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"A Referenced Geometry Based Configuration Scalable Mextram Model for Bipolar Transistors"

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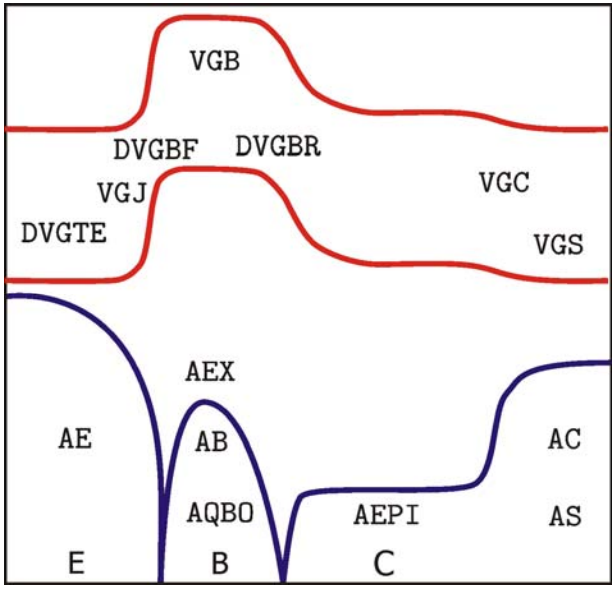
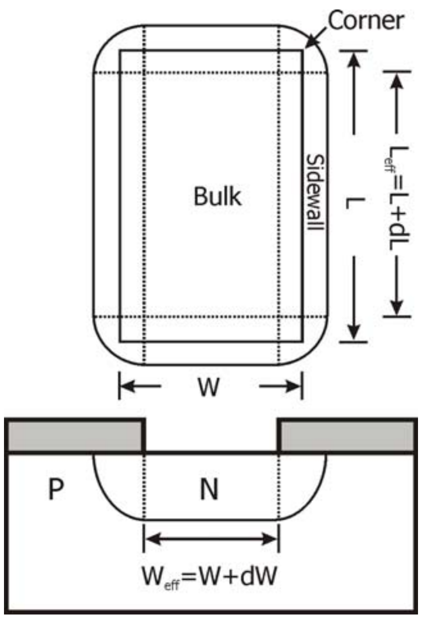
Outline of the presentation

- Introduction to bipolar transistor model scaling.
- A reference geometry based scaling approach for scalable Mextram model.
- Derivation of behavioral reference geometry based scaling equations for multi-emitter finger devices.
- Model implementation in Verilog-A and the unified parameter extraction procedure in IC-CAP.
- Conclusion.

Introduction





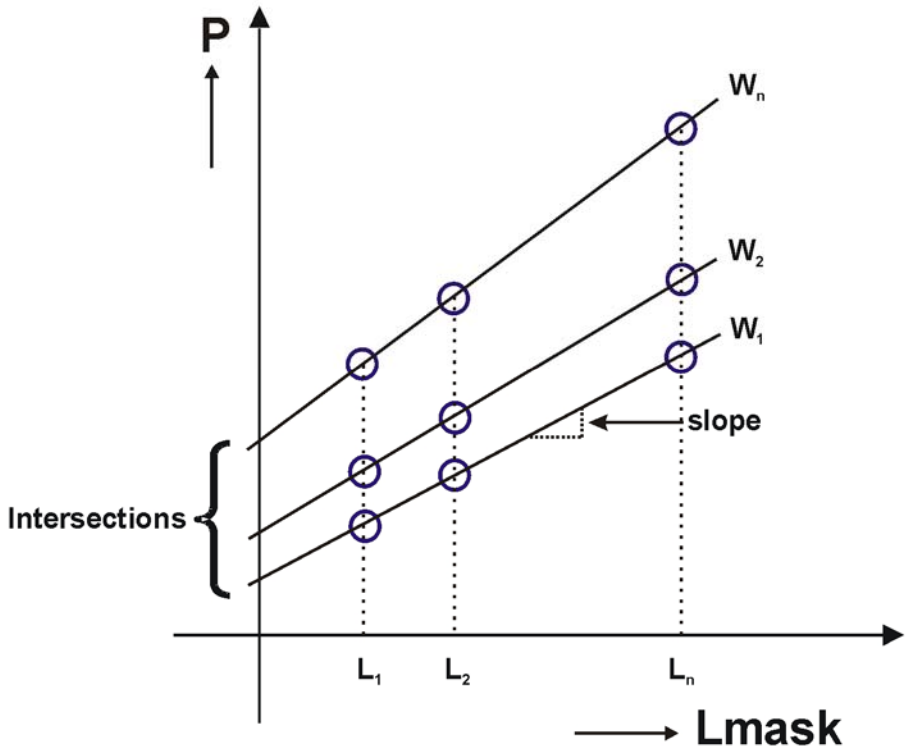
$$t_N = \frac{T}{T_R}$$

$$\frac{P}{P_{REF}} = \begin{cases} 1 & T = T_R \\ f(P_T, t_N) & T \neq T_R \end{cases}$$

$$P = \underbrace{P_A(W+dW)(L+dL)}_{Bulk} + \underbrace{P_W(W+dW) + P_L(L+dL)}_{Sidewall} + \underbrace{P_C}_{Corner}$$

Six geometry parameters in the geometry scaling eqn.: P_A, P_W, P_L, P_C, dW, dL

Introduction



Plotting measured parameters (P) vs. drawn length (L) and width (W) :

$$\mathrm{P} = \left(P_A W + P_A dW + P_L\right) L + \left(P_A dL + P_W\right) W + P_A dWdL + P_L dL + P_W dW + P_C$$

$$Inter = \left(P_A dL + P_W\right) W + P_A dWdL + P_L dL + P_W dW + P_C.$$

$$Slope = P_A W + P_A dW + P_L$$

Four equations for six geometry parameters:

1. $m_{Slope} = P_A$
2. $i_{Slope} = P_A dW + P_L$
3. $m_{Inter} = P_A dL + P_W$
4. $i_{Inter} = P_A dWdL + P_L dL + P_W dW + P_C$

***dW* & *dL* from SEM ??**

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A reference geometry based scaling approach for scalable Mextram Model

Goal : To have four geometry parameters in geometry scaling eqn. and same format as temperature scaling eqn.

Re-arrange scaling eqn. in terms of drawn width and length:

$$\mathrm{P} = P_A WL + \underbrace{\left(P_A dL + P_W\right)}_{P_W} W + \underbrace{\left(P_A dW + P_L\right)}_{P_L} L + \underbrace{P_A dWdL + P_L dL + P_W dW + P_C}_{P_C}.$$

Scaling equations in terms of reference parameters at reference geometry:

$$\frac{\mathrm{P}}{\mathrm{P_R}} = P_A \frac{WL}{W_R L_R} + P_W \frac{W}{W_R} + P_L \frac{L}{L_R} + P_C,$$

$$\frac{\mathrm{P\text{-}P_R}}{\mathrm{P_R}} = P_A \left(\frac{WL}{W_R L_R} - 1\right) + P_W \left(\frac{W}{W_R} - 1\right) + P_L \left(\frac{L}{L_R} - 1\right),$$

$$\frac{\mathrm{P}}{\mathrm{P_R}} = 1 + P_A \left(\frac{WL}{W_R L_R} - 1\right) + P_W \left(\frac{W}{W_R} - 1\right) + P_L \left(\frac{L}{L_R} - 1\right). \quad \textbf{(1)}$$

A reference geometry based scaling approach for scalable Mextram Model

For ratio of two physical quantities:

$$\mathrm{P} = \frac{P_{A1}{}'WL + P_{W1}{}'W + P_{L1}{}'L + P_{C1}{}'}{P_{A2}{}'WL + P_{W2}{}'W + P_{L2}{}'L + P_{C2}{}'}.$$

Bulk component dominates the area of the junction, so the ratio parameter is 1st order approximate as:

$$\mathrm{P} = P_A + P_W \frac{1}{W} + P_L \frac{1}{L} + P_C \frac{1}{WL},$$

$$\frac{\mathrm{P}}{\mathrm{P_R}} = 1 + P_W\left(\frac{W_R}{W} - 1\right) + P_L\left(\frac{L_R}{L} - 1\right) + P_C\left(\frac{W_R L_R}{WL} - 1\right). \tag{2}$$

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A reference geometry based scaling approach for scalable Mextram Model

For parasitic resistance:

Vertical:

$$\frac{\mathbf{P}}{\mathbf{P_R}} = \left(1 + P_A\left(\frac{WL}{W_R L_R} - 1\right) + P_W\left(\frac{W}{W_R} - 1\right) + P_L\left(\frac{L}{L_R} - 1\right)\right)^{-1}. \qquad \textbf{(3)}$$

Lateral:

$$\mathbf{P} = R_{sq}\left(\frac{W}{L} + C\right). \qquad \textbf{(4)}$$

$$\mathbf{P} = (GwW + GlL + Gc)^{-1},$$

$$\frac{\mathbf{P}}{\mathbf{P_R}} = \left(1 + Gw\left(\frac{W}{W_R} - 1\right) + Gl\left(\frac{L}{L_R} - 1\right)\right)^{-1}. \qquad \textbf{(5)}$$

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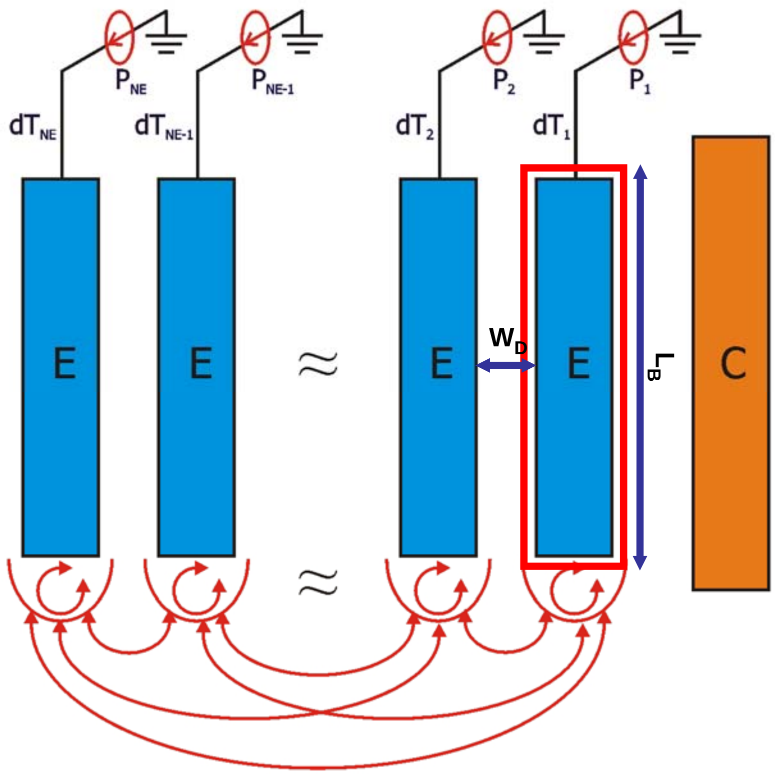
Derivation of geometry scaling equations for multi-emitter fingers bipolar devices



$$\begin{pmatrix} dT_1 \\ dT_2 \\ \vdots \\ dT_{N_E} \end{pmatrix} = \begin{pmatrix} Rth_{1,1} & Rth_{1,2} & \cdots & Rth_{1,N_E} \\ Rth_{2,1} & Rth_{2,2} & \cdots & Rth_{2,N_E} \\ \vdots & \vdots & \vdots & \vdots \\ Rth_{N_E,1} & Rth_{N_E,2} & \cdots & Rth_{N_E,N_E} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ \vdots \\ P_{N_E} \end{pmatrix}$$

$$\Rightarrow Rth_{i,j} = \begin{cases} Rth & i = j, \\ \dfrac{Rthc}{abs(i-j) W_D L_B} & i \neq j. \end{cases}$$

Derivation of geometry scaling equations for multi-emitter fingers bipolar devices

Averaging the temperature rise:

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

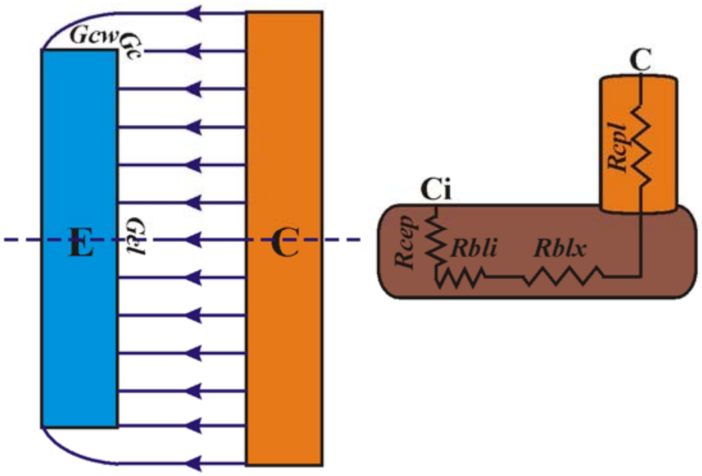
$$= \frac{P}{{N_E}^2}\left(Rth_{1,1} + Rth_{1,2} \cdots Rth_{1,N_E} + Rth_{2,1} + Rth_{22} \cdots Rth_{2N_E} \cdots Rth_{N_E 1} + Rth_{N_E,2} \cdots Rth_{N_E,N_E}\right)$$

$$= \frac{P}{N_E}\left(Rth + \frac{2Rthc}{N_E}\sum_{i=1}^{N_E-1}\frac{N_E - i}{iW_D L_B}\right),$$

$$Rth = \mathrm{RTH_R}\left(1 + \mathrm{RTHA}\left(\frac{W_B L_B}{W_{BR} L_{BR}} - 1\right) + \mathrm{RTHW}\left(\frac{W_B}{W_{BR}} - 1\right) + \mathrm{RTHL}\left(\frac{L_B}{L_{BR}} - 1\right)\right)^{-1},$$

$$RTH = \frac{\mathrm{RTH_R}}{N_E}\left(\left(1 + \mathrm{RTHA}\left(\frac{W_B L_B}{W_{BR} L_{BR}} - 1\right) + \mathrm{RTHW}\left(\frac{W_B}{W_{BR}} - 1\right) + \mathrm{RTHL}\left(\frac{L_B}{L_{BR}} - 1\right)\right)^{-1} + \frac{2\mathrm{RTHC}}{N_E}\sum_{i=1}^{N_E-1}\frac{N_E - i}{iW_D L_B}\right). \qquad (6)$$

Derivation of geometry scaling equations for multi-emitter fingers bipolar devices



Starting from 1E, 1C collector resistance:

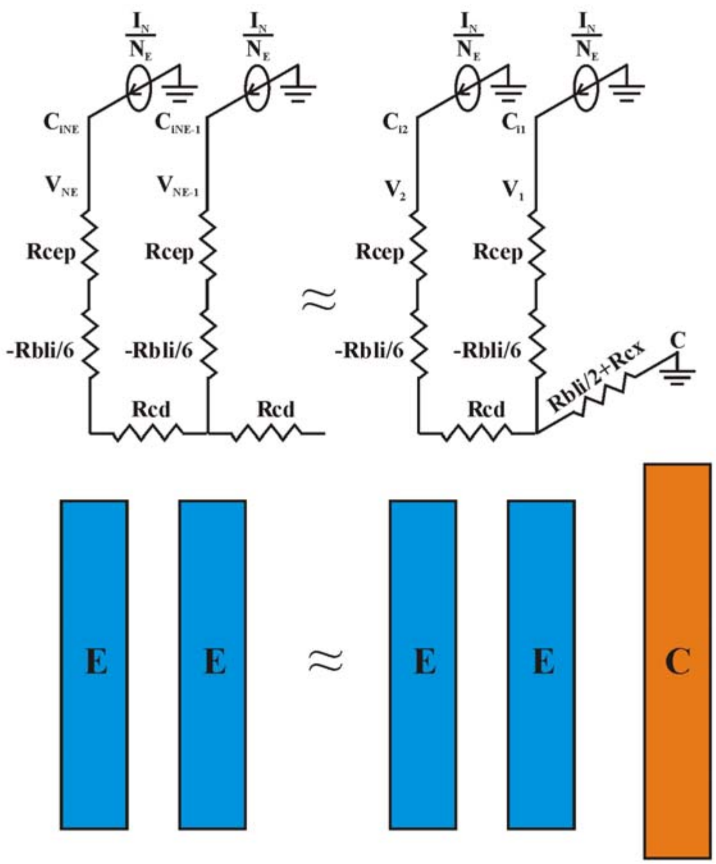
$$RCC = Rcep + Rbli + Rblx + Rcpl$$
$$= Rci + Rcx.$$

$$Rcx^{-1} = GcwW_E + GclL_E + Gc.$$

$$Rci = Rciv\frac{1}{W_E L_E} + Rcih\frac{W_E}{L_E}.$$

$$RCC = \mathrm{RCC_R}\left((1-\mathrm{RCX})\left((1-\mathrm{RCI})\frac{W_E L_{ER}}{L_E W_{ER}} + \mathrm{RCI}\frac{W_{ER}L_{ER}}{W_E L_E}\right) + \mathrm{RCX}\left(1+\mathrm{GCW}\left(\frac{W_E}{W_{ER}}-1\right)+\mathrm{GCL}\left(\frac{L_E}{L_{ER}}-1\right)\right)^{-1}\right).$$

Derivation of geometry scaling equations for multi-emitter fingers bipolar devices

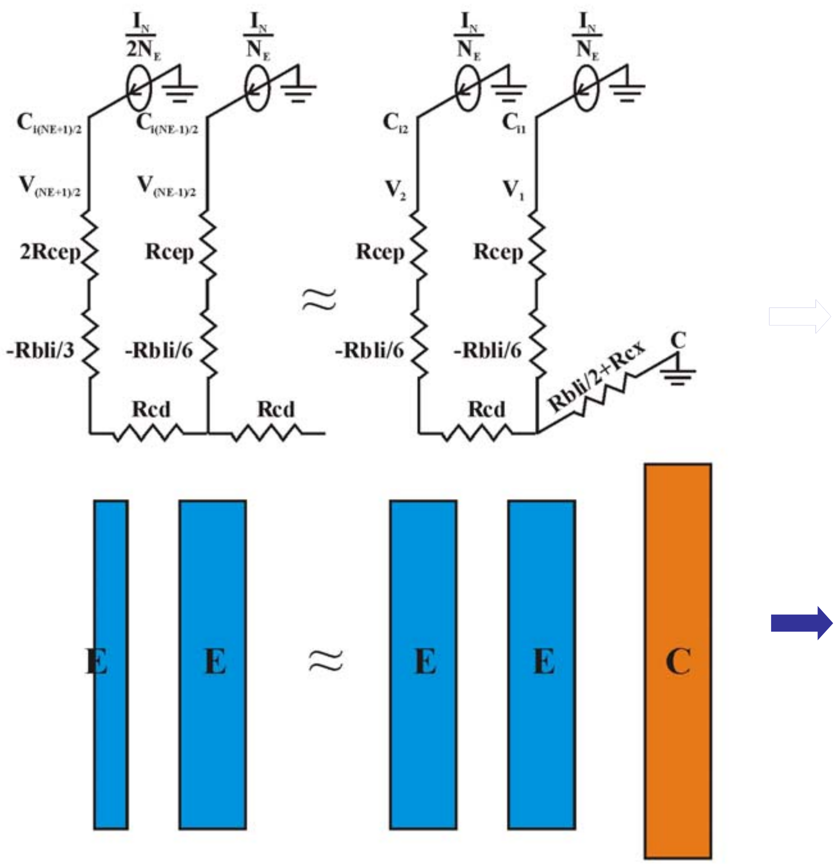


For multi-E, 1C collector resistance:

$$\begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_{N_E-1} \\ V_{N_E} \end{pmatrix} = \begin{pmatrix} Rcep & -\dfrac{Rbli}{6} & 0 & \dfrac{Rbli}{2}+Rcx \\ Rcep & -\dfrac{Rbli}{6} & (N_E-1)\,Rcd & \dfrac{Rbli}{2}+Rcx \\ \vdots & \vdots & \vdots & \vdots \\ Rcep & -\dfrac{Rbli}{6} & \sum\limits_{i=1}^{N_E-2}(N_E-i)Rcd & \dfrac{Rbli}{2}+Rcx \\ Rcep & -\dfrac{Rbli}{6} & \sum\limits_{i=1}^{N_E-1}(N_E-i)\,Rcd & \dfrac{Rbli}{2}+Rcx \end{pmatrix} \begin{pmatrix} \dfrac{I_N}{N_E} \\ \dfrac{I_N}{N_E} \\ \dfrac{I_N}{N_E} \\ I_N \end{pmatrix}$$

$$\begin{aligned} RCC &= \frac{V}{I_N} = \frac{V_1+V_2\cdots V_{N_E}}{I_N N_E} \\ &= \frac{Rcep}{N_E} - \frac{Rbli}{6N_E} + \sum_{i=0}^{N_E-1} i^2 \frac{Rcd}{N_E{}^2} + \frac{Rbli}{2} + Rcx \\ &= \frac{Rcep}{N_E} + \frac{3N_E-1}{6N_E} Rbli + \frac{(N_E-1)(2N_E-1)}{6N_E} Rcd + Rcx \\ &= \frac{Rcep}{N_E} + \frac{N_E}{3} Rbli + \frac{(N_E-1)(2N_E-1)}{6N_E} Rblc + Rcx \end{aligned}$$

Derivation of geometry scaling equations for multi-emitter fingers bipolar devices



For odd-E, 2C collector resistance:

$$\begin{pmatrix} V_1\\ V_2\\ \vdots \\ V_{\frac{(NE-1)}{2}} \\ V_{\frac{(NE+1)}{2}}\end{pmatrix} = \begin{pmatrix} Rcep & -\frac{Rbli}{6} & 0 & \frac{Rbli}{2}+Rcx \\ Rcep & -\frac{Rbli}{6} & \left(\frac{N_E}{2}-1\right)Rcd & \frac{Rbli}{2}+Rcx\\ \vdots&\vdots&\vdots&\vdots\\ Rcep & -\frac{Rbli}{6} & \sum_{i=1}^{\frac{(N_E-3)}{2}}\left(\frac{N_E}{2}-i\right)Rcd & \frac{Rbli}{2}+Rcx \\ Rcep & -\frac{Rbli}{6} & \sum_{i=1}^{\frac{(N_E-1)}{2}}\left(\frac{N_E}{2}-i\right)Rcd & \frac{Rbli}{2}+Rcx\end{pmatrix}\begin{pmatrix}\frac{I_N}{N_E}\\ \frac{I_N}{N_E}\\ \frac{I_N}{N_E}\\ \frac{I_N}{2}\end{pmatrix}$$

$$RCC = \frac{V}{I_N} = \frac{2\left(V_1 + V_2 \cdots V_{\left(N_E-1\right)/2}\right) + V_{\left(N_E+1\right)/2}}{I_N N_E}$$

$$= \frac{Rcep}{N_E} + \frac{3N_E-2}{12N_E}Rbli + \frac{\left(N_E-1\right)\left(N_E-2\right)}{12N_E}Rcd + \frac{Rcx}{2}$$

$$= \frac{Rcep}{N_E} + \frac{N_E}{12}Rbli + \frac{\left(N_E-1\right)\left(N_E-2\right)}{12N_E}Rblc + \frac{Rcx}{2}$$

Derivation of geometry scaling equations for multi-emitter fingers bipolar devices

For even-E, 2C collector resistance:

$$RCC = \frac{Rcep}{N_E} - \frac{Rbli}{6N_E} + 2\sum_{i=0}^{\frac{N_E}{2}-1} i^2 \frac{Rcd}{N_E{}^2} + \frac{Rbli}{4} + \frac{Rcx}{2}$$

$$= \frac{Rcep}{N_E} + \frac{3N_E - 2}{12N_E} Rbli + \frac{(N_E - 1)(N_E - 2)}{12N_E} Rcd + \frac{Rcx}{2}$$

$$= \frac{Rcep}{N_E} + \frac{N_E}{12} Rbli + \frac{(N_E - 1)(N_E - 2)}{12N_E} Rblc + \frac{Rcx}{2}.$$

RCC **can be expressed as a single analytical equation with the number of collector contact as :**

$$RCC = \frac{Rcep}{N_E} + \frac{N_E}{3N_C{}^2} Rbli + \frac{(N_E - 1)(2N_E / N_C{}^2 - 1)}{6N_E} Rblc + \frac{Rcx}{N_C}.$$

Derivation of geometry scaling equations for multi-emitter fingers bipolar devices

Analytical reference based configuration scalable *RCC* scaling equation:

$$RC1 = (1-\mathrm{RCX})\left(\frac{\mathrm{RCI}}{N_E}\frac{W_{ER}L_{ER}}{W_E L_E} + \frac{N_E}{{N_C}^2}(1-\mathrm{RCI})\frac{W_E L_{ER}}{W_{ER}L_E}\right),$$

$$RC2 = \frac{(N_E-1)\left(2N_E/{N_C}^2-1\right)}{6N_E}\mathrm{RCXC}\frac{W_D L_{ER}}{W_{DR}L_E},$$

$$RC3 = \frac{\mathrm{RCX}}{N_C}\left(1+\frac{N_E}{N_C}\mathrm{GCW}\left(\frac{W_E}{W_{ER}}-1\right)+\mathrm{GCL}\left(\frac{L_E}{L_{ER}}-1\right)\right)^{-1},$$

$$\Rightarrow RCC = \mathrm{RCC_R}\left(RC1+RC2+RC3\right). \tag{7}$$

Model implementation in Verilog-A and parameter extraction in IC-CAP

Table I Geometry and Configuration Scaling equations for Scalable Mextram Model

Scalable Parameters	Geometry Dependent	Scaling Equation	Finger Dependent
IS, IK, IBF, IBR	W_E, L_E	(1)	N_E
CJE, CJC, IHC	W_E, L_E	(1)	N_E
ISS, IKS	W_B, L_B	(1)	N_E
CJS	W_C, L_C	(1)	**None**
BF, VEF, VER	W_E, L_E	(2)	**None**
PE, PC, TAUB	W_E, L_E	(2)	**None**
BRI	W_E, L_E	(2)	**None**
PS	W_C, L_C	(2)	**None**
RE, RCV, SCRCV	W_E, L_E	(3)	$1/N_E$
RBV	W_E, L_E	(4)	$1/N_E$
RBC	W_E, L_E	(5)	$1/N_E$
RTH	W_B, L_B	(6)	N_E
RCC	W_E, L_E	(7)	N_E

Model implementation in Verilog-A and parameter extraction in IC-CAP

User defined constants

```
`include   "frontdef.inc"
`define    SELFHEATING
`define    SUBSTRATE
```

Main module

Terminals

```
module    bjt504t_va (c, b, e, s,

   inout   c, b, e, s, dt;
   electrical   c, b, e, s, dt;
   electrical   noi;
```

Parameters

```
`include "parameters.inc"
```

Variables

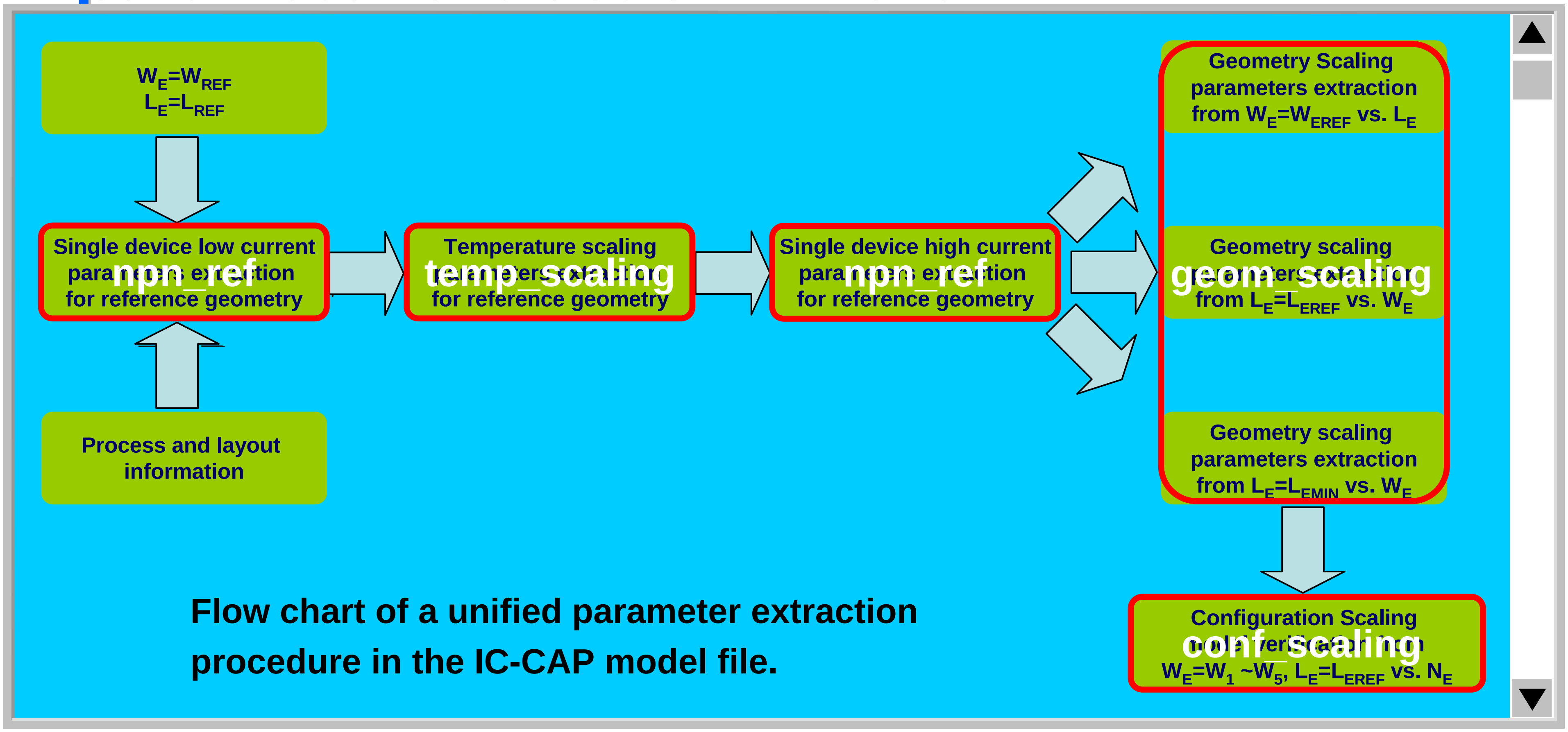
```
`include "variables.inc"
```

Analog block

```
analog begin
`include "geo_scaling.inc“
`include "initialize.inc"
`include "tscaling.inc"
`include "evaluate.inc“
end
endmodule
```

```
ne          = NE;
nc          = NC;
we          = W;
le          = L;
weref       = WREF;
leref       = LREF;
wb          = we+0.3;
lb          = le+0.3;
wbref       = weref+0.3;
lbref       = leref+0.3;
wc          = ne*wb+(ne-1.0)*0.52+nc*1.79+2.0*0.5;
lc          = lb+2.0*0.5;
wcref       = wbref+1.79+2.0*0.5;
lcref       = lbref+2.0*0.5;
IS_scale    = ne*IS*(1.0+ISA*(we*le/(weref*leref)-1.0)
                +ISW*(we/weref-1.0)+ISL*(le/leref-1.0));
IK_scale    = ne*IK*(1.0+IKA*(we*le/(weref*leref)-1.0)
                +IKW*(we/weref-1.0)+IKL*(le/leref-1.0));
RE_scale    = RE/(ne*(1.0+REA*(we*le/(weref*leref)-1.0)
                +REW*(we/weref-1.0)+REL*(le/leref-1.0)))+0.7;
RBV_scale   = (1.0/ne)*RBV*we/weref*leref/le;
RBC_scale   = RBC/(ne*(1.0+RBCL*(le/leref-1.0)
                +RBCW*(we/weref-1.0)));
rc1         = (1.0-RCX)*(RCI/ne*weref*leref/we/le
                +(1.0-RCI)*we/le*leref/weref*ne/nc/nc);
rc2         = RCXC*leref/le*(ne-1)*(2*ne/nc/nc-1)/ne/6.0;
rc3         = RCX/nc/(1.0+ne/nc*RCW*(we/weref-1.0)
                +RCL*(le/leref-1.0));
RCC_scale   = RCC*(rc1+rc2+rc3);
CJE_scale   = ne*CJE*(1.0+CJEA*(we*le/(weref*leref)-1.0)
                +CJEW*(we/weref-1.0)+CJEL*(le/leref-1.0));
CJC_scale   = ne*CJC*(1.0+CJCA*(we*le/(weref*leref)-1.0)
                +CJCW*(we/weref-1.0)+CJCL*(le/leref-1.0));
CJS_scale   = CJS*(1.0+CJSA*(wc*lc/(wcref*lcref)-1.0)
                +CJSW*(wc/wcref-1.0)+CJSL*(lc/lcref-1.0));
VEF_scale   = VEF*(1.0+VEFW*(weref/we-1.0)+VEFL*(leref/le-1.0)
                +VEFC*(weref*leref/(we*le)-1.0));
VER_scale   = VER*(1.0+VERW*(weref/we-1.0)+VERL*(leref/le-1.0)
                +VERC*(weref*leref/(we*le)-1.0));
...
```

Model implementation in Verilog-A and parameter extraction in IC-CAP



Flow chart of a unified parameter extraction procedure in the IC-CAP model file.

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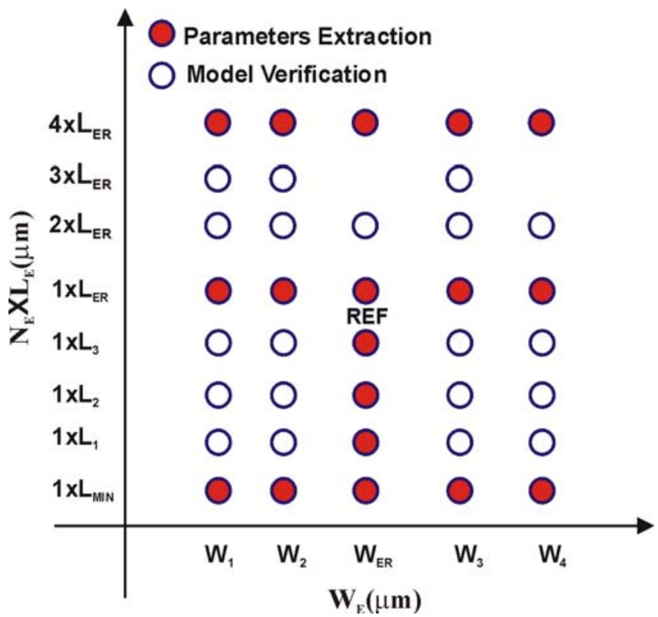
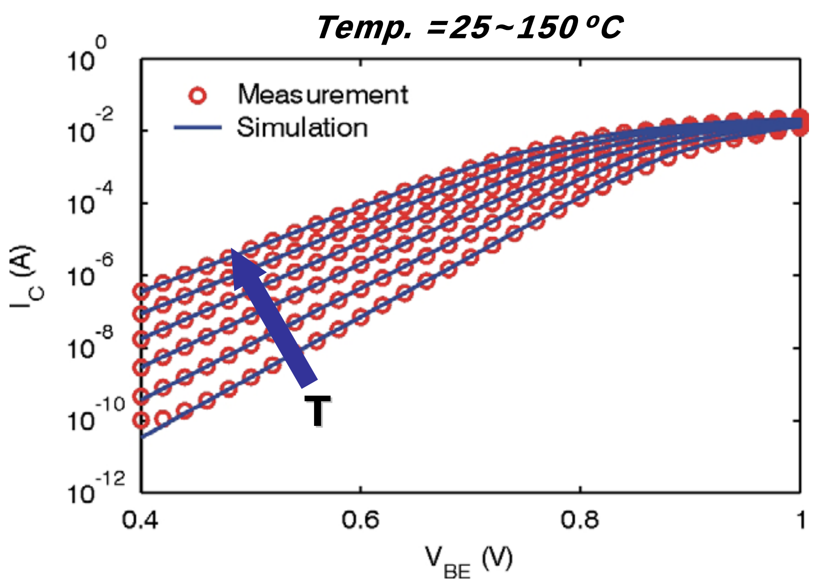
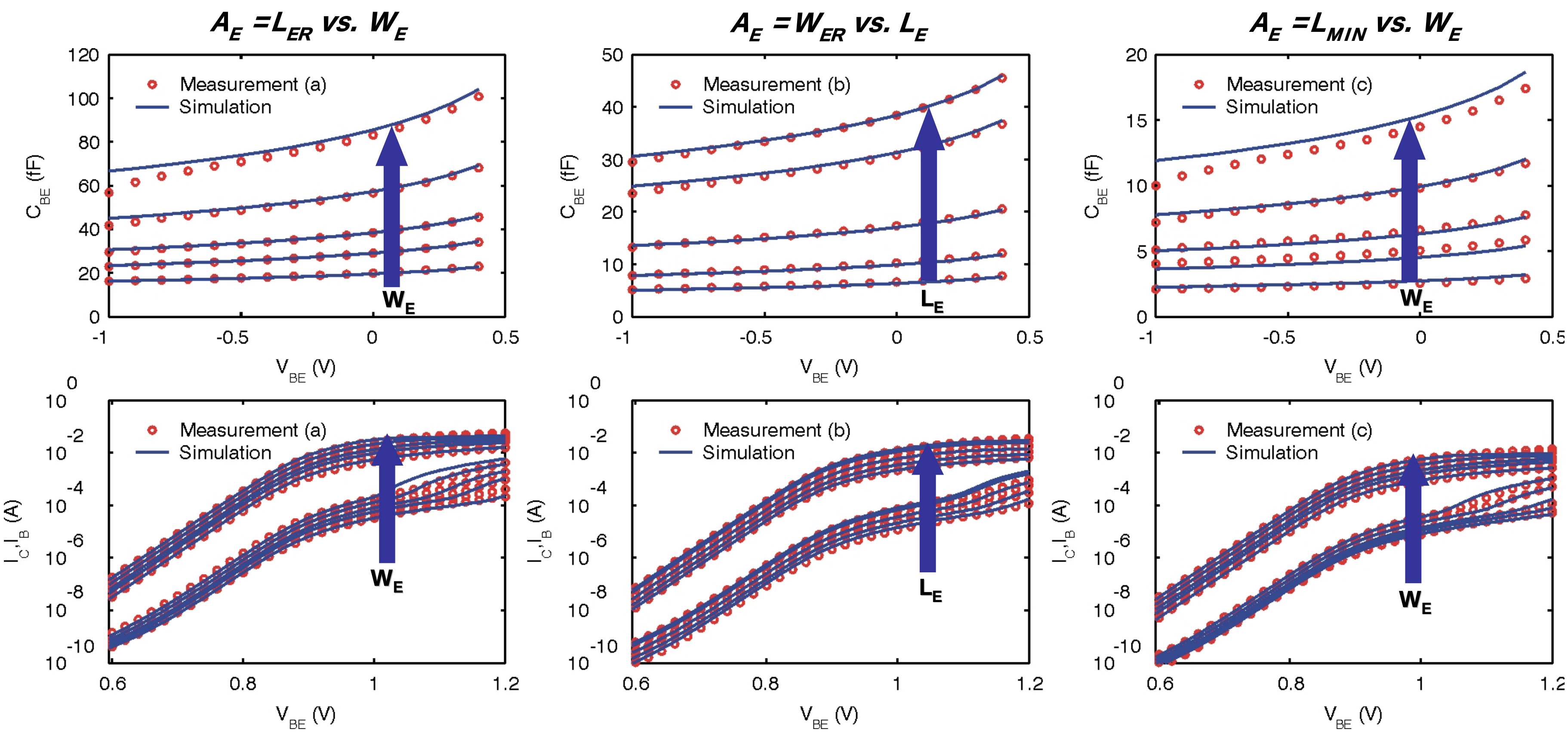
Model implementation in Verilog-A and parameter extraction in IC-CAP





TSMC 0.18 um high-speed SiGe HBT process
W_1, W_2, W_{ER}, W_3, W_4 = 0.2, 0.3, 0.4, 0.6, 0.9 um
L_{MIN}, L_1, L_2, L_3, L_{ER} = 1.7, 2.64, 4.52, 8.28, 10.16 um

Model implementation in Verilog-A and parameter extraction in IC-CAP



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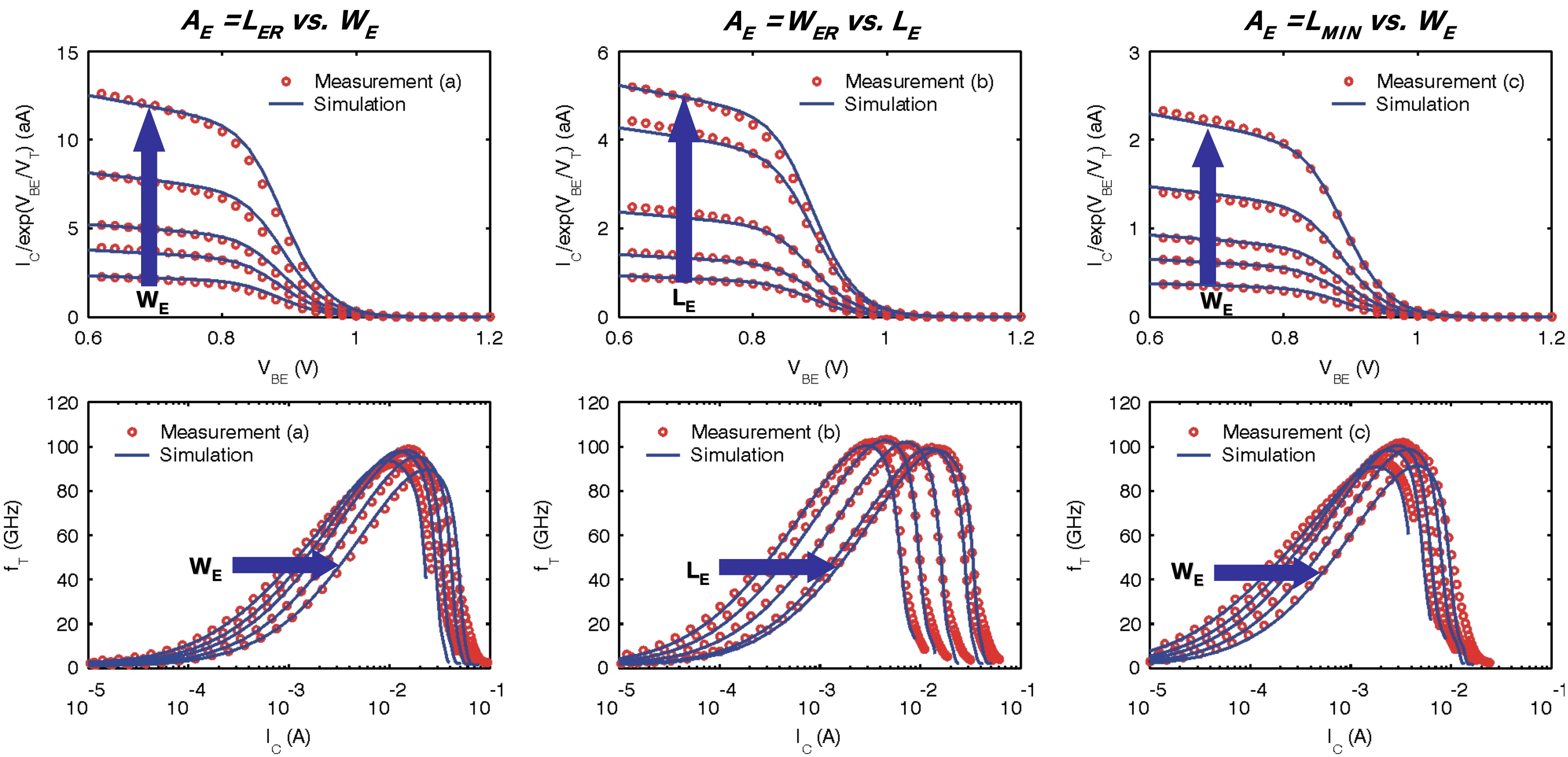

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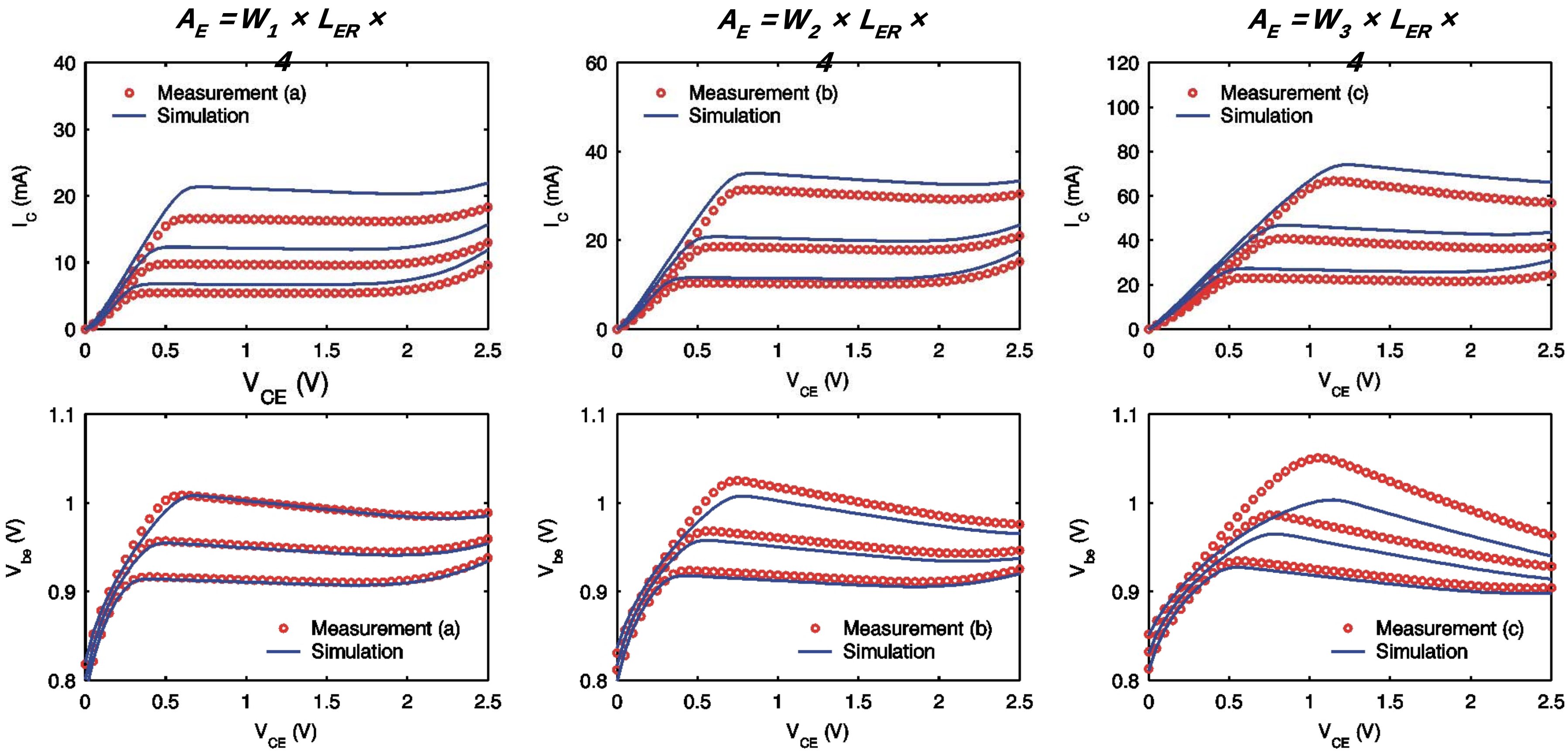

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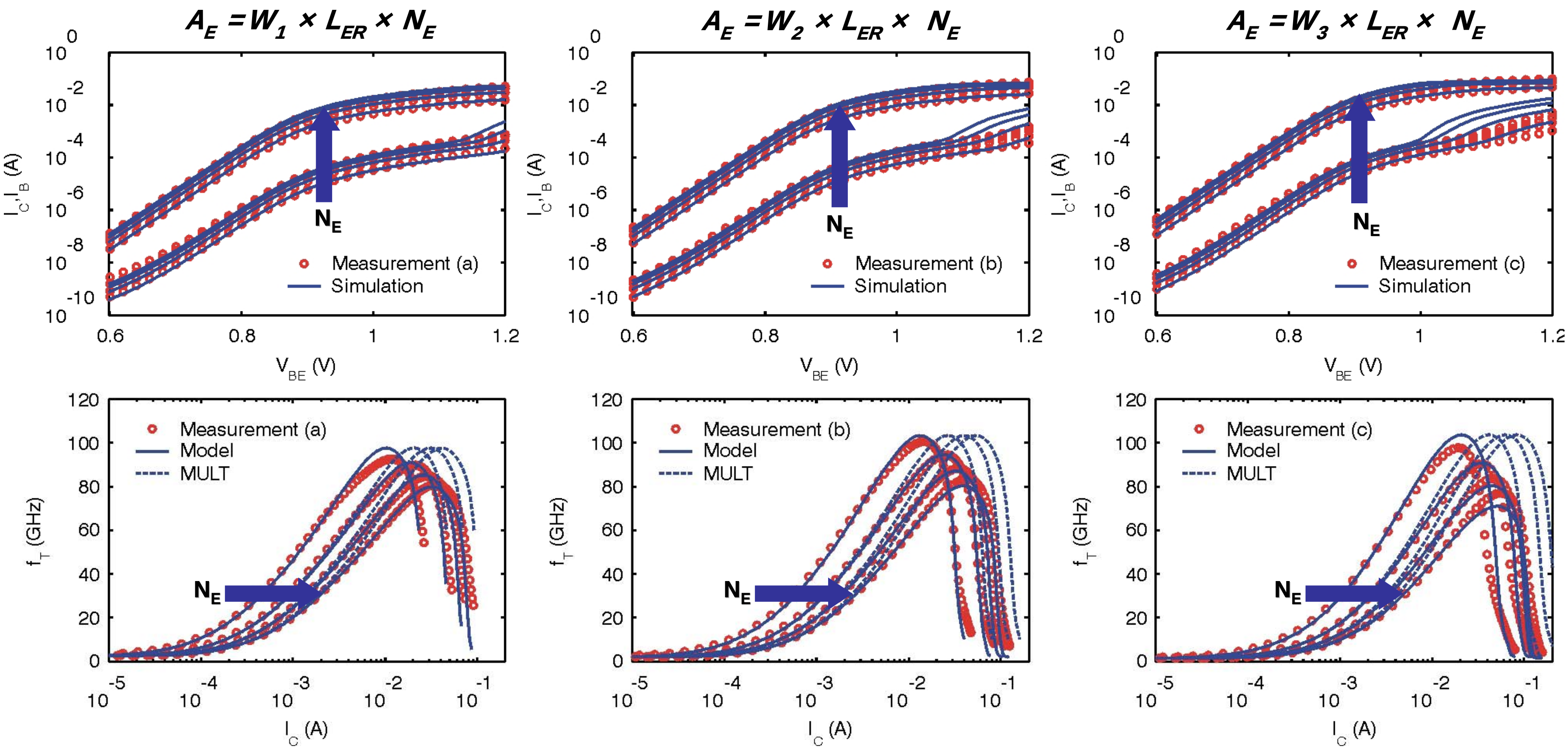

$$\frac{1}{2\pi f_T} = \tau_F + \frac{kT}{qI_C}\left(C_{je} + C_{jc}\right) + RCC \cdot C_{jc}.$$

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Conclusion

- A behavioral referenced based configuration scalable Mextram model has been developed and implemented in AHDL Verilog-A language for advanced circuit design. It is based on scaling of PN junction area for single emitter device and effective collector and thermal node assumption for multi-emitter finger devices.
- The scalable model uses the same set of the standard Mextram model parameters as reference parameters and additional geometry parameters for geometry scaling. Two more parameters RTHC and RCXC are used for configuration scaling, which model the mutual heating effect and collector resistance between adjacent fingers. Instance parameters WE, LE, NE and NC are added for selecting geometry and different layout configurations when using the model.
- The essential feature of the proposed geometry and configuration scaling methodology is a direct extraction of the temperature and geometry parameters from the measured electrical characteristics and the model parameters as reference parameters are extracted only once for a single reference geometry.
- The model simulation results not only fits device characteristic with different geometries but also nicely predicts the f_T degradation with increasing emitter-finger number due to increase of mutual heating and collector delay time. It concludes that the emitter finger number can't be increased without a limit as for emitter area.

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