A Referenced Geometry Based Configuration Scalable Mextram Model for Bipolar Transistors
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Abstract — A behavioral reference based model for configuration scaling of bipolar transistor model parameters is proposed. The model is applicable to bipolar technologies with one or two collector contacts and different number of emitters. The effectiveness of the proposed scaling methodology is verified in case studies using advanced high-speed SiGe HBT technology.

Index Terms — Geometry scaling, Multi-emitter SiGe HBT, Mextram model, thermal resistance, collector resistance.

I. INTRODUCTION
With the coming era of System-on-a-Chip (SoC) there is an ever increasing number of microcircuit and system integrated in a single chip. In order to meet the increasing complexity of the circuit design, a geometry scalable model is crucial for different function blocks in SoC design. However, simple dimensional device scaling is not sufficient to meet all the circuit design requirements. For example, power amplifier applications require larger emitter area \( A_E \) to provide sufficient power output but emitter area can't be extended without limits. When device becomes large, emitter current crowding effect and distributed parasitic resistance will degrade device performance [1][2]. In order to provide high output power level without sacrificing too much of the device performance, it is common practice to employ several transistors in parallel or create Multi-Emitter Devices (MEDs) in power amplifier design. Between these two options, MEDs is preferred for power amplifier application because of its compactness in using chip area.

Advanced bipolar transistor model Mextram [3], which addresses all kinds of high current bipolar transistor effects [4][5], is especially suitable for power device application. In this paper, we would like to extend previously developed a reference based geometry scaling approach for Mextram model [6] to configuration scaling including different contact configurations and emitter numbers for optimal circuit design.

The paper is organized as follows. In Section II, scaling equations for MEDs, based on different layout configurations, are derived. The scalable model implementation and an ICCAP [7] model file for temperature and geometry parameter extraction from different layout configurations is introduced in Section III. The conclusion of this paper is in Section IV.

II. DERIVATION OF SCALING EQUATIONS FOR MULTI-EMITTER FINGER DEVICES

Fig. 1 shows the layout of a multi-emitter SiGe HBT with its emitter (E) and collector (C) labeled. The electrical model parameters that describe currents and capacitances of the intrinsic device are simply scaled with the emitter-finger number while the ratio parameters are kept the same as for the Single-Emitter Device (SED). The resistances that define the current flow in the direction vertical to emitter window scale reciprocally to the number of the emitters.

Fig. 1. Layout of a SiGe HBT structure with \( N_E \) emitters and one collector contact with self-heating and mutual-heating among emitters.

The self- and mutual-heating of emitters schematically presented in Fig. 1 produces non-uniform distribution of the temperature and in principle each emitter operates at different temperature [8]. To represent the real temperature distribution in the MED, there should be a thermal node associated with each emitter. However, Mextram is equipped with only one thermal node, which can only model the average temperature rise of the device. As a result, the temperature rise is...
assumed to be uniform across the active device region, which is the region isolated by shallow trench isolation.

For each emitter, the temperature rise \( (dT) \) produced by the self- and mutual-heating effects can be modeled with an \( N_E \times N_E \) thermal resistance matrix and its power dissipation \( P_i \) as:

\[
\begin{pmatrix}
\frac{dT_1}{dt} \\
\frac{dT_2}{dt} \\
\vdots \\
\frac{dT_{N_E}}{dt}
\end{pmatrix}
= \begin{pmatrix}
Rth_{1,1} & Rth_{1,2} & \cdots & Rth_{1,N_E} \\
Rth_{2,1} & Rth_{2,2} & \cdots & Rth_{2,N_E} \\
\vdots & \vdots & \ddots & \vdots \\
Rth_{N_E,1} & Rth_{N_E,2} & \cdots & Rth_{N_E,N_E}
\end{pmatrix}
\begin{pmatrix}
P_1 \\
P_2 \\
\vdots \\
P_{N_E}
\end{pmatrix}
\]

(1)

where \( Rth \) is equal to the reference geometry, \( Rthc \) is a reference based scaling equation of the active region. \( RTH \), \( RTHW \) and \( RTHL \) are the geometry parameters which account for bulk, sidewall width and length contribution. When the device geometry is equal to the reference geometry, \( Rth \) is equal to \( RTH \). Otherwise, it scales to the evaluated geometry.

\[ Rth = RTH_i \left( 1 + RTHA \left( \frac{W_b L_d}{W_b L_{DR}} - 1 \right) \right) \]

(2)

where \( RTH_i \) is the self-heating thermal resistance at a reference geometry chosen in the available geometry matrix, \( W_b \), \( W_{DR} \) and \( L_{DR} \) are the width, reference width and reference length of the active region. \( RTHA \), \( RTHW \) and \( RTHL \) are the geometry parameters, which account for bulk, sidewall width and length contribution. When the device geometry is equal to the reference geometry, \( Rth \) is equal to \( RTH_i \). Otherwise, it scales to the evaluated geometry.

If \( P_i \), representing the power dissipation at finger \( i \), is assumed to be equal to the total power dissipation \( P \) divided by \( N_E \), the average temperature rise \( dT \) in each emitter finger will be:

\[
dT = \frac{dT_1 + dT_2 + \cdots + dT_{N_E}}{N_E}
\]

(4)

Notice from (4), that when \( N_E \geq 2 \), the effective thermal resistance \( RTH = dT / P \) is increased due to mutual heating effect.

From (3) and (4), the reference base scaling equations for the SED and MED’s \( RTH \), which including self- and mutual-heating thermal resistance becomes:

\[
RTH = \frac{RTH_i \left( 1 + RTHA \left( \frac{W_b L_d}{W_b L_{DR}} - 1 \right) \right) + RTHW \left( \frac{W_b}{W_{DR}} - 1 \right) + RTHL \left( \frac{L_d}{L_{DR}} - 1 \right)}{N_E}
\]

(5)

where \( RTH \) is the geometry parameter for the mutual heating thermal resistance and \( W_{DR} \) is the reference geometry of \( W_b \). If \( W_b \) has a fixed length in the process design rule, it will cancel with \( W_{DR} \).

Similar to temperature distribution, the potential distribution along the lateral collector buried-layer of MED structure will be non-uniform because of the lateral current flow. It should be again described by a single internal collector node of the Mextram model. As a result, the total collector resistance \( (RCC) \) can only be modeled effectively. Starting from the SED with one collector contact, the \( RCC \) that comprises part of the epi-collector resistance \( (Rcep) \) and buried-layer resistance under epi-collector \( (Rbli) \), extrinsic buried-layer resistance \( (Rblx) \) and collector-plug resistance \( (Repl) \), as shown in Fig. 2, is expressed as:

\[
RCC = Rcep + Rbli + Rblx + Repl
\]

(6)

where \( RCI \) is the lumped resistance of \( Rcep \) and \( Rbli \) and \( Rcx \) is the lumped resistance of \( Rblx \) and \( Repl \). Notice also from Fig. 2 that \( Rcx \) is modeled with its conductance at width \( (Gcw) \), length \( (Gcl) \) and corner \( (Gc) \) of the emitter as:

\[
Rcx^{-1} = Gcw W_c + Gcl L_c + Gc.
\]

(7)

Thus, the reference based scaling equation for \( Rcx \) becomes:

\[
Rcx = \frac{Rcx_i \left( 1 + GCW \left( \frac{W_c}{W_{ER}} - 1 \right) + GCL \left( \frac{L_c}{L_{ER}} - 1 \right) \right)}{N_E}
\]

(8)

where \( Rcx_i \) is the \( Rcx \) at the reference geometry. \( GCW \) and \( GCL \) are the width and length geometry parameters. The \( Rci \) is modeled with area and square of the emitter size as:

\[
Rci = Rcep + Rbli
\]

(9)

Where \( Rci \) is the constant geometry parameters for \( Rcep \) and \( Rbli \). From (9), the reference based scaling equation of \( Rci \) becomes:
With $R_{ci}$ being $R_{ci}$ at the reference geometry and \( R_{C1} \) the geometry parameter that models \( R_{cep} \). From (6), (8) and (10), the referenced based scaling equation of the \( RCC \) for a SED with one collector contact is:

$$
R_{ci} = R_{ci} \left( R_{C1} \frac{W_e L_{pe}}{W_e L_{pe}} + (1 - R_{C1}) \frac{W_e L_{pe}}{W_e L_{pe}} \right). \tag{10}
$$

where $R_{C1}$ is the \( RCC \) at the reference geometry and \( RCX \) is the geometry parameter, which represents both \( R_{blx} \) and \( R_{cpl} \).

If the total current \( (I_{N}) \) is equally distributed among emitter fingers, the internal node voltage \( V_{i} \) can be modeled with an \( N_{E} \times 4 \) resistance matrix times four nodal current as:

$$
\begin{pmatrix}
V_{1} \\
V_{2} \\
\vdots \\
V_{N_{E}}
\end{pmatrix} =
\begin{pmatrix}
R_{ex} & 0 & R_{blx} + R_{cx} \\
R_{ex} & 0 & R_{blx} + R_{cx} \\
\vdots & \vdots & \vdots \\
R_{ex} & 0 & R_{blx} + R_{cx}
\end{pmatrix}
\begin{pmatrix}
I_{N} \\
I_{N} \\
\vdots \\
I_{N}
\end{pmatrix}
$$

where \(-R_{blx}/6\) accounts for the distributed effects [9] of the buried collector resistance under emitter so that its effective resistance will become \( R_{blx}/3 \) for single collector contact and \( R_{blx}/12 \) for double collector contact. \( R_{cd} \) is the buried-layer resistance between two adjacent fingers \( R_{blc} \) plus \( R_{blx} \). The effective \( RCC \) is defined as the average nodal voltage \( V \) divided by \( I_{N} \) as:

$$
RCC = \frac{V}{I_{N}N_{E}} = \frac{V_{1} + V_{2} + \ldots + V_{N_{E}}}{I_{N}N_{E}}
$$

$$
= \frac{R_{ex}}{N_{E}} \frac{R_{blx} + \sum_{i=1}^{N_{E}-1} R_{cd} + R_{blx} + R_{cx}}{6R_{cx}}
$$

$$
= \frac{3N_{E} - 1}{6N_{E}} \frac{R_{blx}}{6} + (N_{E} - 1)(2N_{E} - 1) \frac{R_{cd} + R_{cx}}{6N_{E}}
$$

The analysis for the two collector contacts is similar to the single collector contact devices due to the symmetry. In that case, it is sufficient to consider half of the device as shown in Fig. 4, which is half of a MED with odd emitters. Its nodal voltage is modeled using an \((N_{E} + 1)/2 \times 4\) resistance matrix times the node currents as:

$$
\begin{pmatrix}
V_{1} \\
V_{2} \\
\vdots \\
V_{N_{E}}
\end{pmatrix} =
\begin{pmatrix}
R_{ex} & 0 & R_{blx} + R_{cx} \\
R_{ex} & 0 & R_{blx} + R_{cx} \\
\vdots & \vdots & \vdots \\
R_{ex} & 0 & R_{blx} + R_{cx}
\end{pmatrix}
\begin{pmatrix}
I_{N} \\
I_{N} \\
\vdots \\
I_{N}
\end{pmatrix}
$$

$$
= \frac{R_{ex}}{N_{E}} \frac{R_{blx} + \sum_{i=1}^{N_{E}-1} R_{cd} + R_{blx} + R_{cx}}{2}
$$

$$
= \frac{3N_{E} - 1}{6N_{E}} \frac{R_{blx}}{2} + (N_{E} - 1)(2N_{E} - 1) \frac{R_{cd} + R_{cx}}{2}
$$

By averaging the node voltages, the \( RCC \) for an odd emitter with two collector contacts device is:
Fig. 4. Top view and collector impedance network of an odd-emitter, two collector contacts device.

For even number of emitters, its internal nodal voltages are the same as for the single collector contact with half of its emitter fingers and total nodal current. Its collector resistance will be:

\[
RCC = \frac{V}{I_N} = \frac{2(V_1 + V_2 \cdots V_{(N_E/2)}) + V_{(N_E/2)}}{I_N N_E} = \frac{R_{cep} 3 N_E - 2 R_{blc} + (N_E - 1)(N_E - 2)}{12 N_E} R_{cd} + \frac{R_{cep} N_E R_{blc} + (N_E - 1)(N_E - 2) R_{cd} + R_{cep}}{2} \quad (15)
\]

\[
RCC = \frac{R_{cep} 3 N_E - 2 R_{blc} + (N_E - 1)(N_E - 2)}{12 N_E} R_{cd} + \frac{R_{cep} N_E R_{blc} + (N_E - 1)(N_E - 2) R_{cd} + R_{cep}}{2} \quad (16)
\]

It happens that the scaling equations for double collector, odd and even emitter devices are the same. \(RCC\) from (13), (15) and (16) can be expressed as a single analytical equation with the number of collector contact \((N_C)\) as:

\[
RCC = \frac{R_{cep} 3 N_E - 2 R_{blc} + (N_E - 1)(N_E - 2)}{12 N_E} R_{cd} + \frac{R_{cep} N_E R_{blc} + (N_E - 1)(N_E - 2) R_{cd} + R_{cep}}{2} \quad (17)
\]

From (11) and (17), the reference based scaling equation of the \(RCC\) for the SED and MED with different \(N_C\) is combined as a single expression as:

\[
RC1 = (1 - RCX) \left( \frac{R_{C1} W_{ex} L_{ex}}{N_E} + \frac{N_C}{N_C^2} (1 - RC1) W_{ex} L_{ex} \right)
\]

\[
RC2 = \frac{(N_C - 1)(N_C^2 - 1)}{6N_E} R_{C1} W_{ex} L_{ex}
\]

\[
RC3 = \frac{R_{cep} N_E Q_{CW} W_{ex} - 1}{1 + N_E Q_{CW} W_{ex} - 1} + G_{CL} \left( \frac{L_{ex}}{I_{ex} - 1} \right)^{-1}
\]

\[
RCC = RCC_{n} (RC1 + RC2 + RC3).
\]

Where \(RCXC\) is the geometry parameter that models the \(R_{blc}\).

III. MODEL IMPLEMENTATION AND PARAMETER EXTRACTION IN IC-CAP

Based on the scaling equations derived in section II and the previous geometry scaling results [6], the configuration scalable model is utilized as extension of the standard Mextram model implemented in Verilog-A [10] as following:

'include "frontdef.inc"
'define SELFHEATING
'define SUBSTRATE
module bjt504t_va (c, b, e, s, dt);

// External ports
inout c, b, e, s, dt;
electrical c, b, e, s, dt;

// Internal nodes
electrical e1, b1, b2, c1, c2;
electrical noi;

'include "parameters.inc" // Add new instant and geometry parameters in this module.
'include "variables.inc" // Add new variables in this module.

analog begin
'include "geo_scaling.inc" // Geometry scaling equations are added in this module.
'include "initialize.inc"
'include "tscaling.inc"
'include "evaluate.inc"
end
endmodule

In the implemented model, new instance parameters \((NE, NC, WE\) and \(LE)\) and geometry parameters \((RTHA, RTHW\ldots)\) are added in the module "parameters.inc" to account for the layout configuration and geometry scaling of the bipolar devices. The geometry scalable Mextram model parameters \((RTH, RCC\ldots)\) in "parameters.inc" are used as the reference parameters. The scaling
equations for the scalable Mextram model parameters listed in Table I are implemented in "geo_scaling.inc". The geometrical quantities (WB, LB, WC, and LC) in Table I, representing the size of active region and collector-substrate junction, can be scaled with WE and LE based on the design rule of the specific process. Some new variables are added in the module "variables.inc" and used in the module "geo_scaling.inc" for the geometry scaled results of the scaling equations. They will replace the scalable model parameters in the temperature-scaling module "tscaling.inc", which the results that will be used later in the main module "evaluate.inc". As a result, the geometry, configuration and temperature scaling of the bipolar transistor are taken into account in the model evaluation.

<table>
<thead>
<tr>
<th>Scalable Parameters</th>
<th>Geometry Dependent</th>
<th>Finger Dependent</th>
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</thead>
<tbody>
<tr>
<td>IS, IK, IBF, IBR</td>
<td>$W_e, L_e$</td>
<td>$N_e$</td>
</tr>
<tr>
<td>CJJE, CJJC, IHC</td>
<td>$W_e, L_e$</td>
<td>$N_e$</td>
</tr>
<tr>
<td>ISS, IKS</td>
<td>$W_b, L_b$</td>
<td>$N_e$</td>
</tr>
<tr>
<td>CJJS</td>
<td>$W_c, L_c$</td>
<td>$N_e$</td>
</tr>
<tr>
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</tr>
<tr>
<td>PE, PC, TAUB</td>
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<td>none</td>
</tr>
<tr>
<td>BRI</td>
<td>$W_e, L_e$</td>
<td>none</td>
</tr>
<tr>
<td>PS</td>
<td>$W_c, L_c$</td>
<td>none</td>
</tr>
<tr>
<td>RE, RCV, SCRCV</td>
<td>$W_e, L_e$</td>
<td>$1/N_e$</td>
</tr>
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<td>$W_e, L_e$</td>
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<td>$W_e, L_e$</td>
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<td>$W_e, L_e$</td>
<td>(5)</td>
</tr>
<tr>
<td>RCC</td>
<td>$W_e, L_e$</td>
<td>(18)</td>
</tr>
</tbody>
</table>

An extension of the unified parameter extraction procedure for the scalable Mextram model is implemented in an Agilent IC-CAP model file and using high speed SiGe HBTs [11] as a test example. The extraction procedure starts at a selected reference geometry device from the available geometry matrix. The reference parameters are extracted at the Device Under Test (DUT) "npn_ref" from the reference geometry following standard procedure [12] going from low injection towards high injection related parameters. The temperature scaling parameters are extracted in DUT "temp_scaling" before high injection parameters extraction to accurately model the temperature rise from self-heating effect at high current region. Following the high current parameters extraction, extraction of geometry parameters in DUT "geom_scaling" is performed. After geometry parameters extraction, a DUT "conf_scaling" is added for RTHC and RCXC extraction from measured output characteristic of MEDs.

The essential feature of the proposed geometry and configuration scaling methodology is a direct extraction of the geometry parameters from the measured electrical characteristics and the model parameters as reference parameters are extracted only once for a single reference geometry. The MEDs are used for RTHC and RCXC extraction. Without re-extracting any parameter from SEDs after RTHC and RCXC extraction, Fig. 5 shows the model simulated (in solid lines) unity gain bandwidth ($f_T$) vs. collector current ($I_C$) from ADS [13] comparing with the measured data (in circles) from $N_e=1$-$4$, $N_c=2$ and different $A_e$. The model simulation results can accurately predict $f_T$ degradation with increasing emitter finger number but the default Mextram model parameter "MULT" scaling results (in dashed line), which puts MULT SEDs in parallel, is not able to do that. Since the $f_T$ can be simply expressed as a sum of the total forward transit time ($\tau_f$), base-emitter junction capacitance ($C_{jeb}$), base-collector junction capacitance ($C_{jbc}$) and RCC as [14]:

\[
\frac{1}{2\pi f_T} = \tau_f + kT \left( C_{jeb} + C_{jbc} \right) + RCC \cdot C_{jeb}, \tag{19}
\]

the accurate prediction of $f_T$ degradation with $N_e$ from our model validates the thermal resistance and collector resistance scaling results.

IV. CONCLUSIONS

In this paper, the reference geometry based scaling approach for Mextram model has been extended to different layout configuration of bipolar devices. The proposed scaling methodology employs effective thermal and collector node assumption.

The configuration scalable model uses almost the same set of the model parameters as in the geometry scalable model except RTHC and RCXC, which model the mutual heating effect and collector resistance between two adjacent fingers and two additional instance parameters $N_E$ and $N_C$ for different layout configurations. The model nicely predicts the $f_T$ degradation due to increase of mutual heating and the collector delay time with increasing $N_E$. It is concluded that the number of emitters can’t be increased without a limit as for emitter area.

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