EE-612: Lecture 33: Heterojunction Bipolar Transistors

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Outline

I) Introduction

II) BJT Review

III) The Widegap Emitter

IV) Modern HBTs

V) Summary

Reference:
pn heterojunction with no band spike

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

\[ J_p = q \left( \frac{n_{iN}^2}{N_D} \right) \frac{D_P}{W_N} \left( e^{qV_A/k_B T} - 1 \right) \]
pn heterojunction with CB band spike

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

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

Lundstrom EE-612 F06 4
bipolar transistors

double diffused BJT
bipolar transistors: I-V

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

Early effect

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

high-level injection
series resistance etc.

60 mV/decade
heterojunction bipolar transistors

i) wide gap emitter HBT

ii) double heterojunction bipolar transistor
mesa HBTs

$E_{G1} > E_{G2}$

$p^+ base$

$n$ emitter

$n$ collector

$n^+$

semi-insulating substrate

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

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minority carrier injection

base diffusion current

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

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

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

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

\[ \beta = \frac{I_C}{I_B} = \frac{J_n}{J_p} = \frac{N_{DE}}{N_{AE}} \frac{D_n}{D_p} \frac{W_E}{W_B} \]
ac model

\[ I_C = \beta_{DC} I_B \]

\[ i_c = \beta_{ac} i_b \]

\[ I_C = q A_E \left( \frac{n_i^2}{N_{AB}} \right) \frac{D_n}{W_B} e^{qV_{BE}/k_B T} \]

\[ g_m = I_C / (k_B T / q) \]

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

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

\[ \omega_\beta = \frac{1}{r_\pi C_\pi} \]

\[ |\beta(\omega)| = \frac{\beta_{DC}}{\sqrt{1 + \left(\frac{\omega}{\omega_\beta}\right)^2}} \]
\[ |\beta(\omega)| = \frac{\beta_{DC}}{\sqrt{1 + (\omega/\omega_T)^2}} \]

\[ |\beta(\omega_T)| = 1 = \beta_{DC} \frac{\omega_T}{\omega} \]

\[ \omega_T = \beta \omega_T = \frac{\beta}{r_\pi C_\pi} = \frac{g_m}{C_\pi} \]

\[ (\omega_T = 1/r_\pi C_\pi) \]

\[ \omega_T = 2\pi f_T = \frac{g_m}{C_\pi} \]

\[ \tau = \frac{1}{\omega_T} = \frac{1}{2\pi f_T} = \frac{C_\pi}{g_m} \]
high frequency metrics

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

(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, \(f_{\text{max}}\))

\[
f_{\text{max}} = \sqrt{\frac{f_T}{8\pi R_{bb} C_{cb}}}
\]
BJT design

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 $C_{je}$)

$$\beta = \frac{N_{DE} D_n W_E}{N_{AE} D_p W_B}$$
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\[
J_n = q \left( \frac{n_{iB}^2}{N_{AB}} \right) \frac{D_n}{W_B} e^{q V_{BE}/k_B T}
\]

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

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

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

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

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

\[ J_p = q \left( \frac{\bar{n}_{iE}^2}{N_{DE}} \right) \frac{D_p}{W_E} e^{qV_{BE}/k_BT} \]

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

\[ \tau_b = \frac{W_B}{\mu_n \mathcal{E}_{\text{eff}}} \]

\[ \mathcal{E}_{\text{eff}} = \frac{\Delta E_G / q}{W_B} \]
abrupt junction HBTs

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

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

\[ \beta = \frac{N_{DE}}{N_{AE}} \left( \frac{D_p}{W_E} \right) \frac{\nu_{Rp} n_{iB}^2}{n_{iE}^2} e^{-\Delta E_C / k_B T} \]

\[ \beta = \frac{N_{DE}}{N_{AE}} \left( \frac{D_p}{W_E} \right) e^{\Delta E_V / k_B T} \]
double HBJT

- symmetrical operation
- no charge storage when the b-c junction is forward biased
- reduced collector offset voltage
- higher collector breakdown voltage
does $I_C = 0$ at $V_{CE} = 0$?
offset voltage

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

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

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

\[ J_C = J_1 - J_2 - J_3 \]

set \( J_C = 0 \), assume \( V_E = 0 \), solve for \( V_C = V_{OS} \)
offset voltage result

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

\[ \gamma_R = \frac{J_2}{J_3} = \left(\frac{n_{iB}^2}{N_{AB}}\right)\left(\frac{D_n}{W_B}\right) \left(\frac{n_{iC}^2}{N_{DC}}\right)\left(\frac{D_p}{W_C}\right) \] (reverse emitter injection efficiency)

Want a large \( \gamma_R \). Wide bandgap collector helps.

Exercise: show how \( V_{OS} \) depends on \( \Delta E_C \) and junction area differences.
offset voltage reason
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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

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Thickness (Å)</th>
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<tbody>
<tr>
<td>InGaAs 3E19</td>
<td>Si 400</td>
</tr>
<tr>
<td>InP 3E19</td>
<td>Si 800</td>
</tr>
<tr>
<td>InP 8E17</td>
<td>Si 100</td>
</tr>
<tr>
<td>InP 3E17</td>
<td>Si 300</td>
</tr>
<tr>
<td>InGaAs 8E19</td>
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<td>Setback 3E16</td>
<td>Si 200</td>
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<td>Si 240</td>
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<td>Si 30</td>
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<tr>
<td>InP 3E16</td>
<td>Si 1030</td>
</tr>
<tr>
<td>InP 1.5E19</td>
<td>Si 500</td>
</tr>
<tr>
<td>InGaAs 2E19</td>
<td>Si 125</td>
</tr>
<tr>
<td>InP 3E19</td>
<td>Si 3000</td>
</tr>
<tr>
<td>SI-InP substrate</td>
<td></td>
</tr>
</tbody>
</table>

$V_{be} = 0.75 \text{ V}$, $V_{ce} = 1.3 \text{ V}$
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

- 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

InP/GaAsSb/InP DHBT

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

Device Performance: ~400 GHz \( f_\tau \) and ~500 GHz \( f_{\text{max}} \)

Has enabled 150 GHz digital clock rate (static dividers)

Should enable 300 GHz power amplifiers (175 GHz realized with 300 GHz \( f_{\text{max}} \))

Emitter: 500 nm width, 15 \( \Omega \cdot \mu \text{m}^2 \) contact resistivity

Base contact: 300 nm width, 20 \( \Omega \cdot \mu \text{m}^2 \) contact resistivity

Collector: 150 nm thick, 5.1 V breakdown (BVCEO) 5 mA/\( \mu \text{m}^2 \) current density 10 mW/\( \mu \text{m}^2 \) power density @ 2V 15 K/(mW/\( \mu \text{m}^2 \)) thermal resistance
modern HBTs

Key scaling challenges:

- emitter & base contact resistivity
- current density $\rightarrow$ 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: \( R_{\text{sheet}} = 610 \ \text{W/sq}, \ R_{\text{cont}} = 4.6 \ \Omega \times \mu \text{m}^2 \)
Collector: \( R_{\text{sheet}} = 12.1 \ \Omega/\text{sq}, \ R_{\text{cont}} = 8.4 \ \Omega \times \mu \text{m}^2 \)

Courtesy Mark Rodwell, UCSB
high-frequency performance

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

\[ U_{\text{ajbe}} = 0.6 \times 4.3 \, \text{um}^2 \]
\[ I_c = 20.6 \, \text{mA}, \quad V_{ce} = 1.53 \, \text{V} \]
\[ J_e = 8.0 \, \text{mA/um}^2, \quad V_{cb} = 0.6 \, \text{V} \]
\[ f_t = 450 \, \text{GHz}, \quad f_{\max} = 490 \, \text{GHz} \]
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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
The idea of the wide bandgap emitter dates to the 1950’s, but the modern story begins with:


For an update on current practice, see: