Evaluation of single-transistor extraction methods for HBT series resistances

T. Nardmann\textsuperscript{1)}, J. Krause\textsuperscript{1)}, S. Lehmann\textsuperscript{1)}

\textsuperscript{1)}Chair for Electron Devices and Integr. Circuits, Univ. of Technol. Dresden, Germany

nardmann@iee.et.tu-dresden.de, krause@iee.et.tu-dresden.de
http://www.iee.et.tu-dresden.de/iee/eb/eb_homee.html
OUTLINE

1 Preliminary Considerations
2 Base Resistance
3 Emitter Resistance
4 Collector Resistance
5 Conclusion
1 Preliminary Considerations

- HICUM elements $R_B = R_{Bx} + R_{Bi}$, $R_E$ and $R_{Cx}$
- Measured Data from FHG InP DHBTs and SiGe HBTs
1 Preliminary Considerations

• Extraction from terminal data necessary for single-transistor processes or when no test structures are available

• Focus on single-transistor methods that do not require additional measurement efforts

• Many methods may be available that produce slightly different results; test against model or simulation data can be used to evaluate suitability

• Methods need to be evaluated for each technology or process

• Exact description of methods beyond the scope of this talk
2 Base Resistance extraction

2.1 Preliminary considerations

• Base Resistance influences most figures of merit (FoMs) and many further extraction steps

• Geometry dependence well researched; can be estimated based on materials, process and layout

• Many methods available in literature. Evaluated here:
  - Ning and Tang 1984 [1]
  - Modified Circle Impedance (Nakadei1991) [2]
  - McAndrew 2006 [4]
2 Base Resistance extraction

2.2 Ning and Tang

- Based on real vs. ideal base current; ideal value from model
- From ratio of ideal to actual base current, equation for resistance is developed:
  \[
  \left( \frac{m_{BE} \cdot V_T}{I_C} \right) \ln \left( \frac{I_{B,0}}{I_B} \right) = r_E + \frac{(r_E + r_{B_i} + r_{B_x})}{B_f}
  \]
- Authors claim \( r_{B_i}/B_f = \text{const.} \)
- Intercept with y-axis is \( r_E + r_{B_i}/B_f \), slope is \( (r_E + r_{B_x}) \)
- Assumptions (small \( I_{rec} \), only R-influence on \( I_B \)) may not apply

InP result: \( r_{Bx} = 1141 \, \Omega, r_E = -11 \, \Omega \)

SiGe result: \( r_{Bx} = 18 \, \Omega, r_E = -0.11 \, \Omega \)
2 Base Resistance extraction

2.3 Circle Impedance

\[ h_{11\text{corr}} = \frac{1}{y_{11} + y_{12}} = \frac{1}{g_{BE} + j\omega C_{BE}} + \frac{1}{g_B} \]

\[ Im(h_{11\text{corr}}) = \pm \sqrt{\left(\frac{1}{2g_{BE}}\right)^2 - \left(Re(h_{11\text{corr}}) - \frac{1}{g_B} + \frac{1}{2(g_{BE})}\right)^2} \]

- Intercept of semicircle with x-axis (interpolation for f -> \infty) corresponds to R_B

- Fit performed on \( y^2 = R^2 - (x - x_0)^2 \) to avoid imaginary values

- Results questionable; some values of Re(h_{11corr}) negative

- Inconclusive or even inapplicable for modern transistors

SiGe result: \( r_{Bx} = 11 \Omega \)
2 Base Resistance extraction

2.4 Gobert

- AC-based extraction
- According to publication, calculation of $r_{Bi}$ at all bias points not possible
- Asymptote of $\text{Re}(Z_{11}-Z_{12})$ for large currents should give $r_{Bx}$
- Values are in the correct range for both transistors
- Fit function used: $Z = \frac{p_2}{I_B} + p_2$

InP result: $r_{Bx} = 13.4 \, \Omega$

SiGe result: $r_{Bx} = 9.6 \, \Omega$
2 Base Resistance extraction

2.5 McAndrew 2006

• DC method

• Based on difference quotient to determine conductances

• $r_B$ and $r_E$ calculated; both show strong variation in low bias range

\[
\begin{align*}
    r_E &= \frac{1 / G_{\pi}}{B_f \left( 1 + \frac{\partial \log(B_f)}{\partial \log(I_B)} \right) - \frac{G_o}{G_r}} \\
    r_B &= \frac{V_{BE} - V_{B'E'}}{I_B \cdot r_B \cdot (1 + B_f)}
\end{align*}
\]

• Results for $R_E$ similarly erratic, with larger value range

InP result: $r_{Bx} = 0.1 \, \Omega$, $r_E = 6.6 \, \Omega$

SiGe result: $r_{Bx} = 0.2 \, \Omega$, $r_E = 4.1 \, \Omega$
3 Emitter Resistance extraction

3.1 Preliminary considerations

• Many methods exist

• Large influence on DC characteristics due to negative feedback

• Often simple geometry dependence

• When multiple devices available, extraction can be verified via scaling rules

• Methods evaluated
  - $g_{mi}$ method [5]
  - Open-Collector method [6]
  - Gobert 1997 [3]
  - Huszka 2009 [7]
3 Emitter Resistance extraction

3.2 $g_{mi}$

- Uses relationship between $g_m$, $g_{mi}$ and $r_E$
- $g_m$ taken from $\text{Re}(y_{21})$, $g_{mi}$ from model

\[
\frac{1}{g_m} = \frac{1}{g_{mi}} + r_E \left(1 + \frac{1}{\beta_f}\right) + \frac{r_B}{\beta_f}
\]

- for large $\beta_f$, $1/\beta_f$ fractions can be neglected; for InP, several % error can be introduced

- extended version taking into account current dependence of $m_{cf}$ exists and has been used

InP result: $r_E = 8.6 \, \Omega$

SiGe results: $r_E = 2.0 \, \Omega$
3 Emitter Resistance extraction

3.3 Open-collector

- Follows formulation of Gabl and Reisch
- Calculation of \( V_{CE} \) for \( I_C = 0 \) based on physical knowledge
  \[ V_{CE} = r_E I_E + \frac{2V_T}{\mu_{n,c}} \ln \left( 1 + \sqrt{I_E/I_{oS}} \right) \]
  \[ \frac{1}{1 + \frac{\lambda \cdot \mu_{p,c}}{\mu_{n,c}}} \]
- Since some necessary values unknown, preliminary investigation with nonlinear fit
  \[ V_{CE} = x_1 I_E + x_2 \ln \left( 1 + \sqrt{I_E/x_3} \right) \]

SiGe result: \( r_E = 2.6 \, \Omega \)

InP result: \( r_E = 3.0 \, \Omega \)
3 Emitter Resistance extraction

3.4 Gobert

- Extraction from AC measurement

- Original publication uses $I_B$; however, $I_C$ should be used

- Extrapolation of $\text{Re}(Z_{12})$ towards infinite current

- For infinite currents, internal resistances tend to zero

- Extracts values in proper range for both technologies

InP result: $r_E = 3.1 \, \Omega$

SiGe result: $r_E = 2.2 \, \Omega$
3 Emitter Resistance extraction

3.5 Huszka

- Based on $g_{mi}$ method
- Reformulation to eliminate need for linear regression
- $r_E = \frac{\text{Im}(\tilde{h}_{11e})}{\text{Im}(\tilde{h}_{21e})} - \text{Re}\left(\frac{1}{h_{21e}}\right) \cdot \frac{V_T}{I_B}$
- Extraction point for $R_E$ chosen as that with lowest derivative w.r.t. $V_{BE}$
- Good results for both technologies

InP result: $r_E = 3.3 \ \Omega$

SiGe result: $r_E = 4.0 \ \Omega$
4 Collector Resistance extraction

4.1 Preliminary considerations

• Very few methods available in literature
• Extraction usually performed via test structures; even then not trivial
• Calculation from geometry often difficult, many ways of contacting the collector exist
• Impact on DC characteristics usually small
• Incorrect value impacts AC time constants
4 Collector Resistance extraction

4.2 Gobert

- Similar to $R_E$ extraction
- Interpolation of $\text{Re}(Z_{22} - Z_{12})$ towards infinite current
- Results are uncertain
  - For InP, region may be right, but geometry scaling is not satisfactory
  - For SiGe, value is most likely too large

InP result: $r_{Cx} = 26.5 \, \Omega$

SiGe result: $r_{Cx} = 26.5 \, \Omega$
5 Conclusion

Result overview

<table>
<thead>
<tr>
<th>Technology</th>
<th>InP</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>r_{Bi}</td>
<td>r_{Bx}</td>
<td>r_{Cx}</td>
<td>r_{E}</td>
<td>r_{Bi}</td>
<td>r_{Bx}</td>
<td>r_{Cx}</td>
<td>r_{E}</td>
<td>r_{Bi}</td>
<td>r_{Bx}</td>
<td>r_{Cx}</td>
<td>r_{E}</td>
<td>r_{Bi}</td>
<td>r_{Bx}</td>
<td>r_{Cx}</td>
</tr>
<tr>
<td>Ning and Tang</td>
<td>n/a</td>
<td>1142</td>
<td>-</td>
<td>-12</td>
<td>-</td>
<td>18.6</td>
<td>-</td>
<td>-0.1</td>
<td>n/a</td>
<td>102</td>
<td>-</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle Impedance</td>
<td>n/a</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>13.5</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gmi</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open collector</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAndrew</td>
<td>n/a</td>
<td>0.15</td>
<td>-</td>
<td>6.5</td>
<td>n/a</td>
<td>0.15</td>
<td>-</td>
<td>4.2</td>
<td>n/a</td>
<td>-1</td>
<td>-</td>
<td>-0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gobert</td>
<td>-</td>
<td>12.3</td>
<td>25.8</td>
<td>3.3</td>
<td>-</td>
<td>19.2</td>
<td>25.8</td>
<td>1.5</td>
<td>-</td>
<td>5.6</td>
<td>25.7</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huszka</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>model values</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.67</td>
<td>9.32</td>
<td>1.88</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5 Conclusion

• Base resistance
  - no satisfactory method found for $R_B$

• Emitter resistance
  - several methods available with comparable results
  - exact method chosen may depend on process in question
  - Gobert method yields best results wrt. model value

• Collector resistance
  - Only one method found, results are insufficient

• For single-transistor extraction, results are not reliable

• Use of test structures for modern processes highly recommended
Brief method failure analysis

- SiGe: model for $I_{RE}$ and $I_{BE}$ necessary
  - Extraction range for $I_{BE}$ must be chosen high
  - Often only one component assumed in methods

- InP almost ideal logarithmic to very high voltages
  - where $\Delta I_B$ visible: other effects (thermal, current blocking) relevant
  - in lower region, measurement variation relevant ($I_{B,meas} > I_{B,ideal}$)
Acknowledgments

This work was financially supported by the European DOTFIVE project. Wafer material was provided by Infineon. The Fraunhofer Institut für angewandte Festkörperphysik, Freiburg, is acknowledged for providing InP HBTs.

Thank you for your attention
References

Additional slides

• Circle impedance method applied to simulation

\[ r_B \text{ according to circle impedance method} \]
Additional slides

- Gobert $r_{Bx}$ method applied to simulation

$r_{Bx}$ according to Gobert method

![Graph showing $r_{Bx}$ vs. $J_C$]
Additional slides

- Gobert $r_{Cx}$ method applied to simulation
Additional slides

- Gobert $r_E$ method applied to simulation

![Graph showing extraction of $r_E$]

- X: Meas data used in extraction
- Line: Linear fit
- O: Meas data not used in extraction

$Re(Z_{12})$ (Ω) vs. $1/I_C (1/\text{mA})$
Additional slides

- Huszka method applied to simulation

Extraction of $r_e$ according to Huszka
Additional slides

- McAndrew method applied to simulation

\[ r_B \text{ extracted according to McAndrew} \]

Graph showing \( r_B \) in \( \Omega \) vs. \( J_C \) in \( \text{mA/\mu m}^2 \).
Evaluation of single-transistor extraction methods for HBT series resistances

Additional slides

- Ning-Tang method applied to model

![Graph showing extraction of $r_B$ and $r_E$ using Ning-Tang-Method](image)

- Meas points chosen for fit
- Meas points not chosen for fit
- Linear fit
Additional slides

- $g_{mi}$ method applied to simulation
Additional slides

- $r_{Bi}/B_f$ vs. $I_C$ for Ning-Tang method (model results)