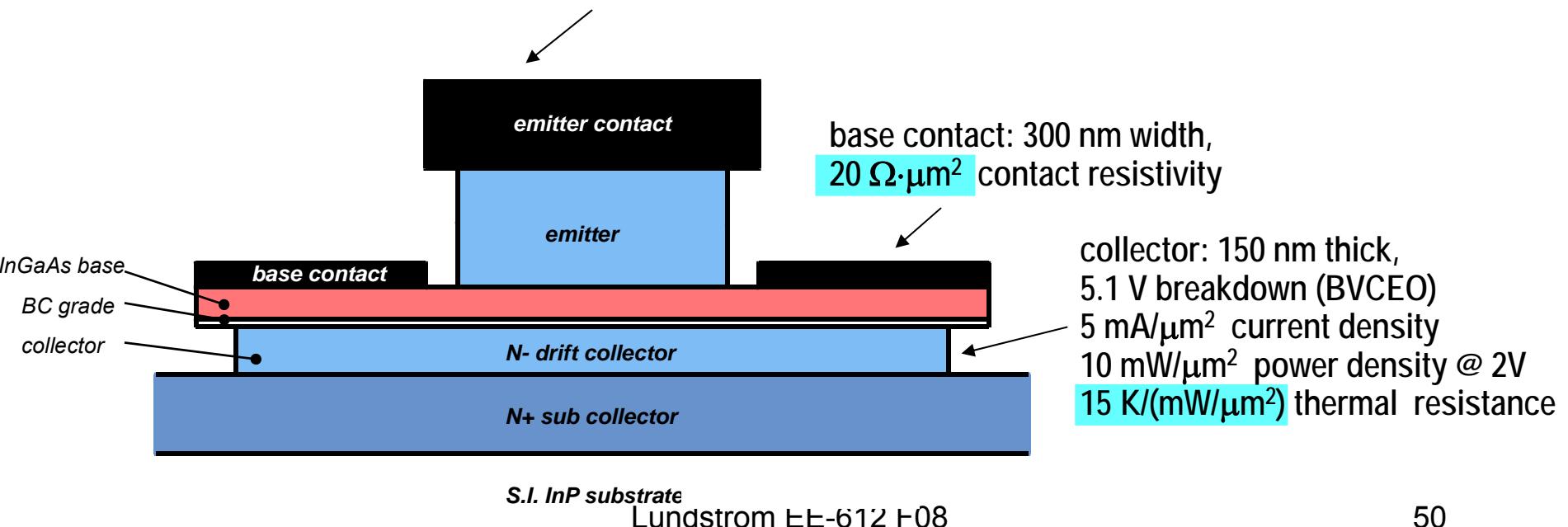


Has enabled 150 GHz digital clock rate (static dividers)



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

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



modern HBTs

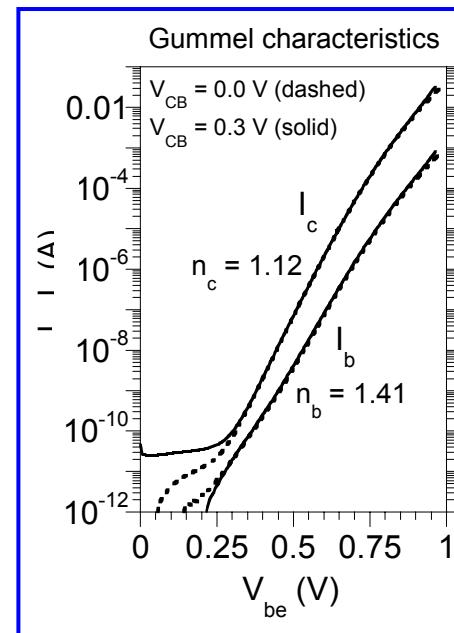
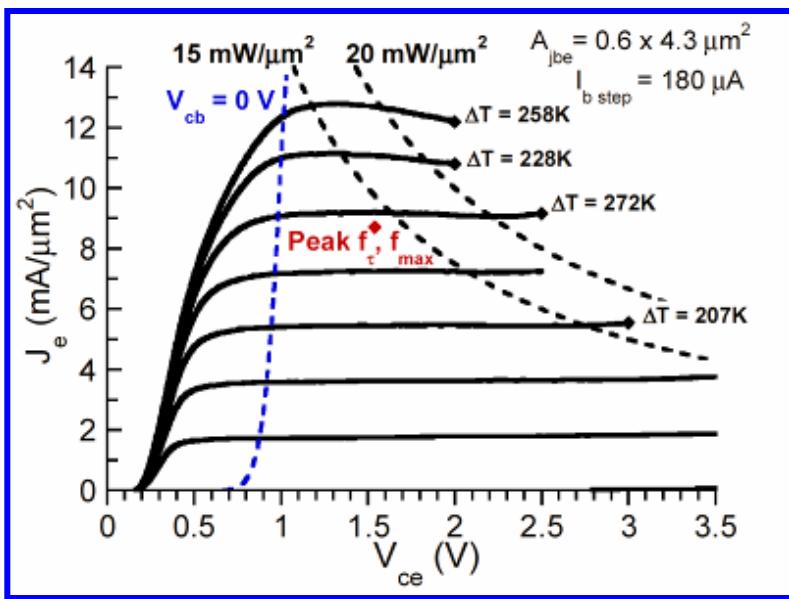
Key scaling challenges:

- *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



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

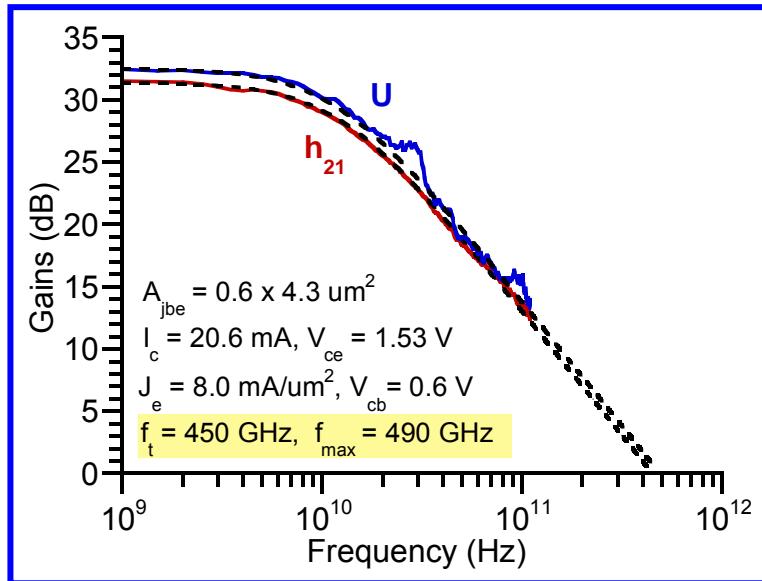
Emitter contact $R_{cont} < 10 \Omega \times \mu\text{m}^2$

Base : $R_{sheet} = 610 \text{ W/sq}$, $R_{cont} = 4.6 \Omega \times \mu\text{m}^2$

Collector : $R_{sheet} = 12.1 \Omega/\text{sq}$, $R_{cont} = 8.4 \Omega \times \mu\text{m}^2$

high-frequency performance

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



Courtesy Mark Rodwell, UCSB

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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.