HICUM/L0 - Extraction results and experience

M. Schroter\textsuperscript{1,2}, S. Lehmann\textsuperscript{1}, B. Ardouin\textsuperscript{3}

\textsuperscript{1}Chair for Electron Devices and Integrated Circuits, Univ. of Technology Dresden, Germany
\textsuperscript{2}Dept. of Electrical and Computer Engin., University of California San Diego, USA
\textsuperscript{3}XMOD Technologies, Bordeaux, France

http://www.iee.et.tu-dresden.de/iee/eb/eb_homee.html

Bipolar Arbeitskreis
Reutlingen, October 2005
OUTLINE

• Introduction
• Temperature dependent model formulation
• High-current correction
• More experimental results
• Summary
Introduction

HICUM / Level0 - status overview

• Version 1.1
  • improved Verilog implementation
    • based on Level2 coding experience
    • equation extensions: avalanche current, rBi, self-heating, limitation for diode currents
  • simulator implementation via model compilers
    • Level0 (due to its simplicity) was initially used to set up model compilers (ADMS, Tiburon)
    • excellent help from Cadence to obtain consistent version at both sites

• Documentation
  • see new web-site
  • not as complete yet as for Level2 (lack of time, financial support)
  • see IEEE TED

• Evaluations for a variety of process technologies
  • Atmel, Infineon, Jazz, ST, ...

  This presentation: additional results
Temperature dependent model formulation

Self-heating

• simple single-pole network with thermal resistance and capacitance

• externally accessible thermal node

\[ \Delta T = P_{th} R_{th} \]

\[ P_{th} = |i_T V_{C'E'}| + |i_{Avl} V_{C'B'}| \]

more terms?

=> still being debated
Bandgap

\[ V_g(T) = V_g(T_0) + k_1 \frac{T}{T_0} \ln \left( \frac{T}{T_0} \right) + k_2 \left( \frac{T}{T_0} - 1 \right) \quad , \quad T_0 = \text{reference temperature} \]
Depletion Capacitances: built-in voltage

\[ V_D(T) = V_{Dj}(T) + 2V_T \ln \left( \frac{1 + \sqrt[4]{1 + 4 \exp \left( -\frac{V_{Dj}(T)}{V_T} \right)}}{2} \right) \]
Depletion Capacitances: built-in voltage

\[
V_{Dj}(T) = V_{Dj}(T_0) \left( \frac{T}{T_0} \right) - V_{g(X,Y)}(0) \left( \frac{T}{T_0} - 1 \right) - m_g V_T \ln \left( \frac{T}{T_0} \right)
\]

with \( V_{Dj}(T_0) = 2V_T \ln \left[ \exp \left( \frac{V_D(T_0)}{2V_T} \right) - \exp \left( - \frac{V_D(T_0)}{2V_T} \right) \right] \)

thermal voltage at reference temperature: \( V_{T0} = \frac{kT_0}{q} \)

coefficient from T dependent bandgap: \( m_g = 3 - \frac{qF_{1VG}}{k_B} \)

average junction bandgap voltage: \( V_{g(X,Y)} = \frac{V_{gX_{eff}} + V_{gY_{eff}}}{2} \)

\( (X,Y) = \{ \text{BE, BC, SC} \} \)
Depletion Capacitances

max. capacitance ratio $a_j(T)$

zero bias capacitance $C_{j0}(T)$

\[ a_j(T) = a_j(T_0) \left( \frac{V_D(T)}{V_D(T_0)} \right) \]

\[ C_{j0}(T) = C_{j0}(T_0) \left( \frac{V_D(T_0)}{V_D(T)} \right)^z \]
Saturation currents

- Transfer current

\[
I_{S}^{*}(T) = I_{S}(T_{0}) \left(\frac{T}{T_{0}}\right)^{\zeta_{CT}} \exp\left[\frac{V_{gB}}{V_{T}(T)}\left(\frac{T}{T_{0}} - 1\right)\right]
\]

- Diodes

\[
I_{XXS}(T) = I_{XXS}(T_{0}) \left(\frac{T}{T_{0}}\right)^{\zeta_{XXT}} \exp\left[\frac{V_{gXX}(0)}{V_{T}(T)}\left(\frac{T}{T_{0}} - 1\right)\right]
\]

with BC current exponential factor \(\zeta_{BCT} = m_{g} + 1 - \zeta_{Ci}\) and substrate current exponential factor \(\zeta_{SCT} = m_{g} + 1 - m_{\mu pS}\), assuming \(m_{\mu pS} = 2.5\).
Saturation currents

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{BE}$</td>
<td>$I_{RES}$</td>
</tr>
<tr>
<td>$I_{RE}$</td>
<td>$I_{RES}$</td>
</tr>
<tr>
<td>$I_{BC}$</td>
<td>$I_{BCS}$</td>
</tr>
<tr>
<td>$I_{SC}$</td>
<td>$I_{SCS}$</td>
</tr>
<tr>
<td>$V_{gXX}$</td>
<td>$V_{gEeff}$</td>
</tr>
<tr>
<td>$V_{gBE}$</td>
<td>calculated</td>
</tr>
<tr>
<td>$V_{gCEff}$</td>
<td>1.114</td>
</tr>
<tr>
<td>$V_{gSEff}$</td>
<td>1.15</td>
</tr>
<tr>
<td>$\zeta_{XXT}$</td>
<td>2.97</td>
</tr>
<tr>
<td>$\zeta_{BET}$</td>
<td>calculated</td>
</tr>
<tr>
<td>$\zeta_{BCT}$</td>
<td>calculated</td>
</tr>
<tr>
<td>$\zeta_{SCT}$</td>
<td>calculated</td>
</tr>
</tbody>
</table>
Series resistances

- same formulation for all series resistances:

\[ r(T) = r(T_0) \left( \frac{T}{T_0} \right)^{\zeta_r}, \quad \zeta_r = \text{temperature coefficient} \]
High-current correction

\[ i_{Tf} = \frac{i_{Tfl}}{\Delta q_{fh} \left( 1 + \frac{q_{p,T}}{q_{p,T}} \right)} \]

with

\[ i_{Tfl} = \frac{i_{Tfi}}{q_{p,T}} \]

and

\[ i_{Tfi} = I_S \exp \left( \frac{V_{BE}}{m_C f V_T} \right) \]

\[ V_{CE}=2.0V, \quad R_{th}=0W/K, \quad I_{Qfh}=1e^{-2}, \quad t_{th}=1e^{-4} \]
Correction charge $\Delta q_{fh}$
comparison with normalized hole charge

$$\Delta q_{fh} = \left( w_{low}^2 + t_{fh} \frac{i_{Qfh}}{I_{CK}} \right) \frac{i_{Tfl}}{I_{Qfh}} \approx \frac{\int_{0}^{Tf} \tau_f dI}{\tau_{f0} I_{Tf}} - 1 \quad \text{with} \quad w_{low} = \frac{w_{i} i_{Tfl}}{w_{C}} = \frac{i_l + \sqrt{i_l^2 + a_{hc}}}{1 + \sqrt{1 + a_{hc}}}$$

$R_{th} = 0 \text{W/K}, I_{Qfh} = 1 \times 10^{-2}, t_{fh} = 1 \times 10^{-4}$

$i_l = 1 - \frac{I_{CK}}{i_{Tfl}}$

$V_{BE}$ [V]

$V_{CE} = 1.0 \text{V}$

$V_{CE} = 1.5 \text{V}$

$V_{CE} = 2.0 \text{V}$
More experimental results

0.18\mu m foundry BiCMOS process

data comparison: measurement (symbols), model (lines)

\( V_{CE/V} = 0.3, 0.5, 1, 2, 3 \)
Forward Gummel characteristics

data comparison: measurement (symbols), model (lines)
Forward output characteristics

(0.2*10, 111)
**Forward output characteristics**

$V_{BE} = (0.65...1)V$, $\Delta V = 0.05V$
Frequency dependence

S-parameter comparison: measurement (symbols), model (lines)

real($S_{11}$) vs. freq

imag($S_{11}$) vs. freq
Frequency dependence

S-parameter comparison: measurement (symbols), model (lines)
Frequency dependence

S-parameter comparison: measurement (symbols), model (lines)

real($S_{12}$)

imag($S_{12}$)
Frequency dependence

S-parameter comparison: measurement (symbols), model (lines)
Summary

• overview on temperature dependent formulation
  => available model parameters, feeling for the characteristics

• comparison with latest data of state-of-the-art 0.18\textmu m BiCMOS process
  => good agreement of all standard device characteristics
  (within the expected validity range of the model)

• apparently high interest in Level0 model
  => implemented already in various commercial simulators
  (see EDA vendors web-sites for present status)

• 2-part IEEE TED paper accepted
  • model background and equations
  • parameter extraction procedure (single geometry)
  • comparison to experimental results with from different technologies
HICUM Workshop

• 2006
  • location: Heilbronn
  • proposed date: June 12 (Mo) & 13 or 13 & 14

• future plans/options
  • moving across continents (Europe, US, Asia)
  • still once a year
  • attach to a conference?
    • US: MTT/RFIC in June, ICMTS in?
    • Europe: ?
    • Asia: ?
  • steering committee?
  • other ideas?