Modification of HiCUM and G-P model card for DFM (Design For Manufacturing) Applications

Sadayuki Yoshitomi

Toshiba Corp, Semiconductor Company
Objective of this work

- **SPICE model (Golden Device)**
- **MASK Design**
- **Process & PT**
- **Assembly**
- **FT**

**DOE/Monte Carlo analysis**

- **Reasonable Estimation**
- **Quick Validation**

**BJT Physical model card**
Key Process variables for Bipolar Transistors’ Fabrication

**Emitter**
- $A_e, N_e, W_e$
- Emitter patterning/Doping concentration

**Base**
- $N_b, W_b, d_{EG}, R_{pinch}$
- Base –epi width Doping concentration / Ge composition

**Collector**
- $N_{sic}, W_{sic}$
- Doping Concentration and Depth of in SiC region

- $N_e, N_E0=3e20$
- $N_b, N_B0=8e18$
- $N_{sic}, N_{sic}=1e17$
- $N_c, N_c=1e19$
Concepts of the DFM functions

(1) Static Characteristics

\[ IB \approx I_{pe} = -\frac{qA_e D_{p-e} n_i^2}{L_{pe} N_{-e}} \exp\left(\frac{qVBE}{kT}\right) \]

\[ Ic \approx I_{nc} = -\frac{qA_c D_{n-b} n_i^2}{W_{-b} N_{-b}} \exp\left(\frac{qVBE}{kT}\right) = IS \cdot \exp\left(\frac{qVBE}{kT}\right) \]

\[ BF \equiv \frac{IC}{IB} = \frac{\left(\frac{qA_c D_{n-b} n_i^2}{W_{-b} N_{-b}}\right)}{\left(\frac{qA_b D_{p-e} n_i^2}{W_{-e} \cdot N_{-e}}\right)} = \frac{D_{n-b} W_{-e} N_{-e}}{D_{p-e} W_{-b} N_{-b}} \]

- \(N_i\) (density of free-electrons)
- \(N_{-e}, N_{-b}\) (Donor in the Emitter, Acceptor in the Base)
- \(D_{n-b}\): Diffusion coefficient of electron in the base
- \(D_{p-e}\), Diffusion coefficient of hole in the emitter
Concepts of the DFM functions

(2) Early Voltage

\[ V_A \cdot C_{JC} = Q_B = A_C \cdot N_b \cdot W_b \]

Accounts for an equivalent voltage for minority carriers needed to fully-charge QB (base charge) via CJC.

(3) Transit time

\[ TF = \frac{W_b^2}{m \cdot D_e} \]

\[ m = 2 \]

Accounts for the transit time of minority carriers traveling in the intrinsic base region with distance of W_B.
Concepts of the DFM functions

(4) Intrinsic base resistance

\[ R_{Bi0} = r_{sbi0} \cdot \frac{b_e}{l_en_e} \cdot \frac{p_b}{W_b} \cdot \left\{ \frac{1}{12} \left( \frac{1}{12} - \frac{1}{28.6} \right) b_e \right\} \equiv \frac{p_b \cdot b_e}{W_b \cdot l_e \cdot n_e} \cdot g_i \]
Concepts of the DFM functions

(5) High Injection

Accounts for the equivalent current providing same amount of currents as that of QB.

G-P

\[ IKF = Ae \cdot \frac{q \int_{0}^{b} N \_ b(x) \cdot dx}{TF} = Ae \cdot \frac{q \cdot m \cdot D \_ e}{W \_ b^2} \int_{0}^{b} N \_ b(x) \cdot dx \]

HiCUM

\[ I_{CK} \approx \frac{v_{\text{eff}}}{r_{Ci0}} \cdot \frac{1}{\sqrt{1 + \left( \frac{v_{\text{eff}}}{V_{\text{lim}}} \right)^2}} \]

\[ r_{Ci0} = \frac{w \_ c}{q \mu_n (N \_ c) N \_ c A_E} \cdot \frac{1}{f_{cs}} \]

\[ V_{\text{lim}} = \frac{v_{sn}}{\mu_n (N \_ c)} w \_ c \]

\[ V_{PT} = \frac{q \cdot N \_ sic}{2\varepsilon_{si}} W \_ sic^2 \]
Formulae of carrier’s mobility and bulk resistances

**Mobility of majority carriers ([6][7] [12])**

\[
\mu_i = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left(\frac{N}{N_{\text{ref}1}}\right)^{\alpha_1}} - \frac{\mu_i}{1 + \left(\frac{N_{\text{ref}2}}{N}\right)^{\alpha_2}}
\]

\[
D_{e(h)} = \frac{kT}{q} \mu_e(h)
\]

**Resistivity**

\[
p_{-i} = 10^{(c_1 \cdot \log_{10}(N_{-i}) + c_2)}
\]

For p-type: \(C_1=-0.699, C_2=11.28\)
For n-type: \(C_1=-0.710, C_2=11.08\)

**Table**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A-As</th>
<th>P</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_{\text{max}}) (cm(^2)V(^{-1})s(^{-1}))</td>
<td>1417.0</td>
<td>1414.0</td>
<td>470.5</td>
</tr>
<tr>
<td>(\mu_{\text{min}}) (cm(^2)V(^{-1})s(^{-1}))</td>
<td>52.2</td>
<td>68.5</td>
<td>44.9</td>
</tr>
<tr>
<td>(\mu_i) (cm(^2)V(^{-1})s(^{-1}))</td>
<td>43.4</td>
<td>56.1</td>
<td>29.0</td>
</tr>
<tr>
<td>(N_{\text{ref}1}) (cm(^{-3}))</td>
<td>9.68E+16</td>
<td>9.20E+16</td>
<td>2.23E+17</td>
</tr>
<tr>
<td>(N_{\text{ref}2}) (cm(^{-3}))</td>
<td>3.43E+20</td>
<td>3.41E+20</td>
<td>6.10E+20</td>
</tr>
<tr>
<td>(\alpha_1)</td>
<td>0.68</td>
<td>0.711</td>
<td>0.719</td>
</tr>
<tr>
<td>(\alpha_2)</td>
<td>2.0</td>
<td>1.98</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Formula for minority carriers

\[
\mu_i^m = \frac{\mu_i}{G(m, c, T)}
\]
Fitting with experimental data


![Graph showing resistivity and mobility as functions of impurity concentration for N-type and P-type materials.](image)

- N-TYPE: Electron
- P-TYPE: Hole
Creation of the DFM function and its implementation

\[ C10 = (qA_E)^2 V_T \mu_B(N_b)N_b^2 = C10(A_E, N_b) \]

\[ KC10 \equiv \frac{c10(A_E, N_b)}{c10(A_{E0}, N_{b0})} \]

\[ = \frac{(qA_E)^2 V_T \mu_B(N_b) \cdot N_b^2}{(qA_{E0})^2 V_T \mu_B(N_{b0}) \cdot N_{b0}^2} \]

\[ = \frac{A_E^2}{A_{E0}^2} \frac{\mu_B(N_b) \cdot N_b^2}{\mu_B(N_{b0}) \cdot N_{b0}^2} \]

\[ = (K_{AE})^2 \cdot \frac{\mu_B(N_b) \cdot N_b^2}{\mu_B(N_{b0}) \cdot N_{b0}^2} \]

\[ New\_C10 = c10(\text{extracted value}) \cdot K_{C10} \]
### List of DFM functions (1)

<table>
<thead>
<tr>
<th>Name</th>
<th>DFM function</th>
<th>HiCUM</th>
<th>Gummel-Poon</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_c10</td>
<td>$(K_{-}Ae)^2 \cdot \frac{\mu_b(N_{-}b) \cdot N_{-}b^2}{\mu_b(N_{-}b0) \cdot N_{-}b0^2}$</td>
<td>C10</td>
<td>IS</td>
</tr>
<tr>
<td>K_hjci</td>
<td>$\exp\left(\frac{a_G}{V_T} (W_{-}b0 - W_{-}b)\right)$</td>
<td>Hjci</td>
<td>(VA)</td>
</tr>
<tr>
<td>K_hjei</td>
<td>$K_{-}Ae \cdot \frac{N_{-}b \cdot W_{-}b - W_{-}b0 \cdot W_{-}b0}{N_{-}b0 \cdot W_{-}b0} \cdot \frac{1}{K_{-}cjci}$</td>
<td>Hjei</td>
<td>(VA)</td>
</tr>
<tr>
<td>K_hfe</td>
<td>$\frac{\mu_n(N_{-}b)N_{-}b^2}{\mu_n(N_{-}b0)N_{-}b0^2} \cdot \frac{\mu_e(N_{-}e)N_{-}e^2}{\mu_e(N_{-}e0)N_{-}e0^2}$</td>
<td>Hfe</td>
<td>--</td>
</tr>
<tr>
<td>K_hfc</td>
<td>$\frac{\mu_n(N_{-}b)N_{-}b^2}{\mu_n(N_{-}b0)N_{-}b0^2} \cdot \frac{\mu_n(N_{-}sic)N_{-}sic^2}{\mu_n(N_{-}sic0)N_{-}sic0^2}$</td>
<td>Hfc</td>
<td>--</td>
</tr>
<tr>
<td>K_Qp0</td>
<td>$K_{-}Ae \cdot \frac{N_{-}b \cdot W_{-}b}{N_{-}b0 \cdot W_{-}b0}$</td>
<td>Qp0</td>
<td>--</td>
</tr>
<tr>
<td>K_tauf0</td>
<td>$\frac{W_{-}b^2 \cdot De(N_{-}b)}{W_{-}b0^2 \cdot De(N_{-}b0)}$</td>
<td>Tauf0</td>
<td>TF</td>
</tr>
<tr>
<td>K_thcs</td>
<td>$\frac{W_{-}sic \cdot \mu_n(N_{-}sic0) \cdot W_{-}bic + W_{-}b}{\mu_n(N_{-}sic) \cdot W_{-}sic0 + W_{-}b0}$</td>
<td>Thcs</td>
<td>--</td>
</tr>
<tr>
<td>K_fthc</td>
<td>$\frac{W_{-}sic \cdot W_{-}sic0 + 2 \cdot W_{-}b0}{W_{-}sic0 \cdot W_{-}sic + 2 \cdot W_{-}b}$</td>
<td>Fthc</td>
<td>--</td>
</tr>
<tr>
<td>K_Vpt</td>
<td>$\frac{N_{-}sic \cdot W_{-}sic}{N_{-}sic0 \cdot W_{-}sic0}$</td>
<td>Vpt</td>
<td>--</td>
</tr>
<tr>
<td>Name</td>
<td>DFM function</td>
<td>HiCUM</td>
<td>Gummel-Poon</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------------------------------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>K_Vpt</td>
<td>$\frac{N_sic \left( W_sic \right)}{N_sic0 \left( W_sic0 \right)^2}$</td>
<td>Vpt</td>
<td>--</td>
</tr>
<tr>
<td>K_tef0</td>
<td>$\frac{1}{W_e^2 \cdot \mu_h (N_e0)}$</td>
<td>Tef0</td>
<td>--</td>
</tr>
<tr>
<td>K_BF</td>
<td>$\frac{W_e \cdot N_e \cdot D_N_b \cdot W_b \cdot N_b \cdot D_N_b}{W_e\cdot D_0\cdot W_e0\cdot W_b\cdot N_b\cdot D_0\cdot N_b\cdot D_0\cdot N_b}$</td>
<td>---</td>
<td>BF</td>
</tr>
<tr>
<td>K_rbi0</td>
<td>$\frac{K_BE \cdot W_b}{p_b0 \cdot W_b0}$</td>
<td>Rbi0</td>
<td>RB</td>
</tr>
<tr>
<td>K_rbx</td>
<td>$\frac{p_b}{w_b}$</td>
<td>Rbx</td>
<td>RBM</td>
</tr>
<tr>
<td>K_rci</td>
<td>$\frac{pc \cdot W_sic - T_depc}{pc_def \cdot W_sic0 - T_depc0}$</td>
<td>Rci</td>
<td>RC</td>
</tr>
<tr>
<td>K_CJxi0</td>
<td>$\frac{1}{K_Ax \cdot \left( N_b \cdot K_Vdxi0 \right)}$</td>
<td>Cjxi0</td>
<td>Cjx</td>
</tr>
<tr>
<td>K_Vdxi0</td>
<td>$\frac{W_b \cdot W_sic \cdot \mu_c (N_sic0)}{W_b0 \cdot W_sic0 \cdot \mu_c (N_sic)}$</td>
<td>Vdxi0</td>
<td>Vjx</td>
</tr>
<tr>
<td>K_tbfvs</td>
<td>$K_Ae \cdot \frac{D_e \cdot W_b0 \cdot N_b}{D_e\cdot 0 \cdot W_b \cdot N_b0}$</td>
<td>Tbfvs</td>
<td>--</td>
</tr>
<tr>
<td>K_IKF</td>
<td>--</td>
<td>---</td>
<td>IKF</td>
</tr>
</tbody>
</table>
Function of BJT physical model card (1)

SPICE model parameters: Function of \( N_b \)

\( N_b \): doping concentration in the base
Function of BJT physical model card

- **fT-IC**: Frequency at which the current gain drops to 1
- **NF50**: Noise figure at 50% power level
- **NFmin**: Minimum noise figure
- **IC, IB**: Collector and base currents, respectively
- **Hfe**: Current gain
- **N_B**: Base concentration: 2e18 to 1.4e19 cm\(^{-3}\) by 2e18 cm\(^{-3}\)
fT vs. Hfe Scattering Plot

Measurement data (230 points)

VBE=0.92V, VC=3V

BJT Physical model card (HiCUM)

N_B Gaussian Nominal value=8e18 +/-10%
W_B Gaussian Nominal value=7um +/-10%

d_fT=16
( =49-33)

d_Hfe=70
( =106-36)

d_fT=18.5
( =62.5-44)

d_Hfe=60
( =150-90)
Gain Circles modelling result (0.4um*8um*16unit)

- **VBE=0.8V, Pinset=-5dBm**
- **VBE=0.85V, Pinset=-5dBm**
- **VBE=0.8V, Pinset=0dBm**
- **VBE=0.9V, Pinset=-5dBm**

[Diagram showing Gain Circles with different parameters]
Power Amplifier for PHS applications

1st-Tr. 0.4u*16u*4*1
2nd-Tr. 0.4u*16u*8*3
3rd-Tr. 0.4u16u*8*12

Pin Pout
Vcc1, Vcc2, Vcc3
Vc1, Vc2
Regulator

TOSHIBA
Leading Innovation

TOSHIBA

18
HiCUM Pin-Pout modelling result (0.4um*16um*4unit)

Pin=2.4 GHz
LoadPull modelling result (0.4um*16um*4unit)

- VBE=0.8V, Pinset=-5dBm
- VBE=0.8V, Pinset=0dBm
- VBE=0.85V, Pinset=-5dBm
- VBE=0.9V, Pinset=-5dBm
Comparison with the measurement (1)

Split samples ( R±10% ) Plus 3 different evaluation boards ( 3states*2 )
HiCUM model (nominal parameters)

Pin - Gp

Pin - I_total
Comparison with the measurement (2)

Good Match between MonteCarlo simulation and measurement

CW  @Pin=-12dBm
R±10%(3 R conditions )  120 samples

Measurement  120 samples

Monte-Carlo simulation by the BJT physical model card

△0.6dB

Amp_1Tone_NF_MC  @Pin=-12dBm
Hicum Physical model card
NB, WB±10%, R±10%  120 trials

△0.6dB
Summary

• Proposed “BJT physical model card” provides
  – Simple structure
    • 9 process variables
      – \( N_b, W_b, d_{EG}, R_{pinch}, A_e, N_e, W_e \) \( N_{sic}, W_{sic} \)
    • Formulae by the use of mobility, bulk resistance, Diffusion coefficients.
      – Reasonable prediction of the device and circuits’ statistics without going through fabrication process.
References

5. WEB resources http://eesof.tm.agilent.com/