ECE606: Solid State Devices
Lecture 20

Heterojunction Bipolar Transistor

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Outline

1. Introduction
2. Equilibrium solution for heterojunction
3. Types of heterojunctions
4. Intermediate Summary
5. Abrupt junction HBTs
6. Graded junction HBTs
7. Graded base HBTs
8. Double heterojunction HBTs
9. Conclusions

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

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

How to make a better Transistor

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

→ Graded Base transport

→ Polysilicon Emitter

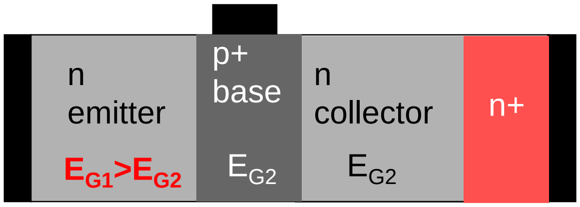
Heterojunction bipolar transistor

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

Emitter bandgap > Base Bandgap

Heterojunction Bipolar Transistors

i) Wide gap Emitter HBT



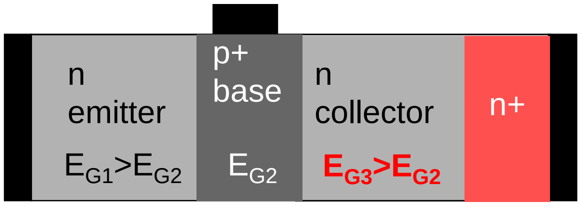
n emitter **$E_{G1}>E_{G2}$**

p+ base E_{G2}

n collector E_{G2}

n+

ii) **Double** Heterojunction Bipolar Transistor



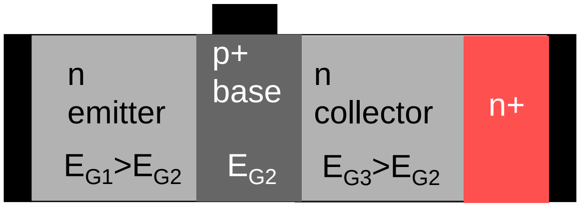
n emitter $E_{G1}>E_{G2}$

p+ base E_{G2}

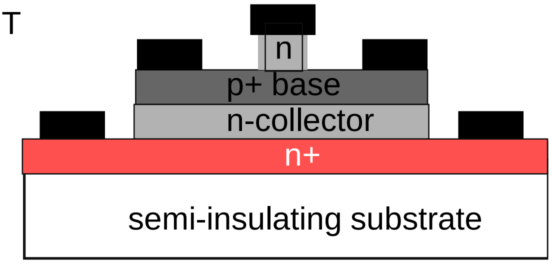
n collector **$E_{G3}>E_{G2}$**

n+

Mesa HBTs



Mesa HBT



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

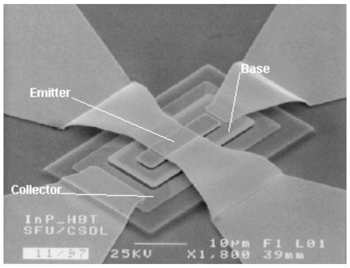
Applications

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.

Background

A heterojunction bipolar transistor



Kroemer

Schokley realized that HBT is possible, but Kroemer really provided the foundation of the field and worked out the details.

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Topic Map

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

Bandgaps and Lattice Matching

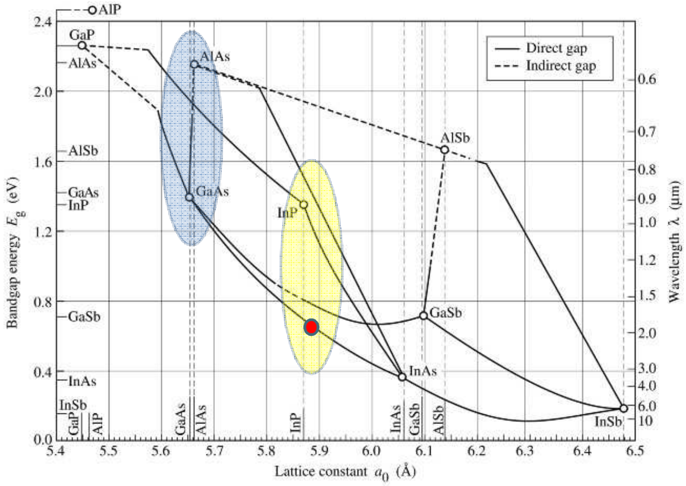


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

Band Diagram at Equilibrium

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

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

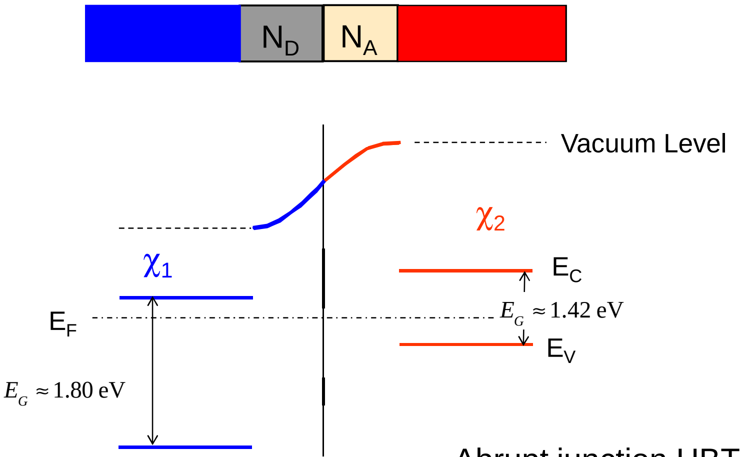
$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Equilibrium

DC dn/dt=0
Small signal dn/dt ~ jωtn
Transient --- Charge control model

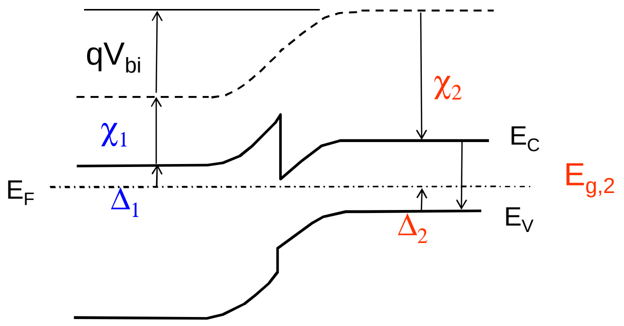
N-Al$_{0.3}$Ga$_{0.7}$As: p-GaAs (Type-I Heterojunction)



Abrupt junction HBT

Built-in Potential: Boundary Condition @Infinity

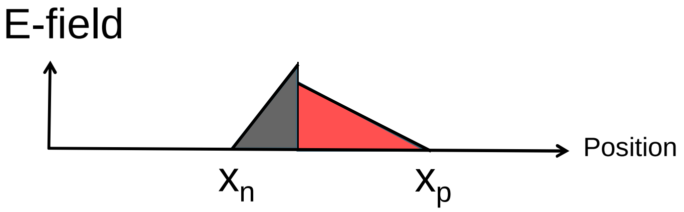
$$\Delta_1 + \chi_1 + qV_{bi} = E_{g,2} - \Delta_2 + \chi_2$$



$$qV_{bi} = E_{g,2} - \Delta_2 - \Delta_1 + \chi_2 - \chi_1$$

$$= k_B T \ln \frac{N_A N_D}{N_{V,2} N_{C,1} e^{-E_{g,2}/k_B T}} + \left(\chi_2 - \chi_1\right)$$

Interface Boundary Conditions



$$D\left(0^-\right) = D\left(0^+\right)$$

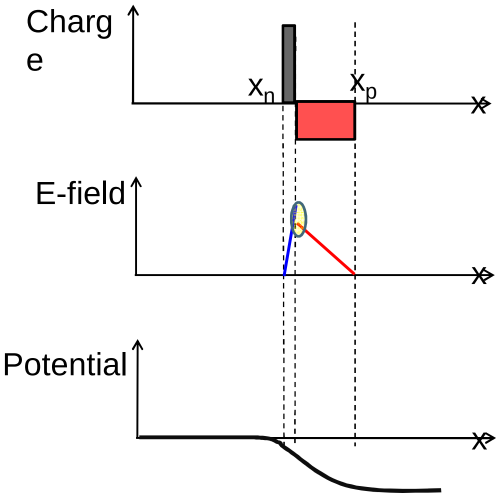
$$\kappa_1 \varepsilon_0 E\left(0^-\right) = \kappa_2 \varepsilon_0 E\left(0^+\right)$$

$$\kappa_1 \varepsilon_0 \left.\frac{dV}{dx}\right|_{0^-} = \kappa_2 \varepsilon_0 \left.\frac{dV}{dx}\right|_{0^+}$$

Displacement is continuous

D is not continuous if there is a surface charge

Analytical Solution for Heterojunctions



$$E\left(0^-\right)=\frac{qN_Dx_n}{k_{s,E}\varepsilon_0}$$

$$E\left(0^+\right)=\frac{qN_Ax_p}{k_{s,B}\varepsilon_0}$$

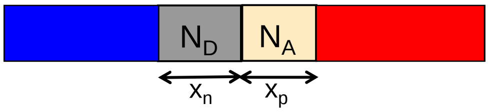
$$\Rightarrow N_Dx_n = N_Ax_p$$

Charge continuity
(independent of k)

$$V_{bi}=\frac{E\left(0^-\right)x_n}{2}+\frac{E\left(0^+\right)x_p}{2}$$

$$=\frac{qN_Dx_n{}^2}{2k_{s,E}\varepsilon_0}+\frac{qN_Ax_p{}^2}{2k_{s,B}\varepsilon_0}$$

Base Emitter Depletion Region



$$N_Ex_{n,BE} = N_Bx_{p,BE}$$

$$V_{bi}=\frac{qN_Ex_{n,BE}{}^2}{2\kappa_{s,E}\varepsilon_0}+\frac{qN_Bx_{p,BE}{}^2}{2\kappa_{s,B}\varepsilon_0}$$

$$\left.\right\} \quad x_n=\sqrt{\frac{2\varepsilon_0}{q}\frac{\kappa_{s,E}\kappa_{s,B}N_B}{N_E\left(\kappa_{s,E}N_B+\kappa_{s,B}N_E\right)}V_{bi}}$$

$$x_p=\sqrt{\frac{2\varepsilon_0}{q}\frac{\kappa_{s,E}\kappa_{s,B}N_E}{N_B\left(\kappa_{s,E}N_B+\kappa_{s,B}N_E\right)}V_{bi}}$$

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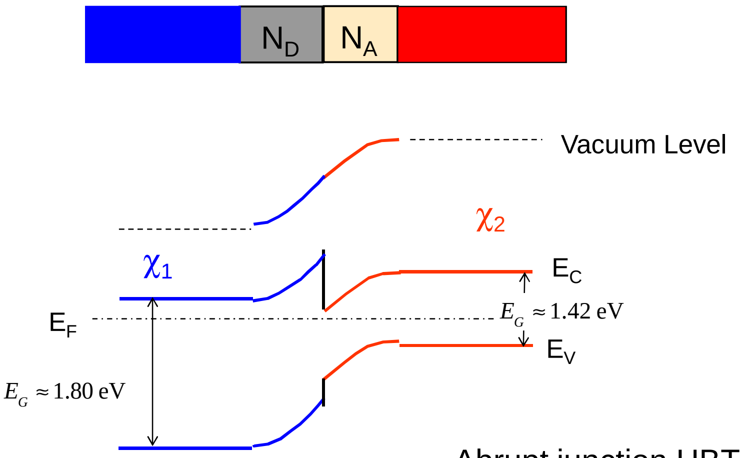
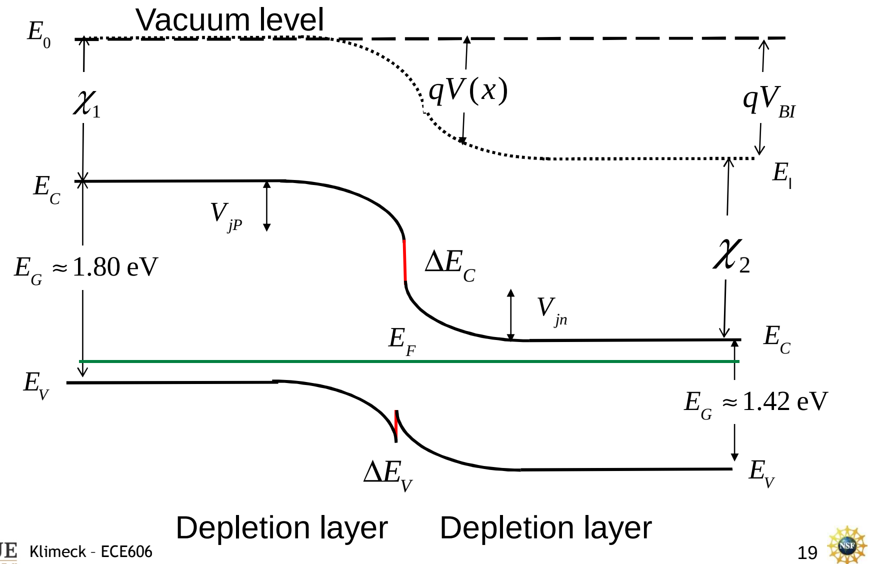
N-$Al_{0.3}Ga_{0.7}As$: p-GaAs (Type-I Heterojunction)

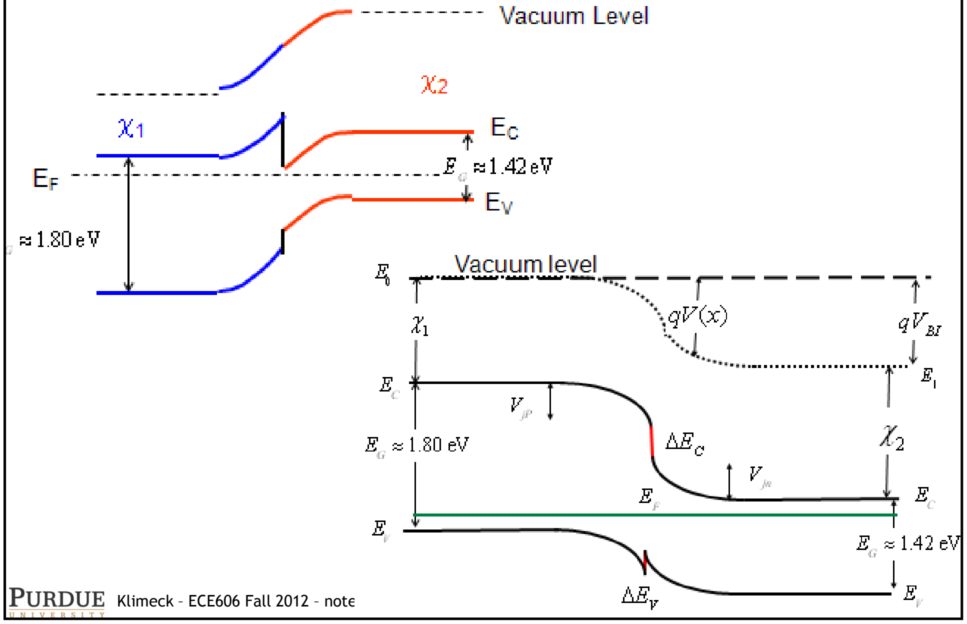


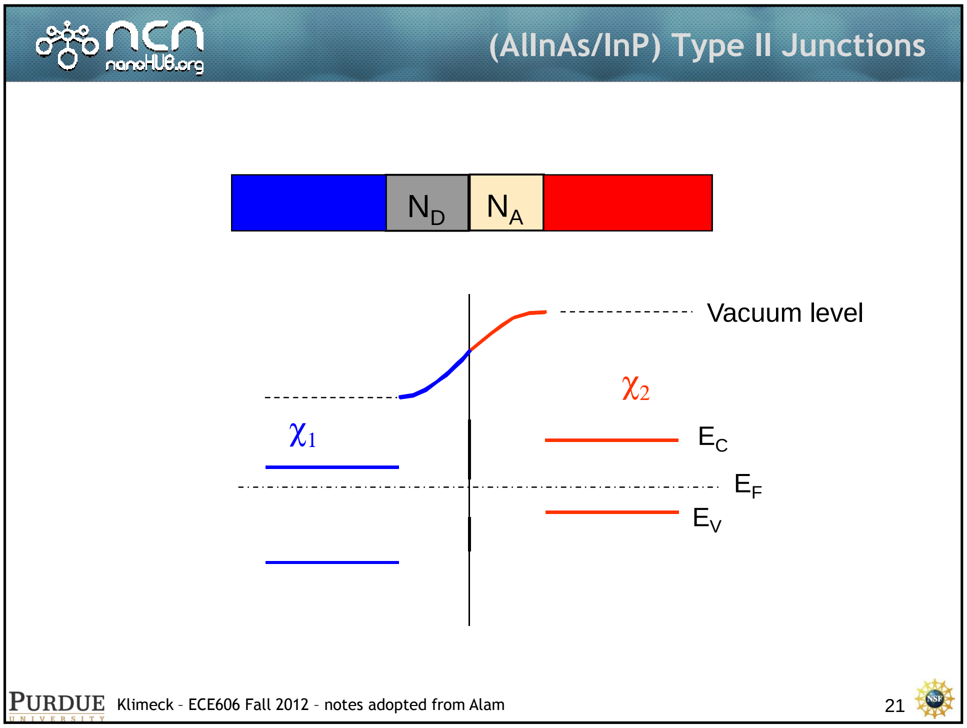
Abrupt junction HBT

P-Al$_{0.3}$Ga$_{0.7}$As : n-GaAs (Type I junctions)

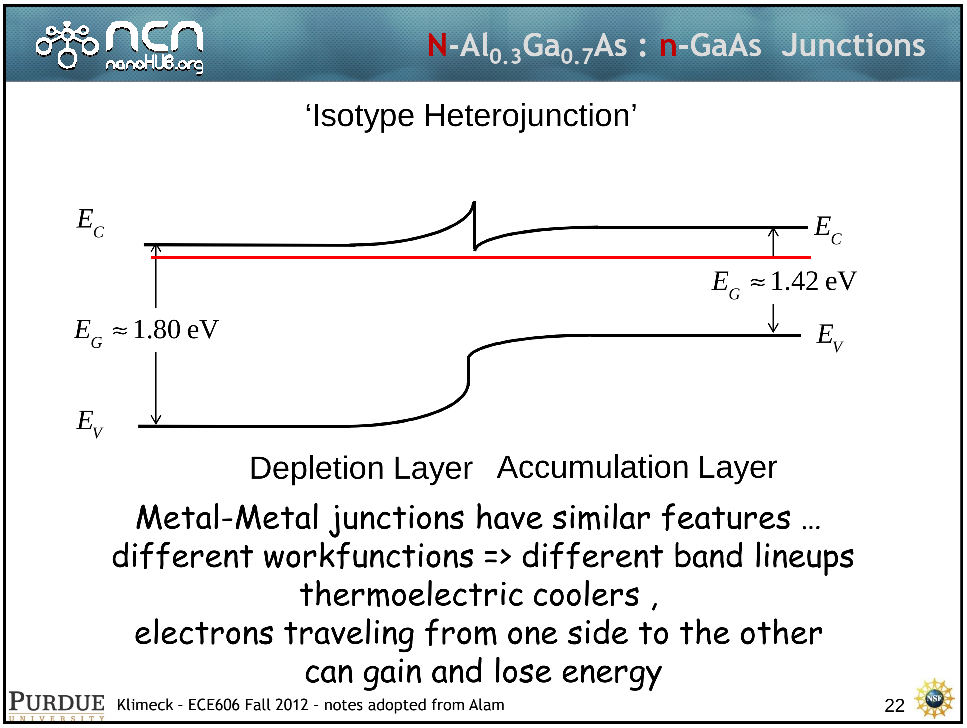


N-p vs P-n of Type I Heterostructure





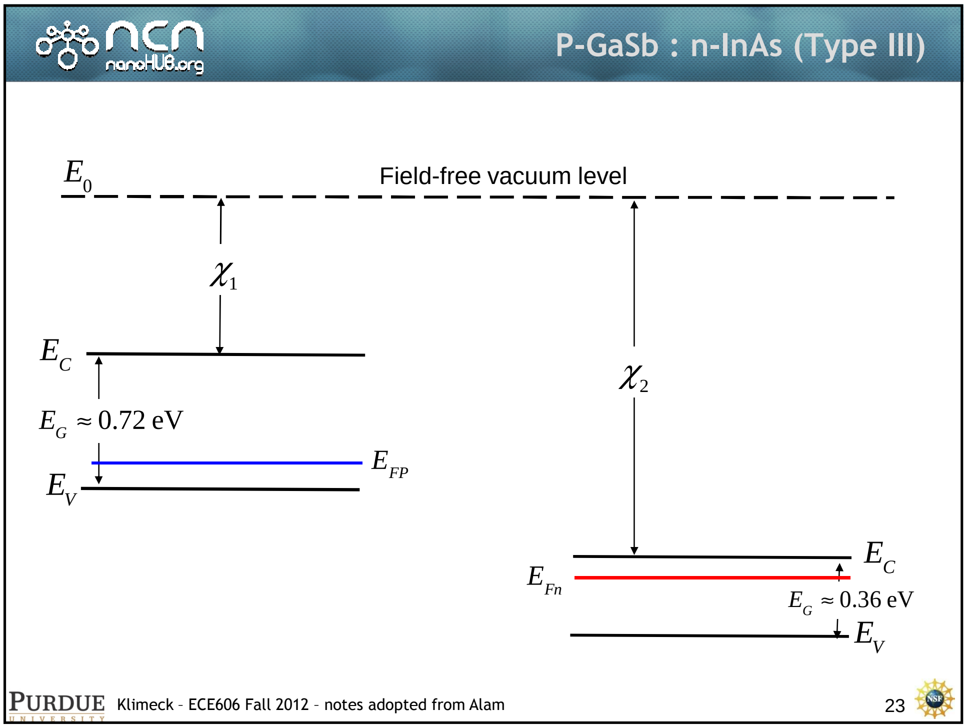
(AlInAs/InP) Type II Junctions



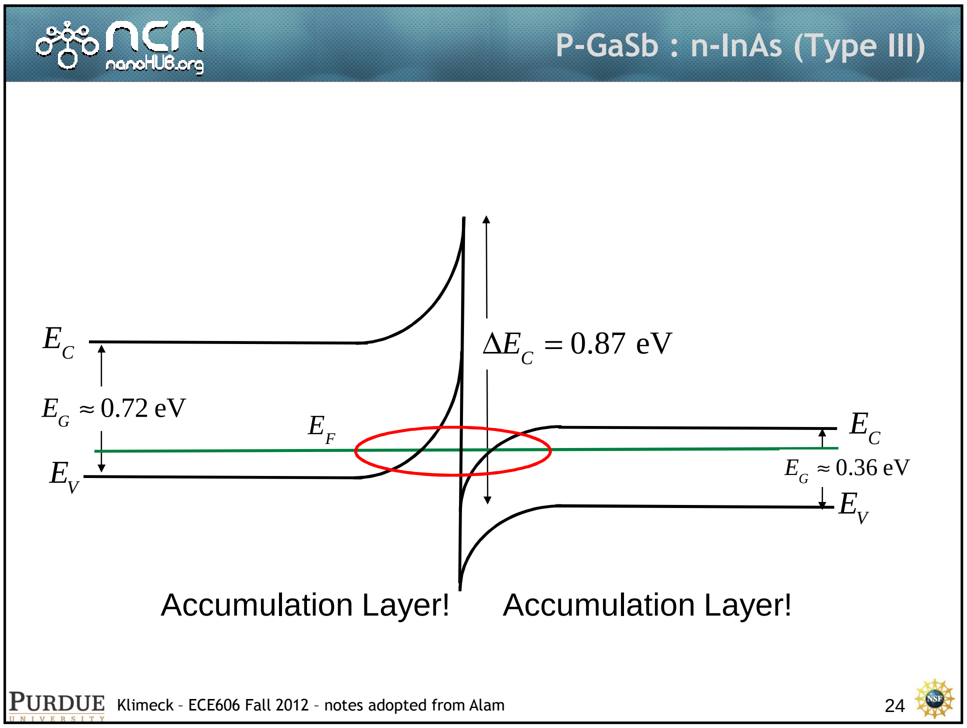
N-$Al_{0.3}Ga_{0.7}As$: n-GaAs Junctions

'Isotype Heterojunction'

Metal-Metal junctions have similar features …
different workfunctions => different band lineups
thermoelectric coolers ,
electrons traveling from one side to the other
can gain and lose energy



P-GaSb : n-InAs (Type III)



P-GaSb : n-InAs (Type III)

Accumulation Layer! Accumulation Layer!

Conclusion

1. Heterojunction transistors offer a solution to the limitations of poly-Si bipolar transistors.

2. Equilibrium solutions for HBTs are very similar to those of normal BJTs.

3. Depending on the alignment, there could be different types of heterojuctions. Each has different usage.

4. We will discuss current transport in HBTs in the next section.

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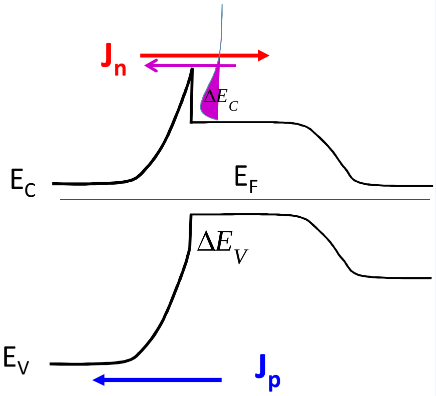
Abrupt Junction HBTs

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



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

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

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

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

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

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

… but we are hoping for even better gain

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

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

Abrupt junction HBT

For full gain, we need graded junction HBT

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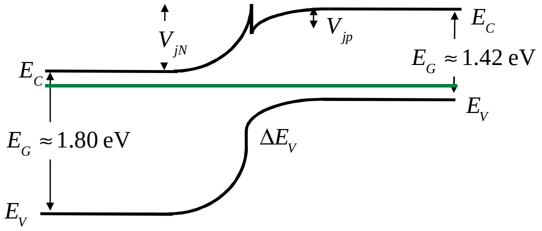
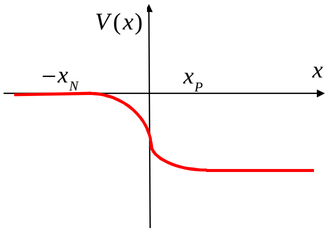
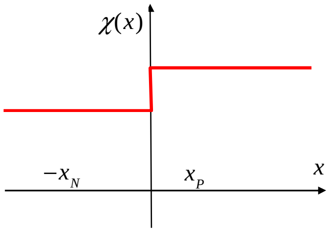
Abrupt Junction

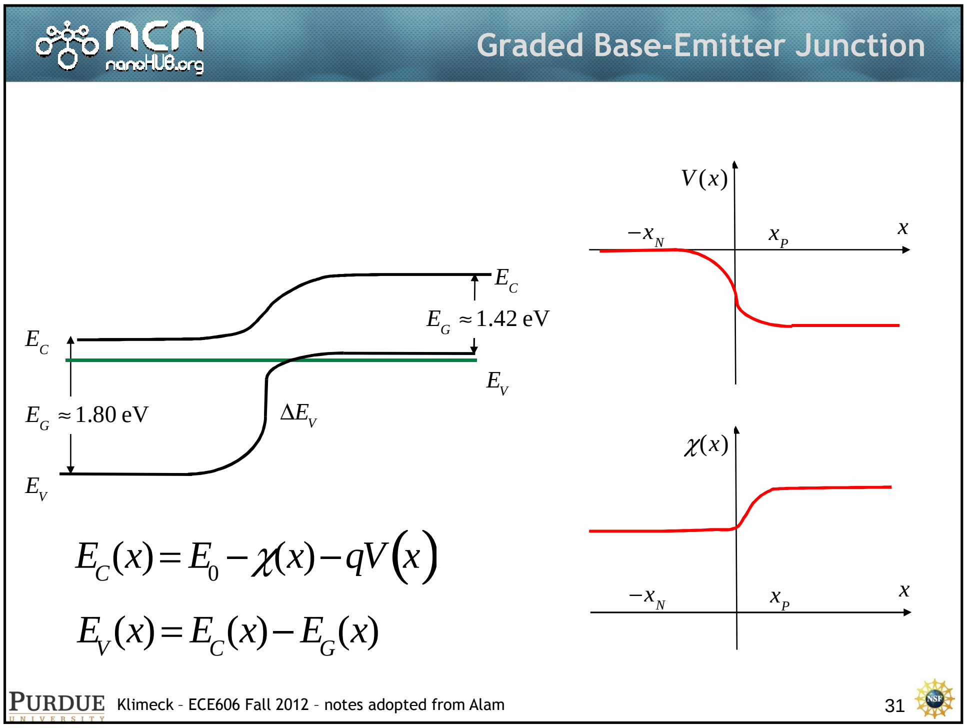






$$E_C(x) = E_0 - \chi(x) - qV(x)$$

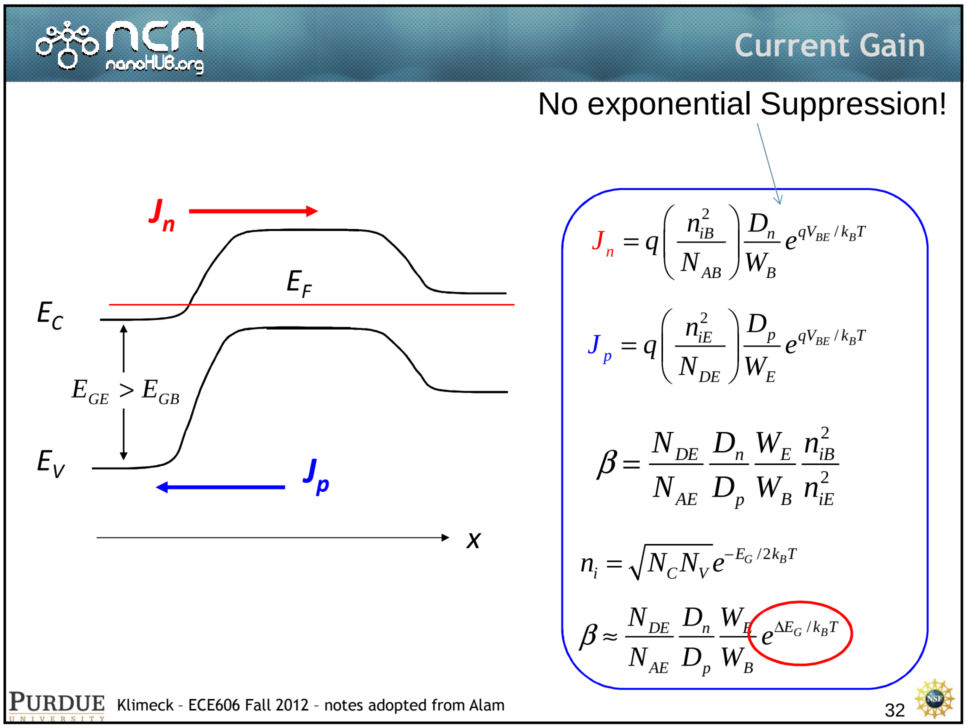
$$E_V(x) = E_C(x) - E_G(x)$$



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

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

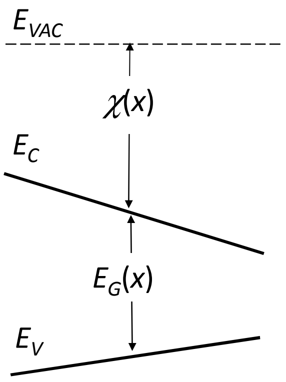
$\frac{D_n/W_B}{\upsilon_s} \longrightarrow$ Graded Base transport

$\upsilon_s \longrightarrow$ Polysilicon Emitter

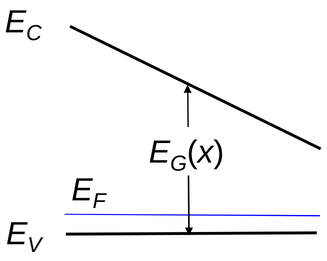
$\frac{n_{i,B}^2}{n_{i,E}^2} \downarrow$ Heterojunction bipolar transistor

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

Graded Bases

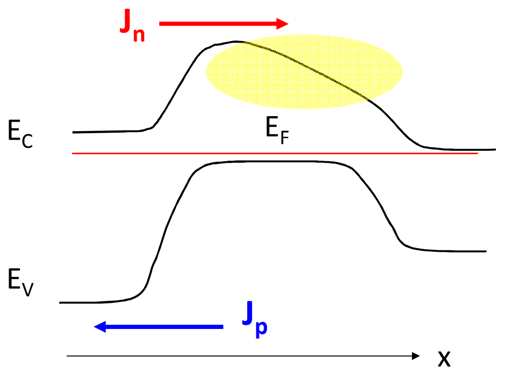


Intrinsic
compositionally graded



Uniformly p-doped
compositionally graded

Graded Base HBTs



Base transit time

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

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

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

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

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

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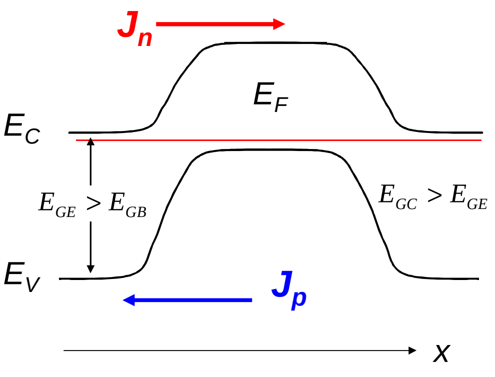
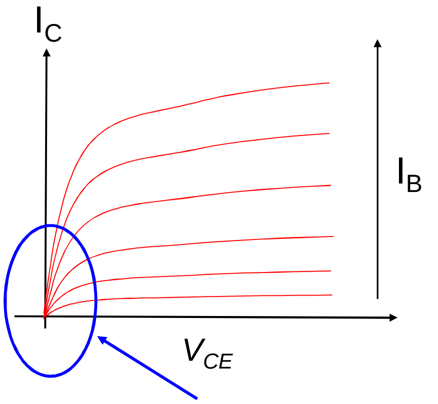
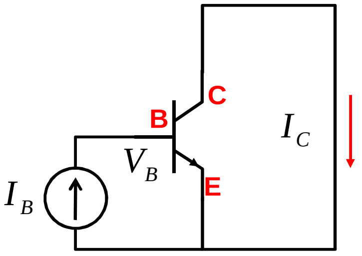
Double HBJT



- Symmetrical operation (simplify circuiots)
- No charge storage when the b-c junction is forward biased (ni is smaller)
- Reduced collector offset voltage
- Higher collector breakdown voltage (higher gap)

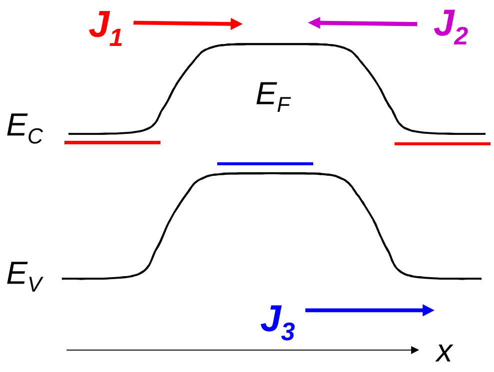
Offset Voltage





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

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

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

Want a large γ_R for small V_{os}. Wide bandgap collector helps.

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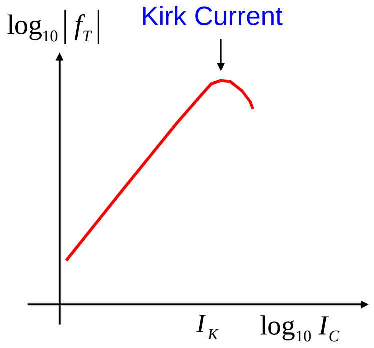
6. Graded junction HBTs
7. Graded base HBTs
8. Double heterojunction HBTs
9. **Conclusions – modern design**

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

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

Putting the Terms Together



Collector transit time

Base transit time

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

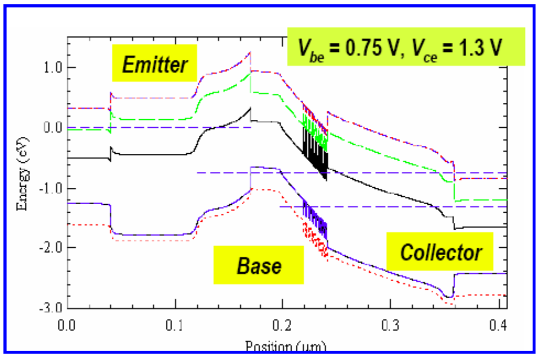
junction charging time …

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

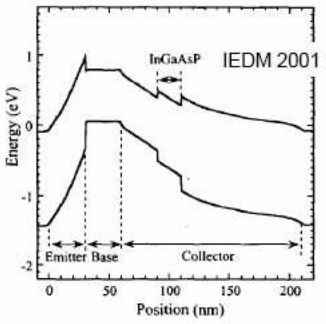


Epitaxial Layer Design (III)

InGaAs/InGaAsP/InP grade

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

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



-suitable for MOCVD growth
- excellent results

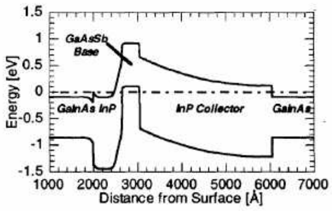
InP/GaAsSb/InP DHBT

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

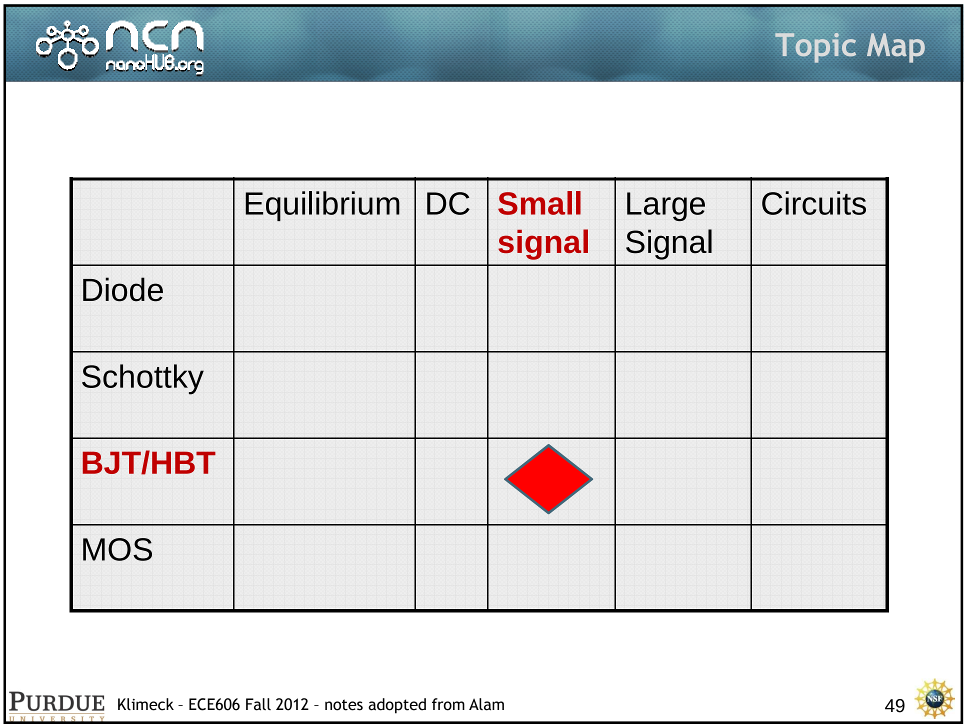
3) Bandgap engineering has potential benefits:
   - -heterojunction launching ramps
   - -compositionally graded bases
   - -elimination of band spikes

4) HBTs have the potential for THz cutoff frequencies. However, it has yield issues and heating and contact R problems.

Outline from previous lecture

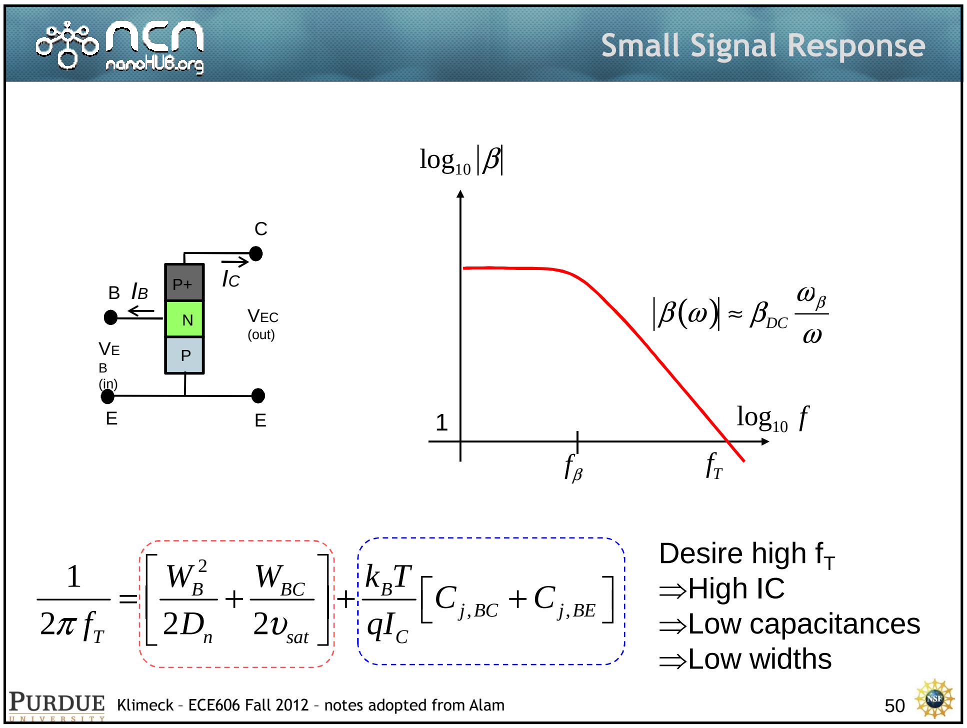
1) Current gain in BJTs
2) Considerations for base doping
3) Considerations for collector doping
4) Intermediate Summary
5) Problems of classical transistor
6) Poly-Si emitter
7) Short base transport
8) **High frequency response**
9) Conclusions

REF: SDF, Chapter 10



Topic Map

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

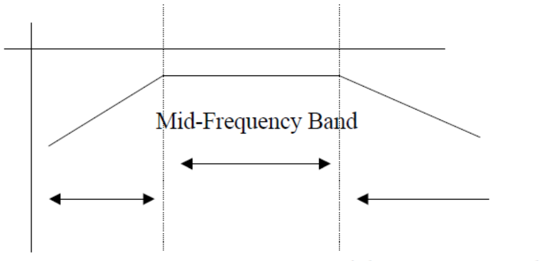


Small Signal Response

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

Desire high f_T
⇒High IC
⇒Low capacitances
⇒Low widths

Frequency Response

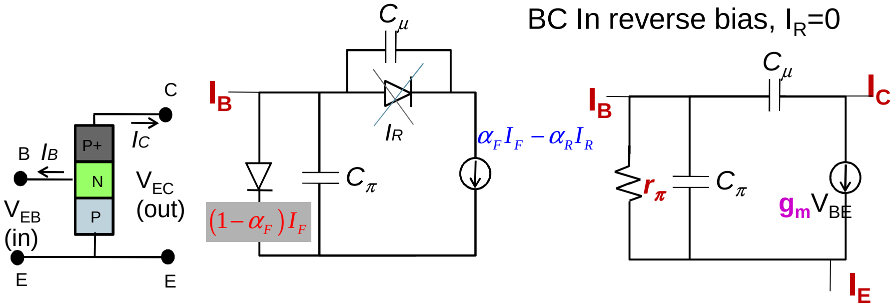


- The gain of an amplifier is affected by the capacitance associated with its circuit.
- This capacitance reduces the gain in both the low and high frequency ranges of operation.
- The reduction of gain in the low frequency band is due to the coupling and bypass capacitors selected. They are essentially short circuits in the mid and high bands.
- The reduction of gain in the high frequency band is due to the internal capacitance of the amplifying device, e.g., BJT, FET, etc.
- This capacitance is represented by capacitors in the small signal equivalent circuit for these devices. They are essentially open circuits in the low and mid bands.

Small Signal Response (Common Emitter) From Ebers Moll Model

DC Circuit

=> AC small signal Circuit
BC In reverse bias, I_R=0



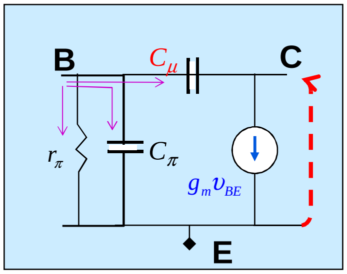
$$\frac{1}{r_\pi} = \frac{dI_B}{dV_{BE}} = \frac{d\left[(1-\alpha_F)I_F\right]}{dV_{BE}} = \frac{qI_B}{k_B T} = \frac{1}{\beta_{DC}}\frac{qI_C}{k_B T}$$

$$I_F = I_{F0}\left(e^{qV_{BE}/kT} - 1\right)$$

$$g_m = \frac{d(\alpha_F I_F)}{dV_{BE}} = \frac{qI_C}{k_B T}$$

$$\delta(\alpha_F I_F) = g_m \delta V_{BE} = g_m \upsilon_{BE}$$

Short Circuit Current Gain



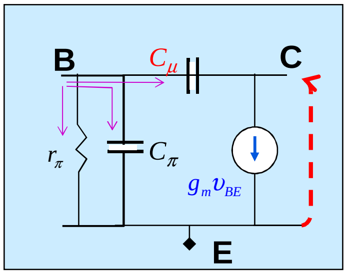
$$\beta(f)=\frac{i_C}{i_B}=\frac{g_m v_{BE}+j\omega C_\mu v_{CB}}{\left(\frac{1}{r_\pi}v_{BE}+j\omega C_\pi v_{BE}\right)+j\omega C_\mu v_{BC}}$$

$$\beta(f_T)\equiv 1=\left|\frac{g_m-j\cancel{\omega_T}C_\mu}{\left(\cancel{\frac{1}{r_\pi}}+j\omega_T C_\pi\right)+j\omega C_\mu}\right|\approx\left|\frac{g_m}{j\omega_T\left(C_\pi+C_\mu\right)}\right|$$

$$\frac{1}{\omega_T}\equiv\frac{1}{2\pi f_T}=\frac{C_\pi+C_\mu}{g_m}:$$

$$\frac{k_B T}{qI_C}C_{d,BC}\overset{\downarrow}{=}\frac{C_{d,BC}}{dI_C/dV_{BE}}=\frac{dQ_B}{dI_C}$$

Short Circuit Current Gain

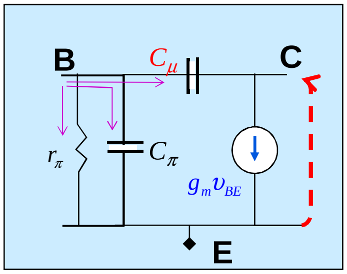


$$\beta(f_T)\equiv 1=\left|\frac{g_m-j\cancel{\omega_T}C_\mu}{\left(\cancel{\frac{1}{r_\pi}}+j\omega_T C_\pi\right)+j\omega C_\mu}\right|\approx\left|\frac{g_m}{j\omega_T\left(C_\pi+C_\mu\right)}\right|$$

$$\frac{1}{\omega_T}\equiv\frac{1}{2\pi f_T}=\frac{C_\pi+C_\mu}{g_m}:$$

$$\frac{k_B T}{qI_C}C_{d,BC}\overset{\downarrow}{=}\frac{C_{d,BC}}{dI_C/dV_{BE}}=\frac{dQ_B}{dI_C}$$

Short Circuit Current Gain



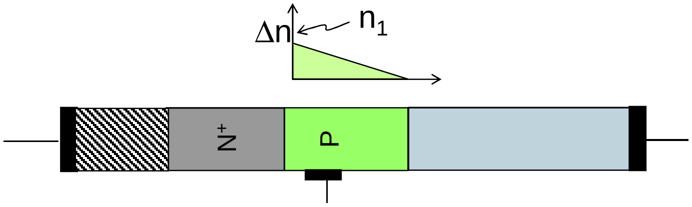
$$\frac{1}{\omega_T} \equiv \frac{1}{2\pi f_T} = \frac{C_\pi + C_\mu}{g_m} = \boxed{\frac{k_B T}{q I_C}\left(C_{j,BC} + C_{j,BE}\right)} + \boxed{\frac{k_B T}{q I_C}\left(C_{d,BC} + \cancel{C_{d,BE}}\right)}$$

$$\downarrow$$

$$\frac{k_B T}{q I_C} C_{d,BC} = \frac{C_{d,BC}}{dI_C / dV_{BE}} = \frac{dQ_B}{dI_C}$$

Base Transit Time

Ref. Charge control model

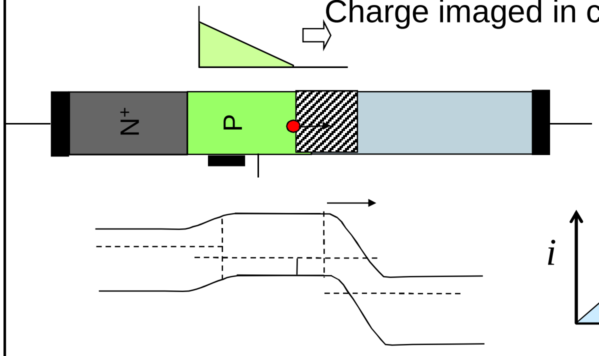


$$\boxed{\frac{dQ_B}{dI_C} = \frac{Q_B}{I_C} = \frac{q\frac{1}{2}n_1 W_B}{q\frac{n_1}{W_B}} = \frac{W_B^2}{2D_n}}$$

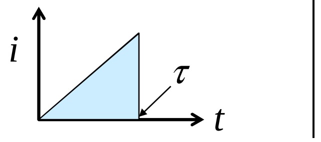
Base transit time

Collector Transit Time

Electrons injected into collector depletion region – very high fields more than diffusion => drift => acceleration of carriers
Charge imaged in collector



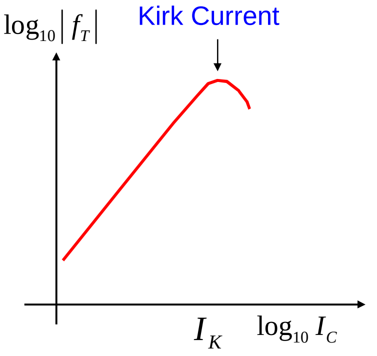
$$\tau = \frac{W_{BC}}{v_{sat}} ?$$



$$\tau_{eff,BC} = \frac{q}{i} = \frac{\tau}{2} = \frac{W_{BC}}{2v_{sat}}$$

$$\frac{1}{2} \times i \times \tau = q$$

Putting the Terms Together



Collector transit time

Base transit time

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

Junction charging time

Do you see the motivation to reduce WB and W_{BC} as much as possible?
What problem would you face if you push this too far ?

Increasing I_C too high reduces W_{BC} and increases the overall capacitance => frequency rolls off….

High Frequency Metrics

(current-gain cutoff frequency, f_T)

$$\tau = \frac{1}{2\pi f_T} = \frac{W_B^2}{2D_n} + \frac{W_{BC}}{2\upsilon_{sat}} + \frac{k_B T/q}{I_C}\left(C_{j,BE} + C_{j,BC}\right) + \left(R_{ex} + R_c\right)C_{cb}$$

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

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

Summary

We have discussed various modifications of the classical BJTs and explained why improvement of performance has become so difficult in recent years.

The small signal analysis illustrates the importance of reduced junction capacitance, resistances, and transit times.

Classical **homojunctions** BJTs can only go so far, further improvement is possible with **heterojunction** bipolar transistors.