Temperature Dependence of the Relevant Sheet Resistances in SiGe Heterojunction Bipolar Transistors

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November 25th, 2016
AK Bipolar, München
Agenda

1. Introduction
2. Physics of Semiconductors Conductivity
3. Temperature Dependence of Resistances in HBT Models
4. Sheet Resistance Measurements
5. Results
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November 25th, 2016
Introduction

Already at university we learn:

Semiconductors are “hot” conductors – contrary to metals!

But is it really so simple?

In our SiGe heterojunction bipolar transistor (HBT) models:

\[ R_*(T) = R_*(T_{NOM}) \cdot \left( \frac{T}{T_{NOM}} \right)^\zeta_{R*} \]

with temperature coefficient \( \zeta_{R*} = 0 \) in default \( \rightarrow \) no dependence of \( R \) on \( T \)!

The actual series resistances to model are

- Emitter resistance \( R_E \rightarrow \zeta_{RE} \)
- Internal base resistance \( R_{bi} \rightarrow \zeta_{RBI} \)
- External base resistance \( R_{bx} \rightarrow \zeta_{RBX} \)
- External collector resistance \( R_{cx} \rightarrow \zeta_{RCX} \)

Now, how do we get the zetas?

- Just fine tuning of HBT characteristics ?
- Or check \( R(T) \) of special sheet resistance test structures in range \([-40^\circ C...125^\circ C]\) ?
Temperature dependence of resistivity in semiconductors:

\[ \rho(T) = \frac{1}{q\left(\mu_n(T)n(T) + \mu_p(T)p(T)\right)} \]

- For intrinsic semiconductors: \( n_i \propto T^{1.5} \cdot \exp\left[\frac{-E_G(T)}{2k_B T}\right] \)
- \( n_i(T) \) is dominated by \( \exp\left[-\frac{1}{T}\right] \)
Physics of Semiconductors Conductivity

Temperature dependence of resistivity in semiconductors:

\[ \rho(T) = \frac{1}{q(\mu_n(T)n(T) + \mu_p(T)p(T))} \]

- For doped semiconductors:
  - High T (>100°C): \( n_i \) dominates
  - Low T (<-100°C): freeze out of dopants
  - Medium T: dopants fully activated \( \rightarrow n \approx \text{constant} \)

\[ N_D = 10^{15} \text{ cm}^{-3} \]

Sze, Sem. Dev., 1985
Temperature dependence of resistivity in semiconductors:

\[ \rho(T) = \frac{1}{q(\mu_n(T)n(T) + \mu_p(T)p(T))}, \mu(T) = q \frac{\tau_c(T)}{m} \]

- Mean collision time:
  \[ \frac{1}{\tau_C} = \frac{1}{\tau_{C,\text{lattice}}} + \frac{1}{\tau_{C,\text{impurity}}} \]

- At high temperatures and low doping lattice scattering dominates:
  \[ \mu(T) \propto T^{-\frac{3}{2}} \]

- At low temperatures and high doping impurity scattering dominates:
  \[ \mu(T) \propto T^{+\frac{3}{2}} \]
Conductivity of Semiconductors

Temperature dependence of resistivity in semiconductors:

\[ \rho(T) = \frac{1}{q(\mu_n(T)n(T) + \mu_p(T)p(T))}, \mu(T) = q \frac{\tau_c(T)}{m} \]

Altogether \( \rho(T) \) looks like:

http://www.physik.uni-wuerzburg.de/einfuehrung/SS06/13%20Leitung%20Festkoerper.pdf

http://www.ihp-microelectronics.com | © 2016 - All rights reserved | Temperature Dependence Resistances – AK Bipolar | November 25th, 2016
Temperature Dependence of Resistances in HBT Models

Examples from different models of high-performance SiGe HBTs:

\[ R^*_T (T) = R^*_T (T_{NOM}) \cdot \left( \frac{T}{T_{NOM}} \right)^{\zeta_{R^*}} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Model A (HICUM)</th>
<th>Model B (HICUM)</th>
<th>Model C (VBIC)</th>
<th>Model D (HICUM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ζ_{RBi}</td>
<td>0.30</td>
<td>0.5</td>
<td></td>
<td>-1.0</td>
</tr>
<tr>
<td>ζ_{RBx}</td>
<td>0.06</td>
<td>0.3</td>
<td>0.4</td>
<td>-0.5</td>
</tr>
<tr>
<td>ζ_{RCx}</td>
<td>-0.03</td>
<td>0.0</td>
<td>0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>ζ_{RE}</td>
<td>-0.96</td>
<td>-1.0</td>
<td>-0.5</td>
<td>-1.6</td>
</tr>
</tbody>
</table>

- Models B and C belong to SG13, models A and D to other HBTs.
- ζ_{RE} is always negative (-0.5 ... -1.0), others vary between (-1.0 .... 0.5)
Sheet Resistance Measurements

Kelvin measurement test structure:

Sheet resistance $R_S = R \frac{W}{L}$

For statistics: RS measurements at 9 dies.
# Sheet Resistance Measurements

## 4 types of layers:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPLYA</td>
<td>Emitter poly-Si on p-doped epi base</td>
<td>$\rightarrow ??$</td>
</tr>
<tr>
<td>EPLYX</td>
<td>Emitter poly-Si on oxide (no Emitter window)</td>
<td>$\rightarrow \zeta_{RE}$</td>
</tr>
<tr>
<td>BPLY</td>
<td>p$^+$-doped external base on oxide</td>
<td>$\rightarrow \zeta_{RBx}$</td>
</tr>
<tr>
<td>CX</td>
<td>n$^+$ collector under oxide</td>
<td>$\rightarrow \zeta_{RCx}$</td>
</tr>
</tbody>
</table>

**Example technology:**

IHP’s SG13 high-performance HBT ($f_T/f_{max} = 250$GHz/300GHz)
Results I

Temperature dependence of external base (BPLY) and collector (CX):

Models:
- $\zeta_{RBx}$: 0.1…0.4 $\rightarrow$ o.k.
- $\zeta_{RCx}$ around 0 $\rightarrow$ coefficient to low?!
Results II

Temperature dependence of EPLA and poly-crystalline emitter layer (EPLYX):

Temperature dependence of EPLA and poly-crystalline emitter layer (EPLYX):

\[ R_S = R_{S,300K} \times \left( \frac{T}{300} \right)^{0.49} \]

Does result represent \( \zeta_{RBI} \) ?? Then models A-C o.k.

\[ R_S = R_{S,300K} \times \left( \frac{T}{300} \right)^{-0.28} \]

Models: \( \zeta_{RE} < -0.5 \) \( \rightarrow \) coefficient to low?!
The temperature dependence of semiconductor sheet resistance not well defined in the technologically most interesting temperature range around 300K.

Models provide temperature coefficients $\zeta_{RE}$, $\zeta_{RBi}$, $\zeta_{RBx}$, and $\zeta_{RCx}$. Their default value is 0.

$R_S(T)$ are best fitted linearly.

Measurement of sheet resistances representing in the temperature range [-40°C...125°C] leads to

<table>
<thead>
<tr>
<th>$\zeta_{RE}$</th>
<th>$\zeta_{RBi}$</th>
<th>$\zeta_{RBx}$</th>
<th>$\zeta_{RCx}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Thank you for your attention!

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