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ECE606: Solid State Devices
Lecture 31: Heterojunction Bipolar Transistor (II)

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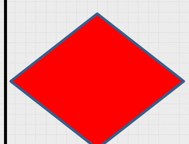
Topic Map

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

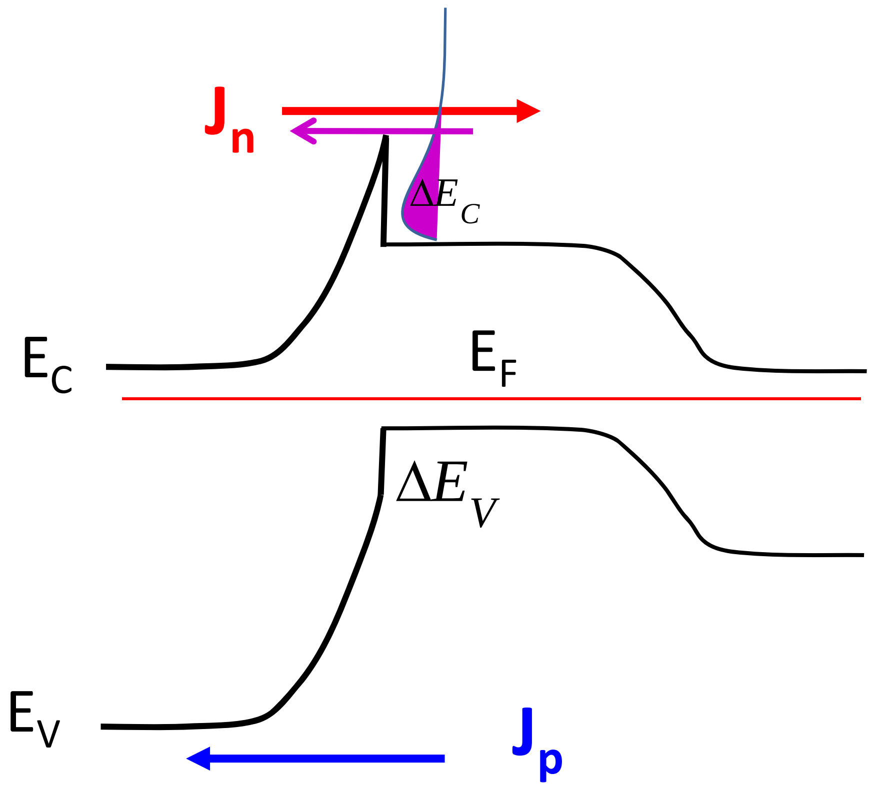
Outline

1. **Abrupt junction HBTs**
2. Graded junction HBTs
3. Graded base HBTs
4. Double heterojunction HBTs
5. Conclusions

REF. "Heterostructure Fundamentals," by Mark Lundstrom, Purdue University,1995.

Abrupt Junction HBTs

$$J_{n,B\rightarrow E} = q\left(\frac{n_{iB}^2}{N_B}\right)\upsilon_{Rp}e^{-\Delta E_C/k_BT} = J_n(V_{BE}=0)$$



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

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

$$\beta = \frac{N_E}{N_B}\frac{\upsilon_{Rp}}{\left(D_p/W_E\right)}\left[\frac{n_{iB}^2}{n_{iE}^2}e^{-\Delta E_C/k_BT}\right]$$

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

Gain in abrupt npn BJT defined only by valence band discontinuity!

… but we are hoping for even better gain

$$\beta \rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{D_p / W_E} \sim \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{D_p / W_E} e^{(\Delta E_g)\beta}$$

$$\beta = \frac{N_E}{N_B} \frac{\upsilon_{R,p}}{\left(D_p / W_E\right)} e^{\Delta E_V / k_B T}$$

Abrupt junction HBT

For full gain, we need graded junction HBT

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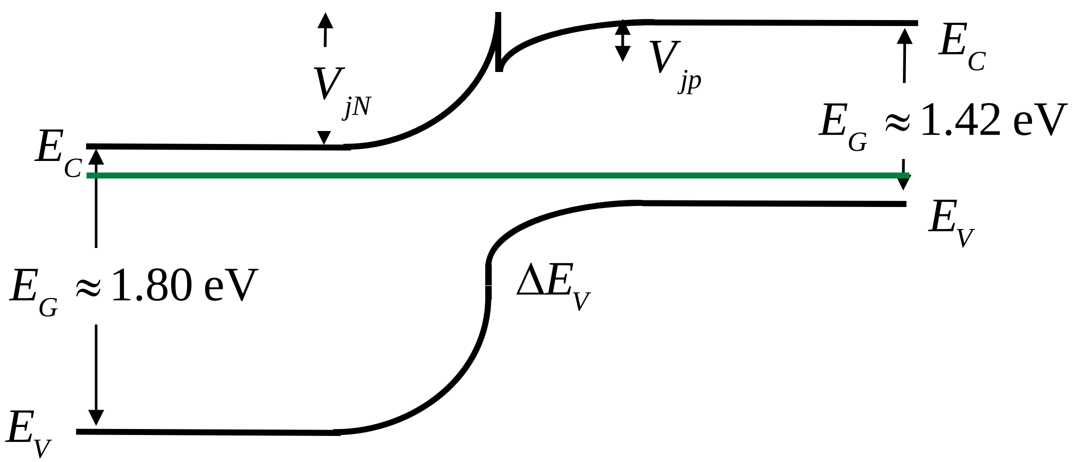
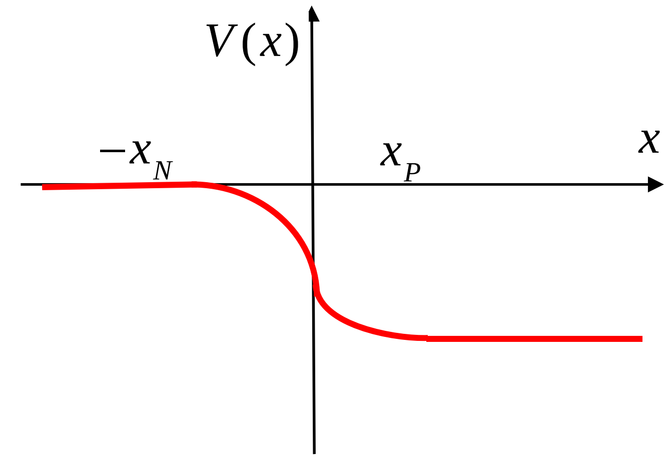
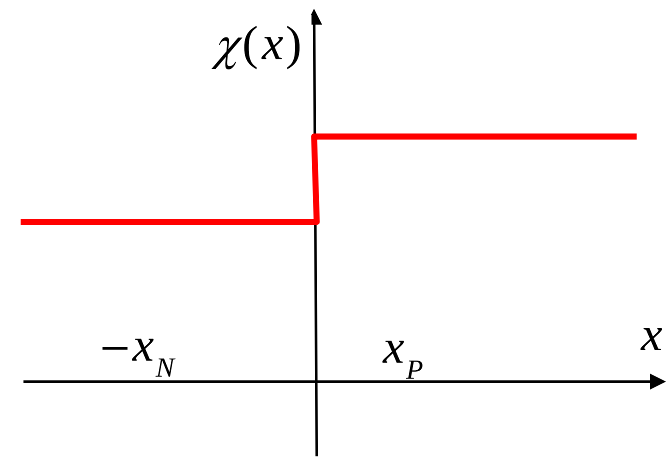
Abrupt Junction



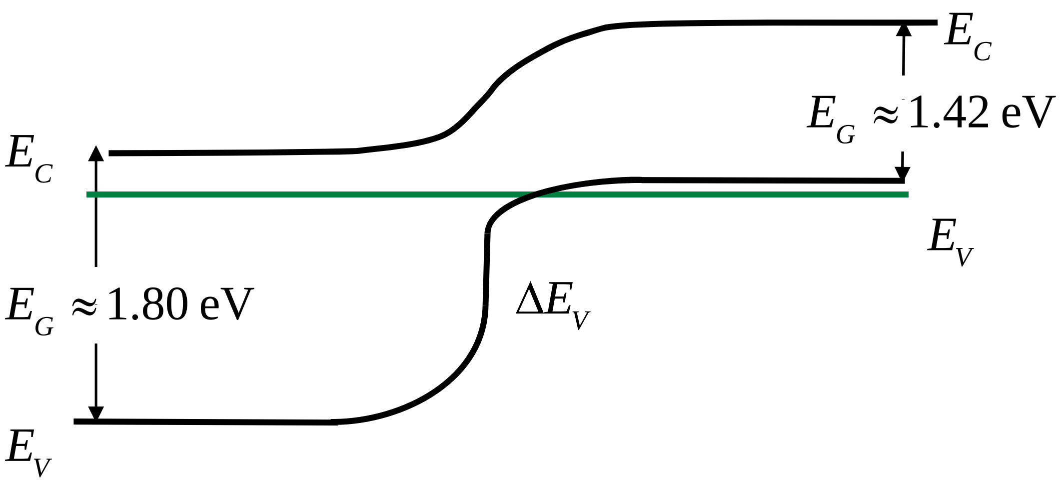


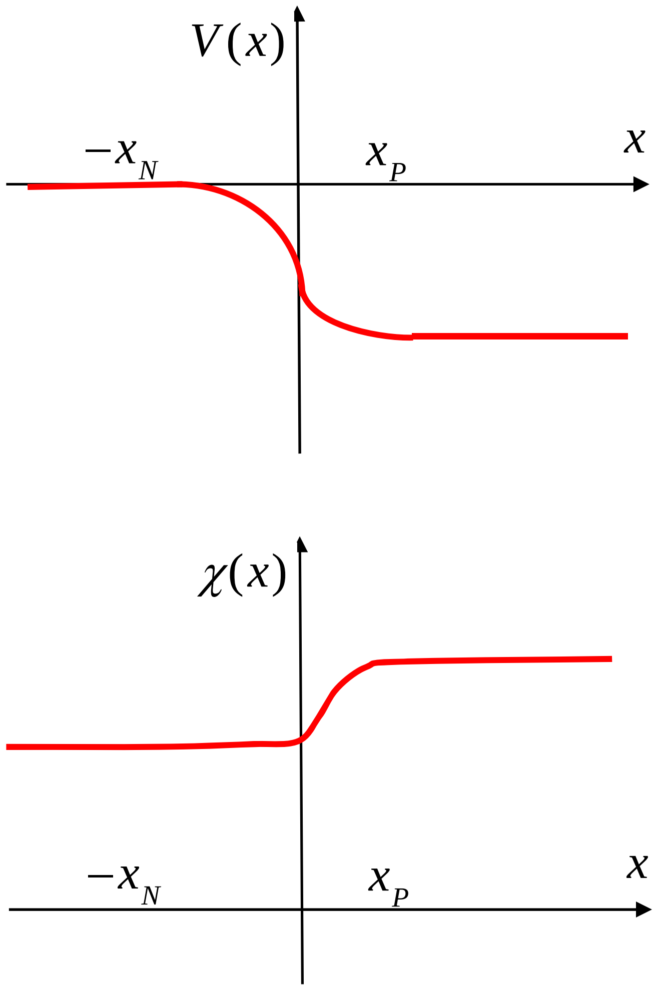


$$E_C(x) = E_0 - \chi(x) - qV(x)$$

$$E_V(x) = E_C(x) - E_G(x)$$

Graded Base-Emitter Junction

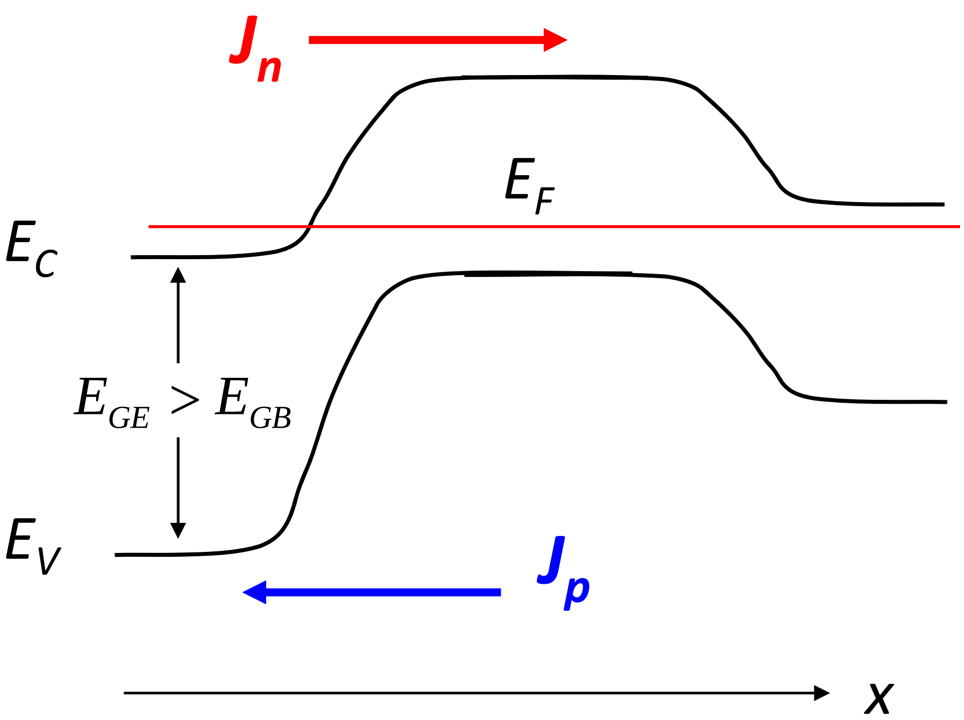




$$E_C(x) = E_0 - \chi(x) - qV(x)$$

$$E_V(x) = E_C(x) - E_G(x)$$

Current Gain



No exponential Suppression!

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

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

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

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

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

Advantages of HBT: Inverted Base Doping

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

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 $C_{j,BE}$)

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

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How to make a better Transistor

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

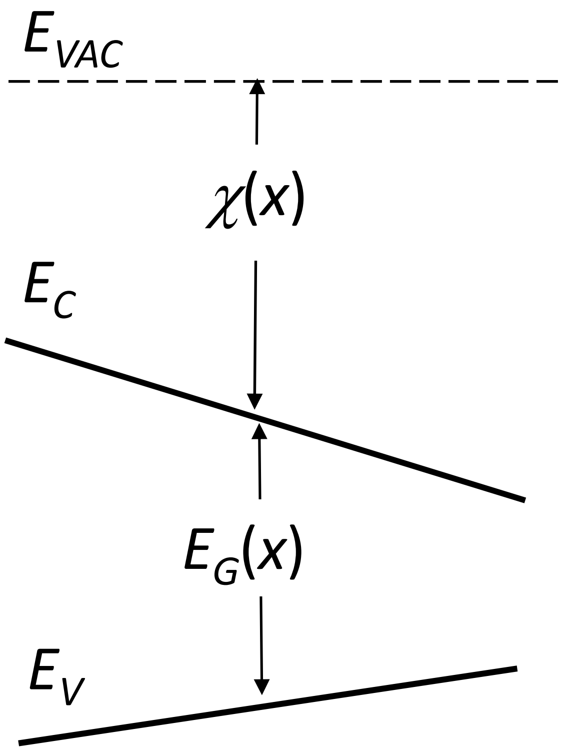
→ Graded Base transport

→ Polysilicon Emitter

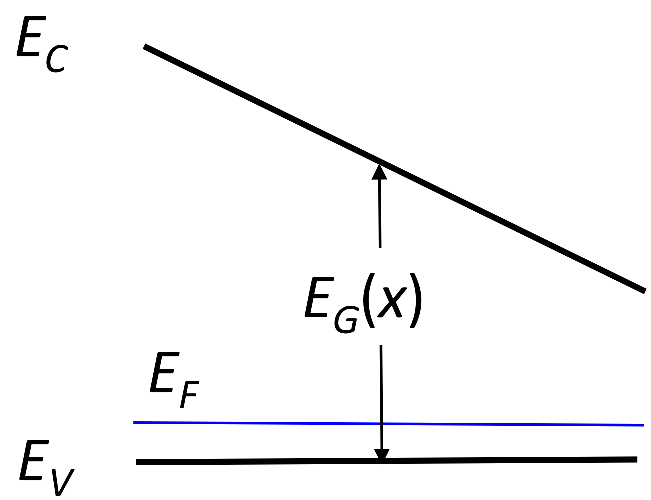
↓ Heterojunction bipolar transistor

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

Graded Bases

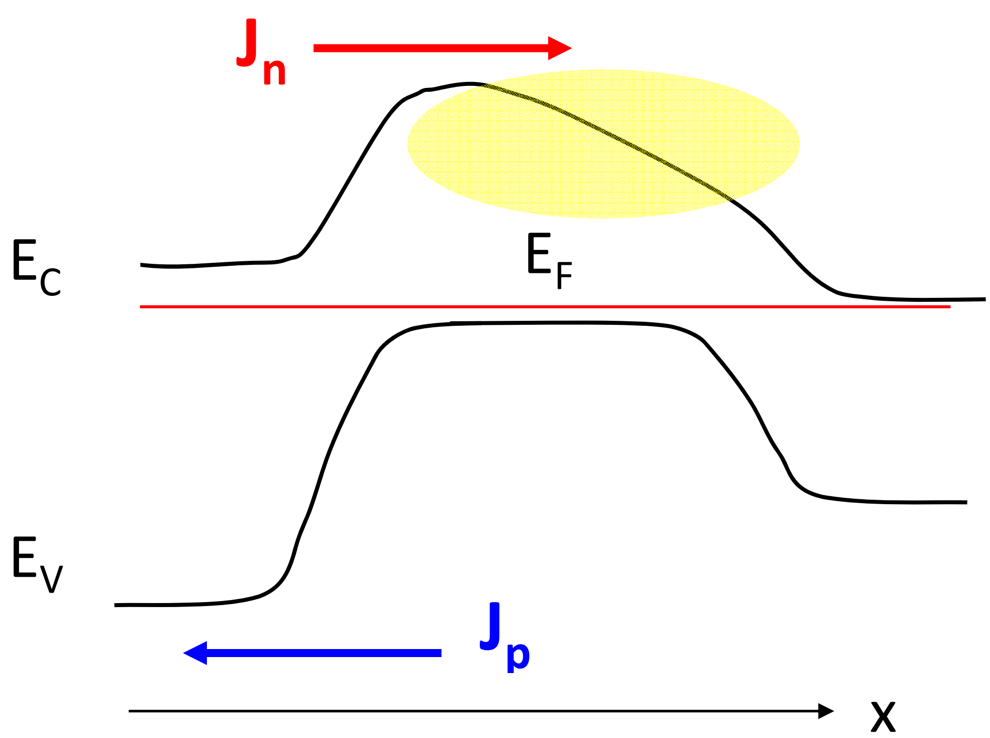


Intrinsic
compositionally graded



Uniformly p-doped
compositionally graded

Graded Base HBTs



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

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

$$\beta_{DC} = \frac{N_E}{N_B}\frac{D_n}{D_p}\frac{W_E}{W_B}\frac{\overline{n}_{iB}^2}{n_{iE}^2}$$

$$\tau_b = \frac{W_B}{\mu_n \mathcal{E}_{eff}} << \frac{W_B^2}{2D_n}$$

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

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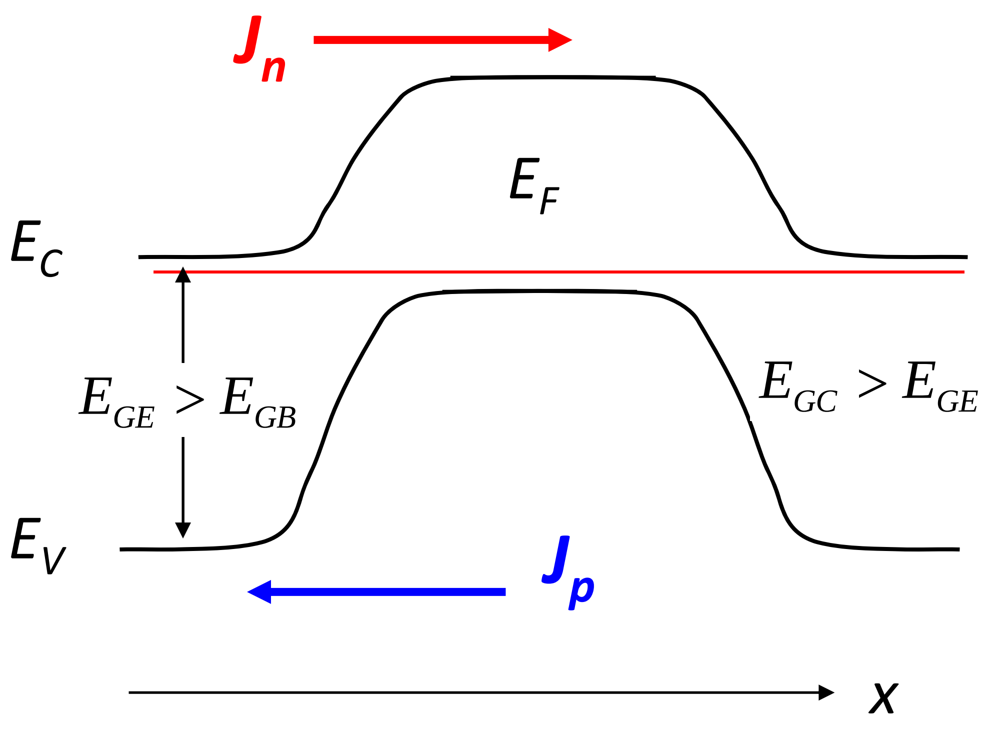
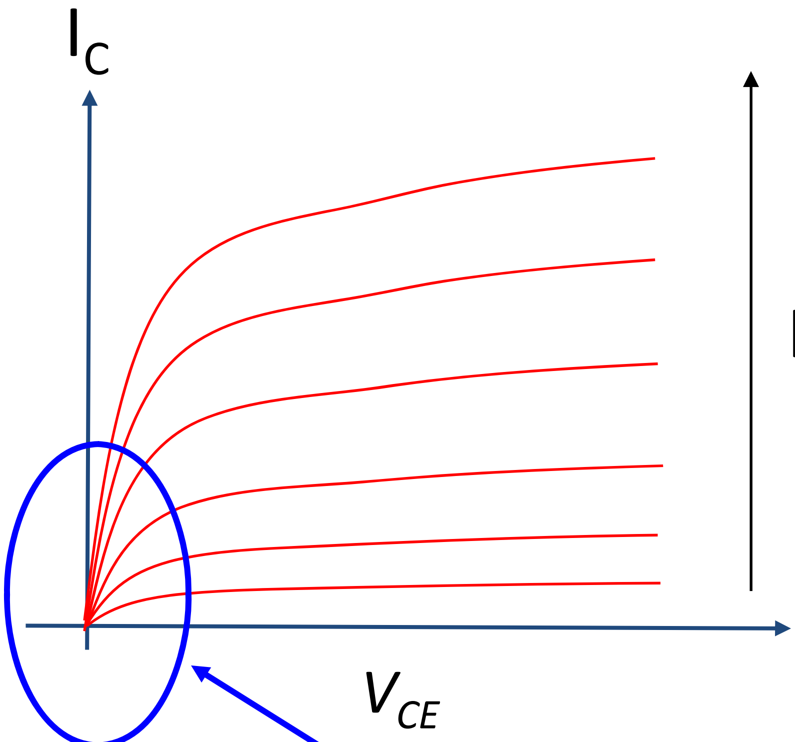
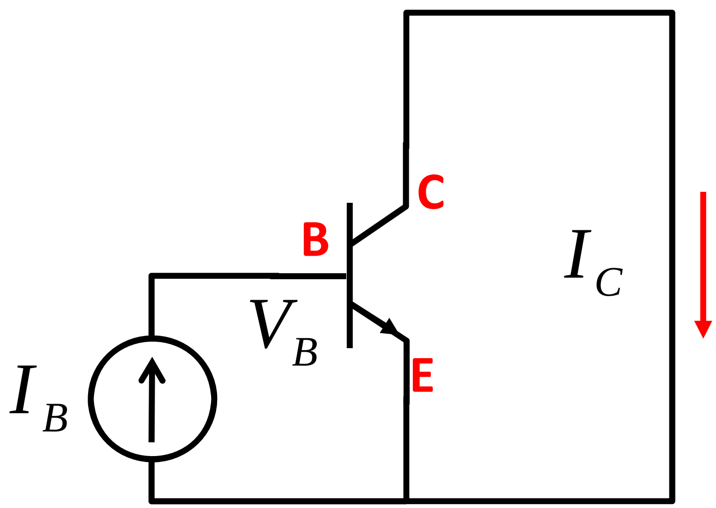
Double HBJT



- Symmetrical operation
- No charge storage when the b-c junction is forward biased
- Reduced collector offset voltage
- Higher collector breakdown voltage

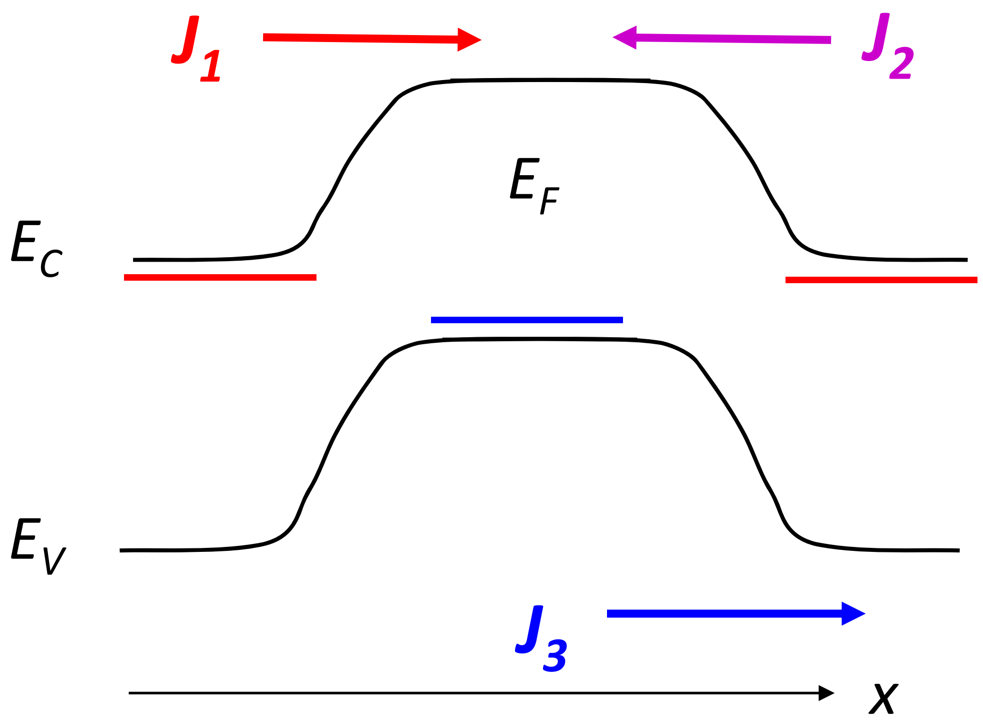
Offset Voltage





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

Offset Voltage



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

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

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

$$J_C = J_1 - J_2 - J_3$$

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 for small V_{os}. Wide bandgap collector helps.

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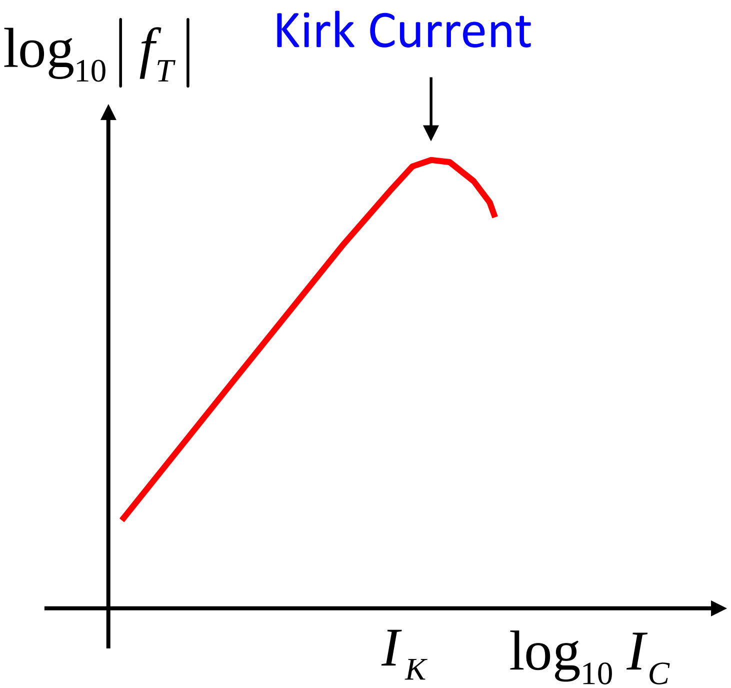
Putting the Terms Together



Collector transit time

Base transit time

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

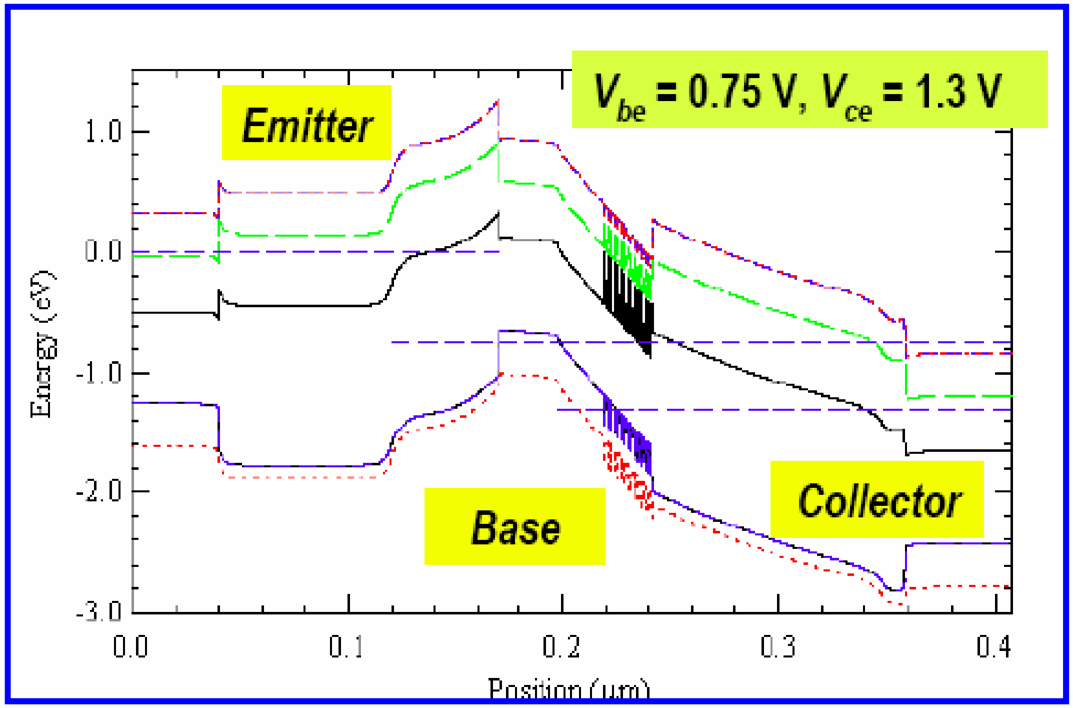
junction charging time ...

Quations: Why does HBTs have such high performance ?

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

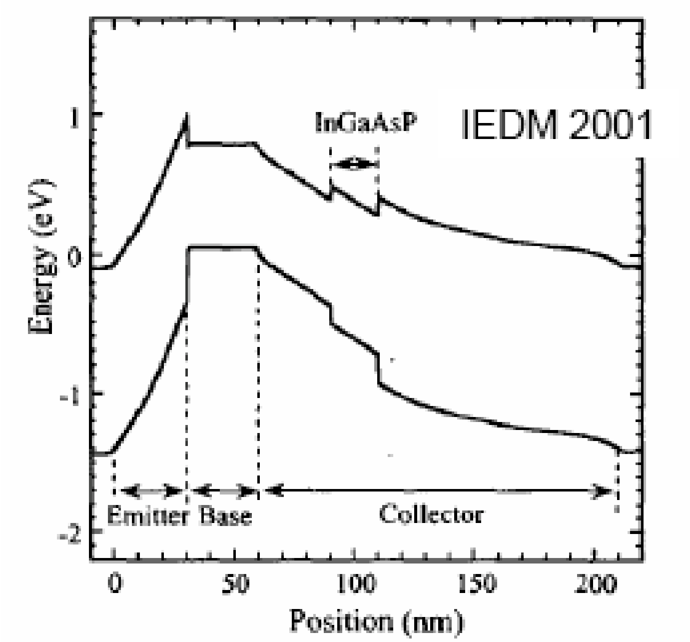


Epitaxial Layer Design (III)

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



-suitable for MOCVD growth
- excellent results

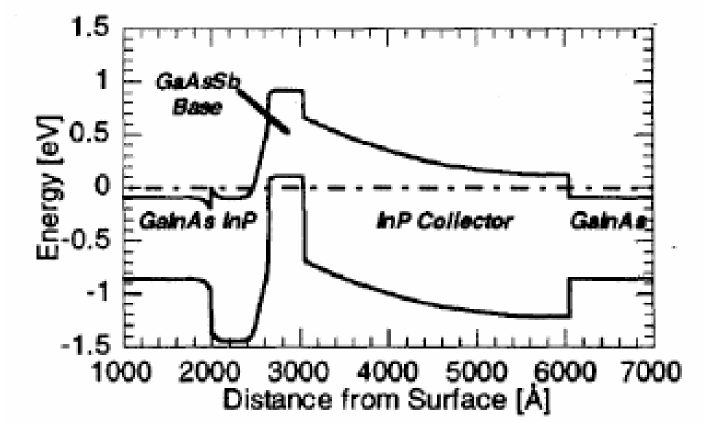
InP/GaAsSb/InP DHBT

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

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.
However, it has yield issues and heating and contact R problems.