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

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<thead>
<tr>
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<th>Equilibrium</th>
<th>DC</th>
<th>Small signal</th>
<th>Large Signal</th>
<th>Circuits</th>
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<tbody>
<tr>
<td>Diode</td>
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<td>Schottky</td>
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<td>BJT/HBT</td>
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<td><strong>Red Diamond</strong></td>
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<td>MOS</td>
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</table>
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

\[ J_{n,B\rightarrow E} = q \left( \frac{n_{iB}^2}{N_B} \right) \nu_R p e^{-\Delta E_C / k_B T} = J_n(V_{BE} = 0) \]

\[ J_n = q \left( \frac{n_{iB}^2}{N_B} \right) \nu_R p e^{-\Delta E_C / k_B T} e^{qV_{BE} / k_B T} \]

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

\[ \beta = \frac{N_E}{N_B} \frac{\nu_R}{D_p / W_E} \left[ \frac{n_{iB}^2}{n_{iE}^2} e^{-\Delta E_C / k_B T} \right] \]

\[ \beta = \frac{N_{DE}}{N_{AE}} \frac{\nu_R}{D_p / W_E} e^{\Delta E_V / k_B T} \]

Gain in abrupt npn BJT defined only by valence band discontinuity!
... but we are hoping for even better gain

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

$$\beta = \frac{N_E}{N_B} \left( \frac{\nu_{R,p}}{D_p / W_E} \right) e^{\Delta E_v / k_BT} \quad \text{Abrupt junction HBT}$$

For full gain, we need graded junction HBT
Outline

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

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

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

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

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

\[ \beta \approx \frac{N_{DE} D_n W_E}{N_{AE} D_p W_B} e^{\Delta E_G / k_B T} \]
Advantages of HBT: Inverted Base Doping

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

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” \( N_{AB} \gg N_{DE} \)
Outline

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How to make a better Transistor

\[ \beta_{\text{poly,ballistic}} \to \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{D_n/W_B}{v_s} \to \text{Graded Base transport} \]

Heterojunction bipolar transistor

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

Polysilicon Emitter
Graded Bases

$E_{\text{VAC}}$

$\chi(x)$

$E_C$

$E_G(x)$

$E_V$

Intrinsic compositionally graded

Uniformly p-doped compositionally graded
Graded Base HBTs

\[ J_n = q \left( \frac{n_{iB}^2}{N_B} \right) \frac{D_n}{W_B} e^{qV_{BE} / k_B T} \]

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

\[ \beta_{DC} = \frac{N_E}{N_B} \frac{D_n}{D_p} \frac{W_E}{W_B} \frac{n_{iB}^2}{n_{iE}^2} \]

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

\[ \mathcal{E}_{eff} = \frac{\Delta E_G}{q} \]

Alam ECE-606 S09
Outline

1. Abrupt junction HBTs
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5. Conclusions
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

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

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

(Reverse Emitter injection efficiency)

Want a large \( \gamma_R \) for small \( V_{os} \). Wide bandgap collector helps.
1. Abrupt junction HBTs
2. Graded junction HBTs
3. Graded base HBTs
4. Double heterojunction HBTs
5. Conclusions: modern design
Putting the Terms Together

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

Kirk Current

Collector transit time

Base transit time

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

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>InGaAs</td>
<td>3E19 Si 400 Å</td>
</tr>
<tr>
<td>InP</td>
<td>3E19 Si 800 Å</td>
</tr>
<tr>
<td>InP</td>
<td>8E17 Si 100 Å</td>
</tr>
<tr>
<td>InP</td>
<td>3E17 Si 300 Å</td>
</tr>
<tr>
<td>InGaAs</td>
<td>8E19 → 5E19 C 300 Å</td>
</tr>
<tr>
<td>Setback</td>
<td>3E16 Si 200 Å</td>
</tr>
<tr>
<td>Grade</td>
<td>3E16 Si 240 Å</td>
</tr>
<tr>
<td>InP</td>
<td>3E18 Si 30 Å</td>
</tr>
<tr>
<td>InP</td>
<td>3E16 Si 1030 Å</td>
</tr>
<tr>
<td>InP</td>
<td>1.5E19 Si 500 Å</td>
</tr>
<tr>
<td>InGaAs</td>
<td>2E19 Si 125 Å</td>
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<tr>
<td>InP</td>
<td>3E19 Si 3000 Å</td>
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<tr>
<td>SI-InP substrate</td>
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</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/cm²

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

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**InP/GaAsSb/InP DHBT**

InP/GaAsSb/InP DOUBLE HETEROJUNCTION Bipolar Transistors with High Cut-Off Frequencies and Breakdown Voltages


- 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

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- suitable for MOCVD growth
- excellent results
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.