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

Sadayuki Yoshitomi

Toshiba Corp, Semiconductor Company

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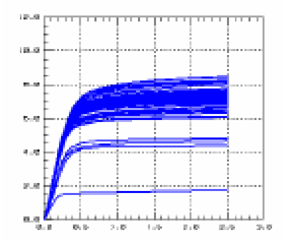
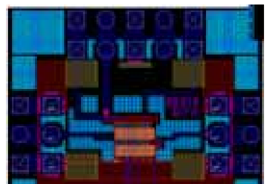
Objective of this work

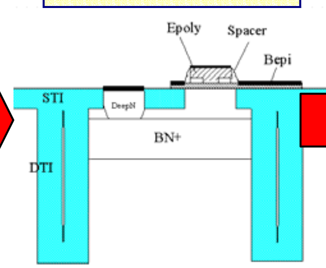
SPICE model (Golden Device)



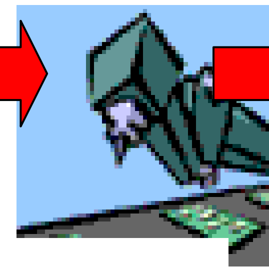
MASK Design



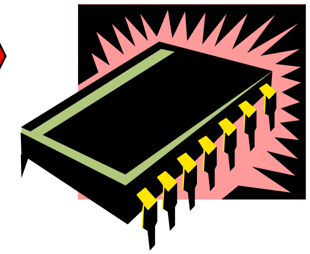
Process&PT



Assembly



FT



DOE/MonteCarlo analysis

Reasonable Estimation.

Quick Validation

BJT Physical model card

Reasonable estimation of process fluctuation.
Uses “COMMON Key Word” for process/circuit designers.

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,Rpinch

Base –epi width Doping concentration / Ge composition

N_e

N_E0=3e20

N_b

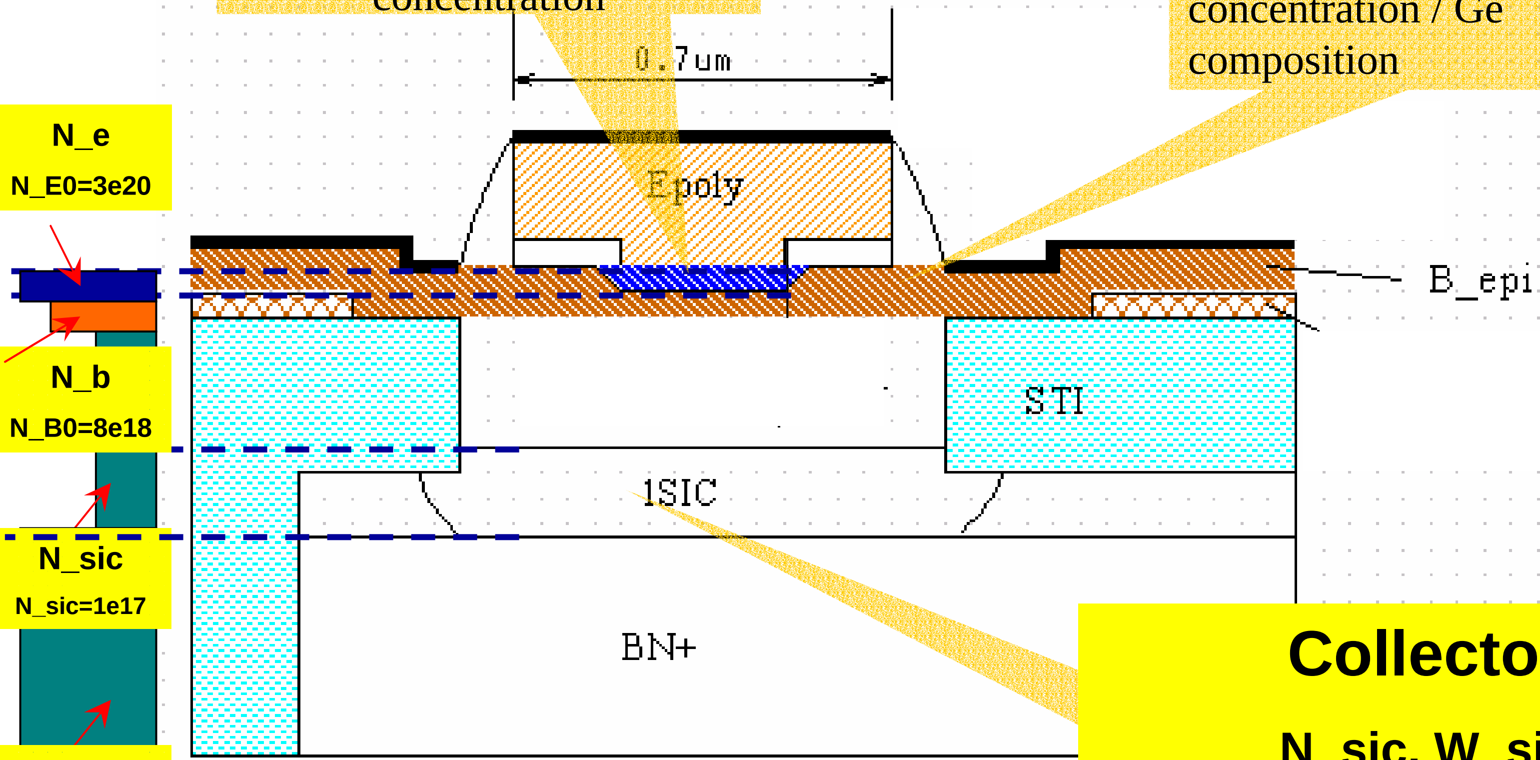
N_B0=8e18

N_sic

N_sic=1e17

N_c

N_c=1e19

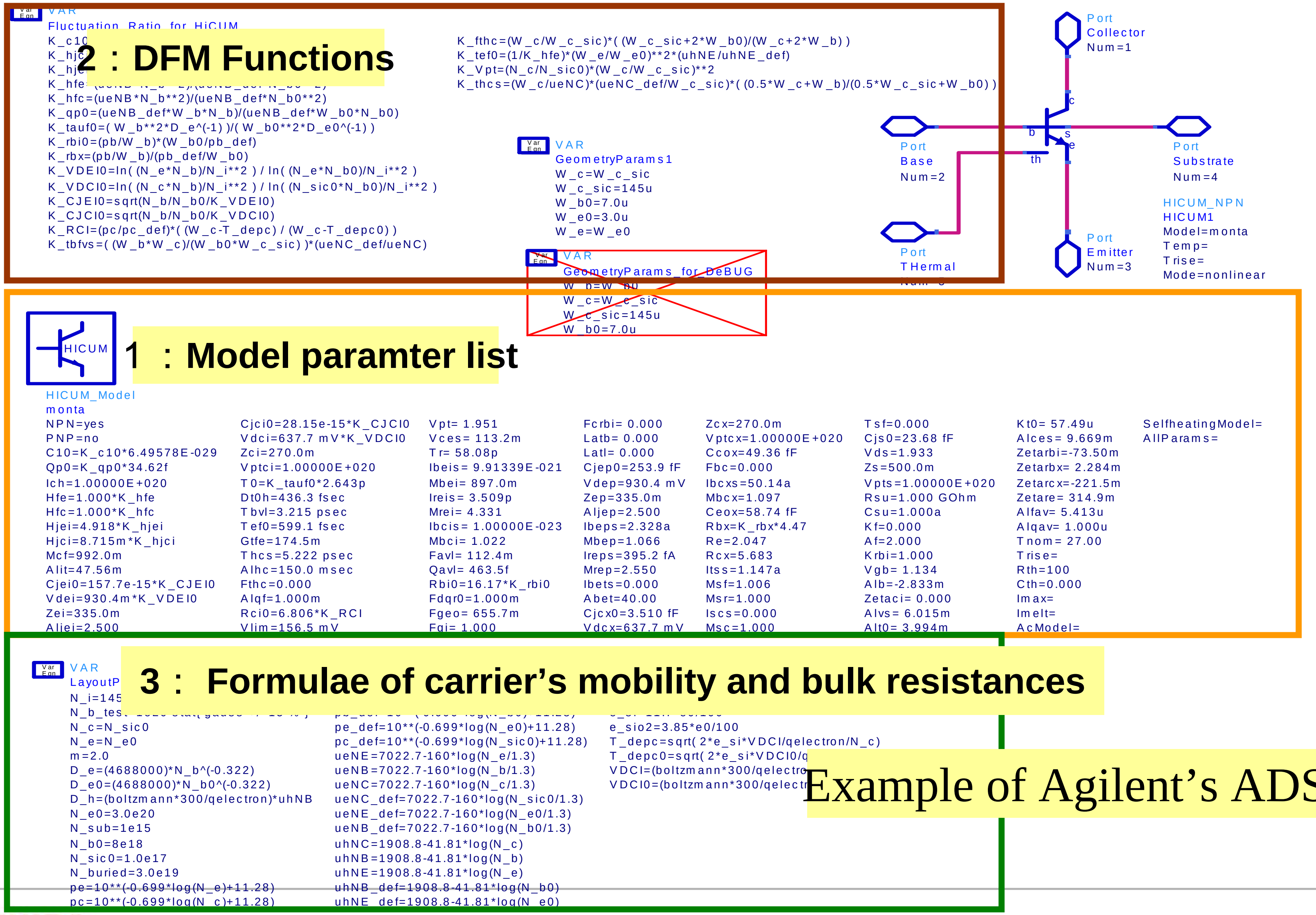


Collector

N_sic, W_sic

Doping Concentration and Depth of in SiC region

Structure of BJT Physical Model Card



Concepts of the DFM functions

(1) Static Characteristics

Ignoring recombination current

$$IB \approx Ipe = -\frac{qA_e D_{p\_e} n_i^2}{L_{pe} N_{\_e}} \exp(\frac{qVBE}{kT})$$

$$Ic \approx Inc = \frac{-qA_c D_{n\_b} n_i^2}{W\_bN\_b} \exp(\frac{qVBE}{kT}) \equiv IS \cdot \exp(\frac{qVBE}{kT})$$

=C10/Qb0

$$BF \equiv \frac{IC}{IB} = \frac{(\frac{qA_c D_{n\_b} n_i^2}{W\_bN\_b})}{(\frac{qA_b D_{p\_e} n_i^2}{W\_e \cdot N\_e})} = \frac{D_{n\_b} W\_eN\_e}{D_{p\_e} W\_bN\_b}$$

•Ni (density of free-electrons)

•N_e, N_b（Donor in the Emitter, Acceptor in the Base

•Dn_b:Diffusion coefficient of electron in the base

•Dp_e, Diffusion coefficient of hole in the emitter

Concepts of the DFM functions

(2) Early Voltage

$$V_A = \frac{Q_B}{h_{jci} C_{JC} - \left.\frac{dQ_f}{dV_{C'E'}}\right|_{VB'E'}}$$

$$V_A \cdot CJC = Q_B = A_C \cdot N\_b \cdot W\_b$$

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

(3) Transit time

TF0

$$TF = \frac{W\_b^2}{m \cdot D\_e}$$

$$m = 2$$

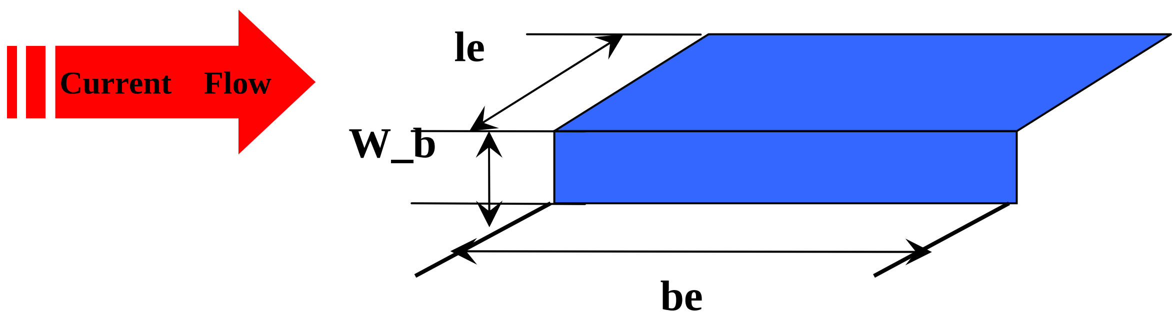
Accounts for the transit time of minority carriers traveling in the intrinsic base region with distance of W_B

Concepts of the DFM functions

(4) Intrinsic base resistance

$$R_{Bi0} = r_{sbi0} \cdot \frac{b_e}{l_e n_e} \cdot \frac{p\_b}{W\_b} \cdot \left\{ \frac{1}{12} \left(\frac{1}{12} - \frac{1}{28.6} \right) \frac{b_e}{l_e} \right\} \equiv \boxed{p\_b \cdot \frac{b_e}{W\_b \cdot l_e \cdot n_e}} \cdot g_i$$

Base Sheet Rsistance



Concepts of the DFM functions

(5) High Injection

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

G-P

$$IKF = Ae \cdot \frac{q \int_0^{w\_b} N\_b(x) \cdot dx}{TF} = Ae \cdot \frac{q \cdot m \cdot D\_e}{W\_b^2} \int_0^{w\_b} N\_b(x) \cdot dx$$

HiCUM

$$I_{CK} \approx \frac{v_{ceff}}{r_{Ci0}} \frac{1}{\sqrt{1 + \left(\frac{v_{ceff}}{V_{\lim}} \right)^2}}$$

$$r_{Ci0} = \frac{w\_c}{q\mu_n(N\_c)N_{\_c}A_E} \cdot \frac{1}{f_{cs}}$$

$$V_{\lim} = \frac{v_{sn}}{\mu_n(N\_c)} w\_c$$

$$V_{PT} = \frac{q \cdot N\_sic}{2\varepsilon_{si}} W\_sic^2$$

Formulae of carrier's mobility and bulk resistances

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

$$\mu_i = \mu_{\min} + \frac{\mu_{\max} - \mu_{\min}}{1 + \left(N / N_{ref1} \right)^{\alpha 1}} - \frac{\mu_l}{1 + \left(N_{ref2} / N \right)^{\alpha 2}}$$

Parameter	A-As	P	B
μ_{max} ($cm^2V^{-1}s^{-1}$)	1417.0	1414.0	470.5
μ_{min} ($cm^2V^{-1}s^{-1}$)	52.2	68.5	44.9
μ_l ($cm^2V^{-1}s^{-1}$)	43.4	56.1	29.0
N_{ref1}(cm^{-3})	9.68E+16	9.20E+16	2.23E+17
N_{ref2}(cm^{-3})	3.43E+20	3.41E+20	6.10E+20
α1	0.68	0.711	0.719
α2	2.0	1.98	2.0

$$D_{e(h)} = \frac{kT}{q} \mu_{e(h)}$$

Formula for minority carriers

$$\mu_i^m = \frac{\mu_i}{G(m,c,T)}$$

Resistivity

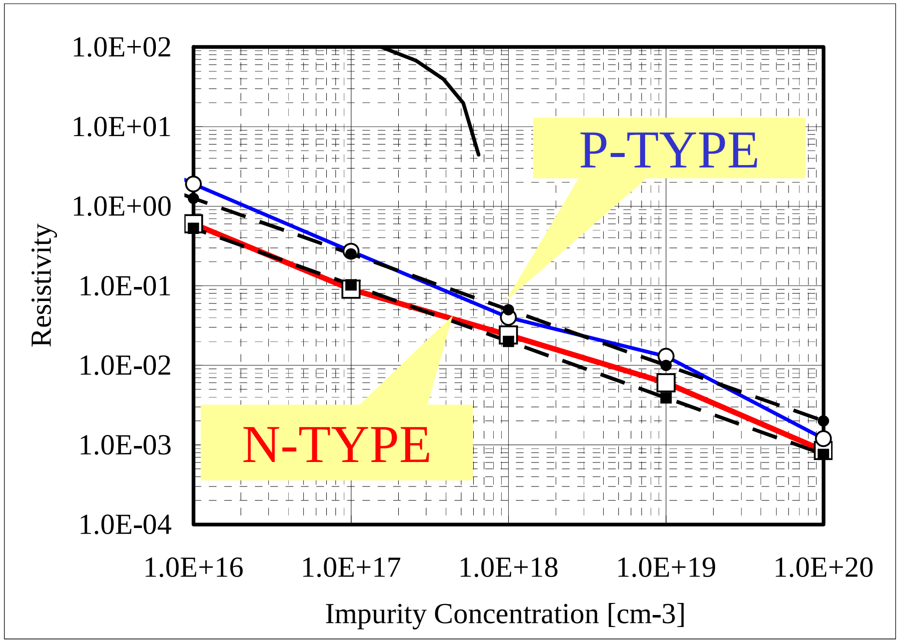
$$p\_i = 10^{(c1 \cdot \log 10(N\_i) + c2)}$$

For p-type: C1=-0.699, C2=11.28

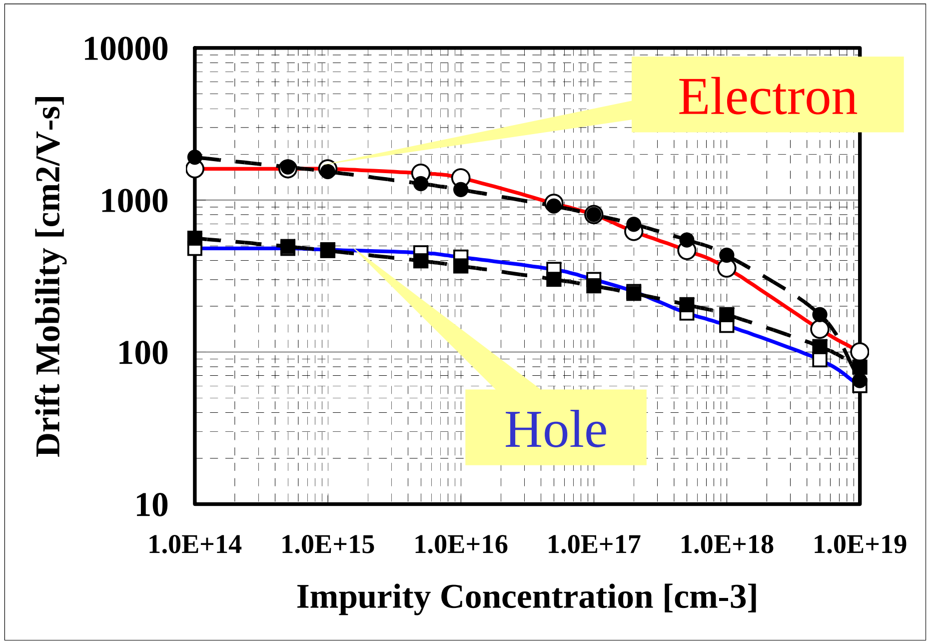
For n-type: C1=-0.710, C2=11.08

Fitting with experimental data

Resistivity [11]



Mobility [6,7,12]



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)

Name	DFM function	HiCUM	Gummel-Poon
K_c10	$(K\_Ae)^2 \cdot \frac{\mu_B(N\_b)\cdot N\_b^2}{\mu_B(N\_b0)\cdot N\_b0^2}$	**C10**	**IS**
K_hjci	$\exp\left(\frac{a_G}{V_T}(W\_b0 - W\_b)\right)$	**Hjci**	**(VA)**
K_hjei	$K\_Ac \cdot \frac{N\_b \cdot W\_b}{N\_b0 \cdot W\_b0} \bullet \frac{1}{Kcjci}$	**Hjei**	**(VA)**
K_hfe	$\frac{\mu_n(N\_b)N\_b^2}{\mu_n(N\_b0)N\_b0^2} \frac{\mu_n(N\_e)N\_e^2}{\mu_n(N\_e0)N\_e0^2}$	**Hfe**	**--**
K_hfc	$\frac{\mu_n(N\_b)N\_b^2}{\mu_n(N\_b)N\_b0^2} \frac{\mu_n(N\_sic)N\_sic^2}{\mu_n(N\_sic)N\_sic0^2}$	**Hfc**	**--**
K_Qp0	$K\_Ae \cdot \frac{N\_b \cdot W\_b}{N\_b0 \cdot W\_b0}$	**Qp0**	**--**
K_tauf0	$\frac{W\_b^2 \cdot De(N\_b)^{-1}}{W\_b0^2 \cdot De(N\_b0)^{-1}}$	**Tauf0**	**TF**
K_thcs	$\frac{W\_sic}{\mu n(N\_sic)} \cdot \frac{\mu n(N\_sic0)}{W\_sic0} \cdot \frac{\frac{W\_sic}{2} + \frac{W\_b}{G}}{\frac{W\_sic0}{2} + \frac{W\_b0}{G}}$	**Thcs**	**--**
K_fthc	$\frac{W\_sic}{W\_sic0} \frac{W\_sic0 + 2 \cdot W\_b0}{W\_sic + 2 \cdot W\_b}$	**Fthc**	**--**
K_Vpt	$\frac{N\_sic}{N\_sic0}\left(\frac{W\_sic}{W\_sic0}\right)^2$	**Vpt**	**--**

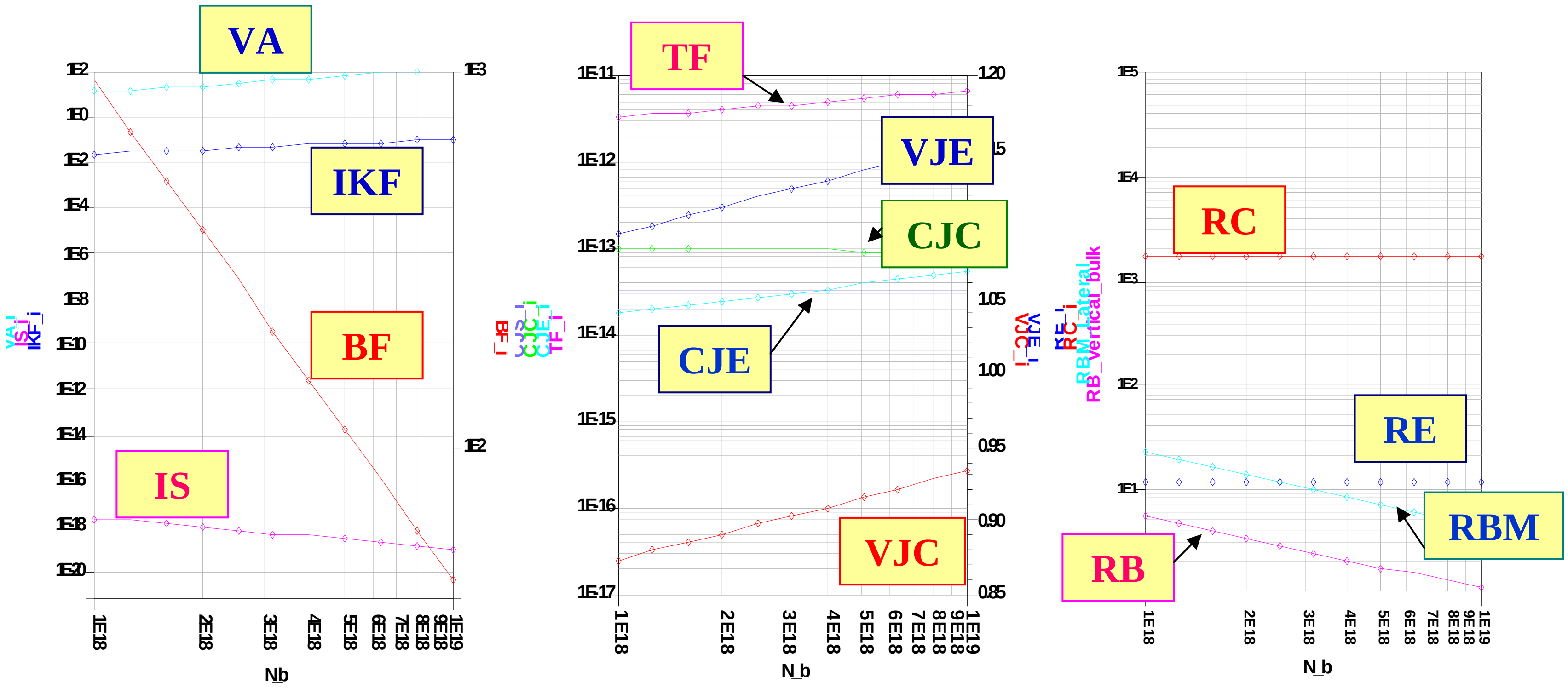
List of DFM functions (2)

Name	DFM function	HiCUM	Gummel-Poon
K_Vpt	$\frac{N\_sic}{N\_sic0}\left(\frac{W\_sic}{W\_sic0}\right)^2$	Vpt	--
K_tef0	$\frac{1}{K\_BF}\frac{W\_e^2\cdot\mu h(N\_e0)}{W\_e0^2\cdot\mu h(N\_e)}$	Tef0	--
K_BF	$\frac{W\_e\cdot N\_e}{W\_e0\cdot N\_e0}\frac{D_n(N\_B)}{D_n(N\_B0)}\frac{W\_b\cdot N\_b}{W\_b0\cdot N\_b0}\frac{D_p(N\_b)}{D_p(N\_b0)}$	---	BF
K_rbi0	$\frac{K\_BE}{K\_Le}\cdot\frac{\frac{p\_b}{W\_b}}{\frac{p\_b0}{W\_b0}}$	Rbi0	RB
K_rbx	$\frac{p\_b/w\_b}{p\_b0/w\_b0}$	Rbx	RBM
K_rci	$\frac{pc}{pc\_def}\cdot\frac{W\_sic-T\_depc}{W\_sic0-T\_depc0}$	Rci	RC
K_CJxi0	$\mathrm{K\_Ax}\cdot\sqrt{\frac{N\_b}{N\_b0}\cdot\frac{1}{\mathrm{KVdxi0}}}$	Cjxi0	Cjx
K_Vdxi0	$\frac{\ln\frac{N\_e(N\_sic)\cdot N\_b}{N\_i^2}}{\ln\frac{N\_e0(N\_sic0)\cdot N\_b0}{N\_i^2}}$	Vdxi0	Vjx
K_tbfvs	$\frac{W\_b\cdot W\_sic}{W\_b0\cdot W\_sic0}\cdot\frac{\mu c(N\_sic0)}{\mu c(N\_sic)}$	Tbfvs	--
K_IKF	$K\_Ae\cdot\frac{D\_e}{D\_e0}\cdot\frac{W\_b0}{W\_b}\cdot\frac{N\_b}{N\_b0}$	---	IKF

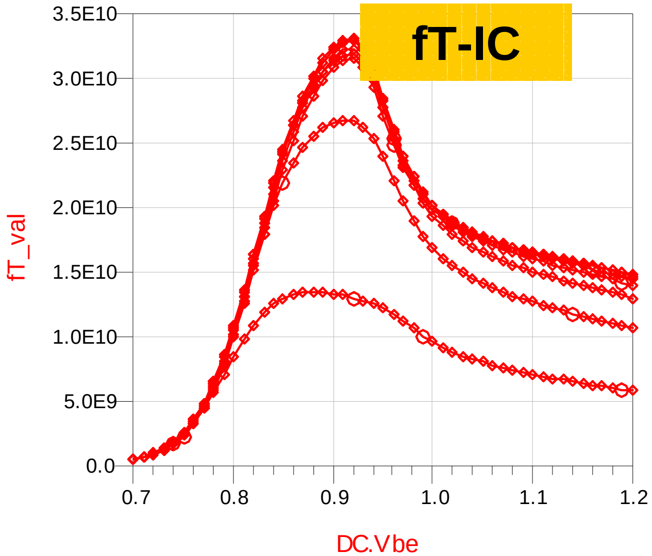
Function of BJT physical model card (1)

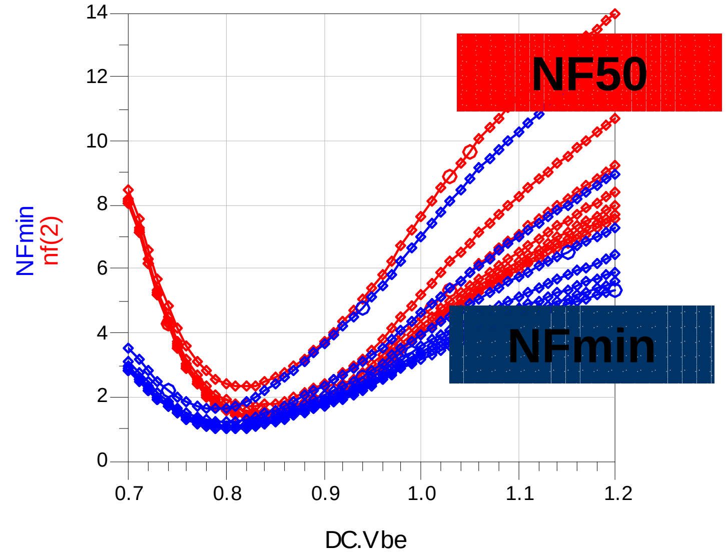
SPICE model parameters: Function of (N_b)

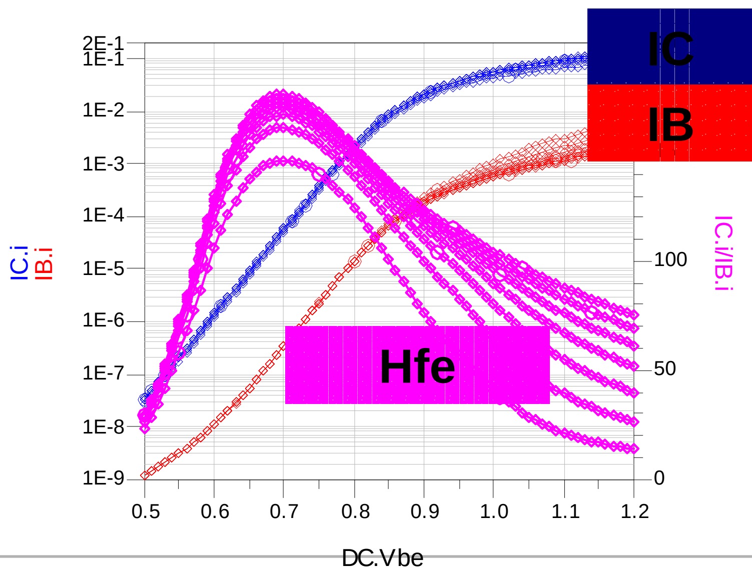
N_b:doping concentration in the base



Function of BJT physical model card







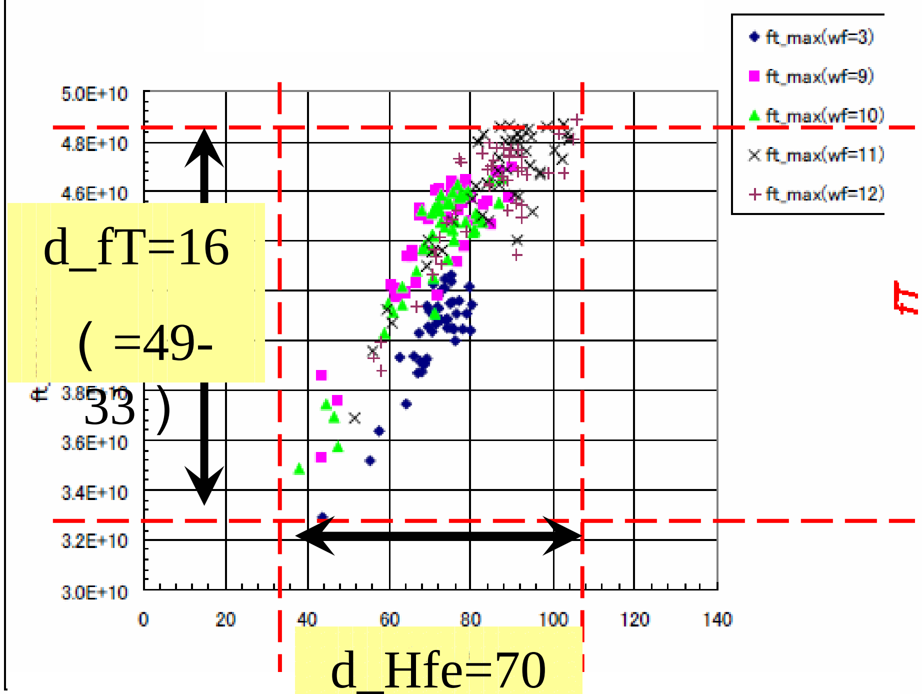
N_B : 2e18 to 1.4e19 cm-3

by 2e18 cm-3

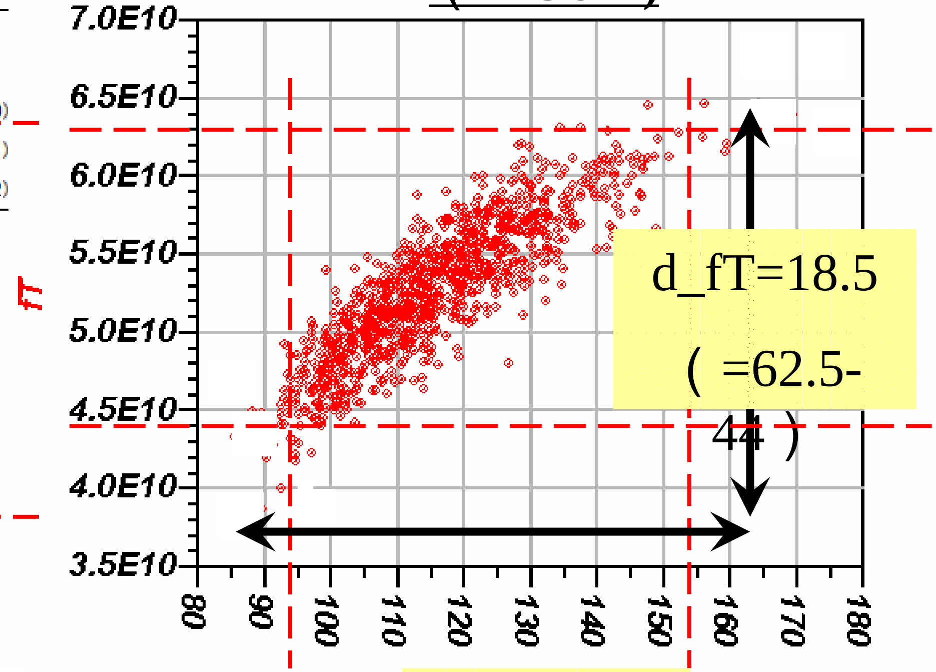
fT vs. Hfe Scattering Plot

VBE=0.92V,VC=3V

Measurement data (230 points)



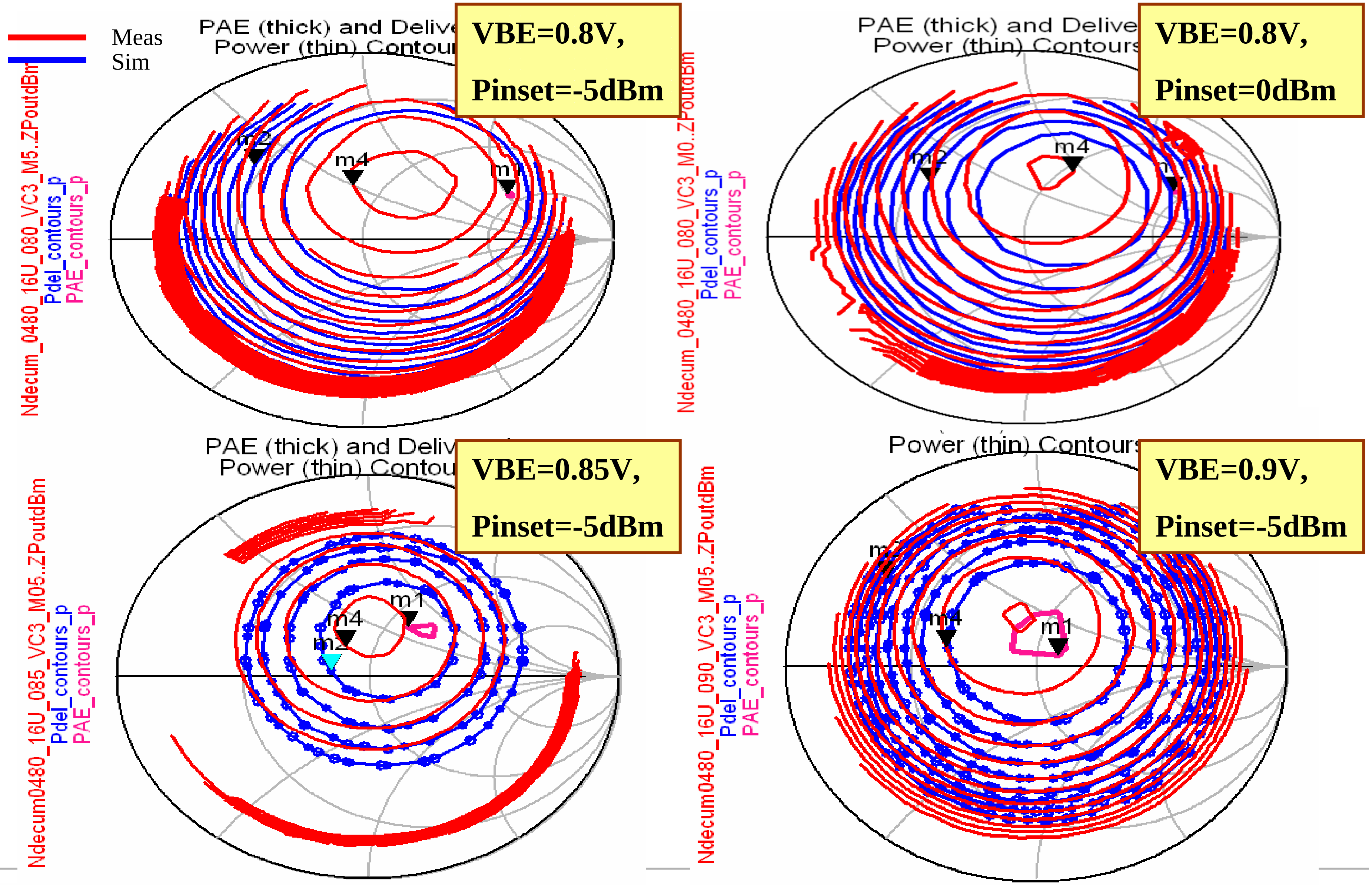
BJT Physical model card (HiCUM)



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

W_B Gaussian Nominal value=7ucm +/-10%

GainCircules modelling result (0.4um*8um*16unit)



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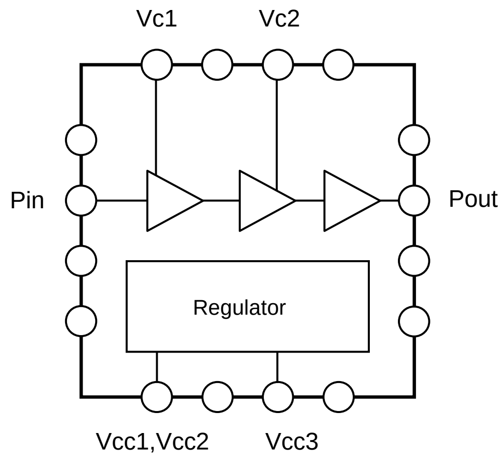
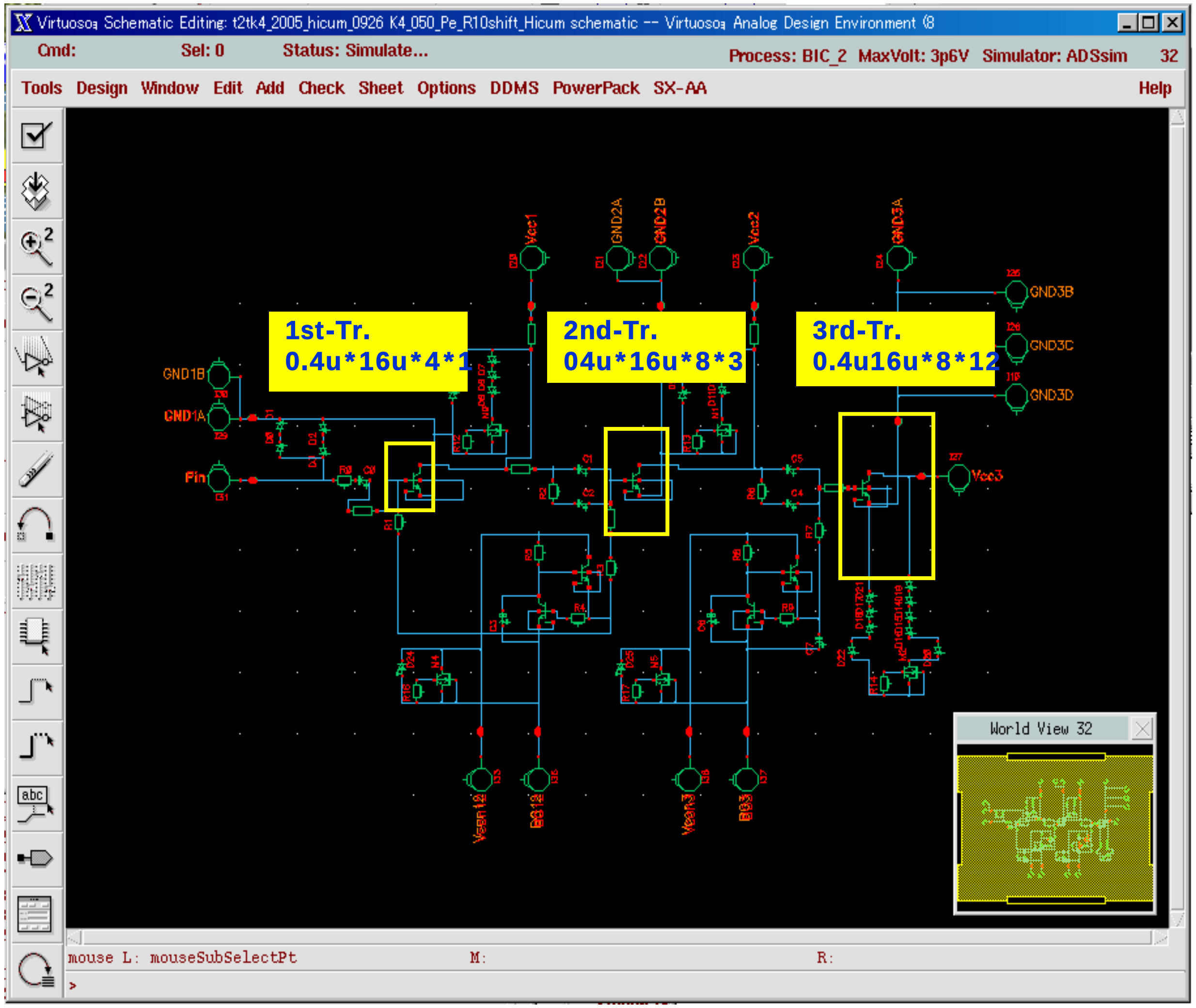
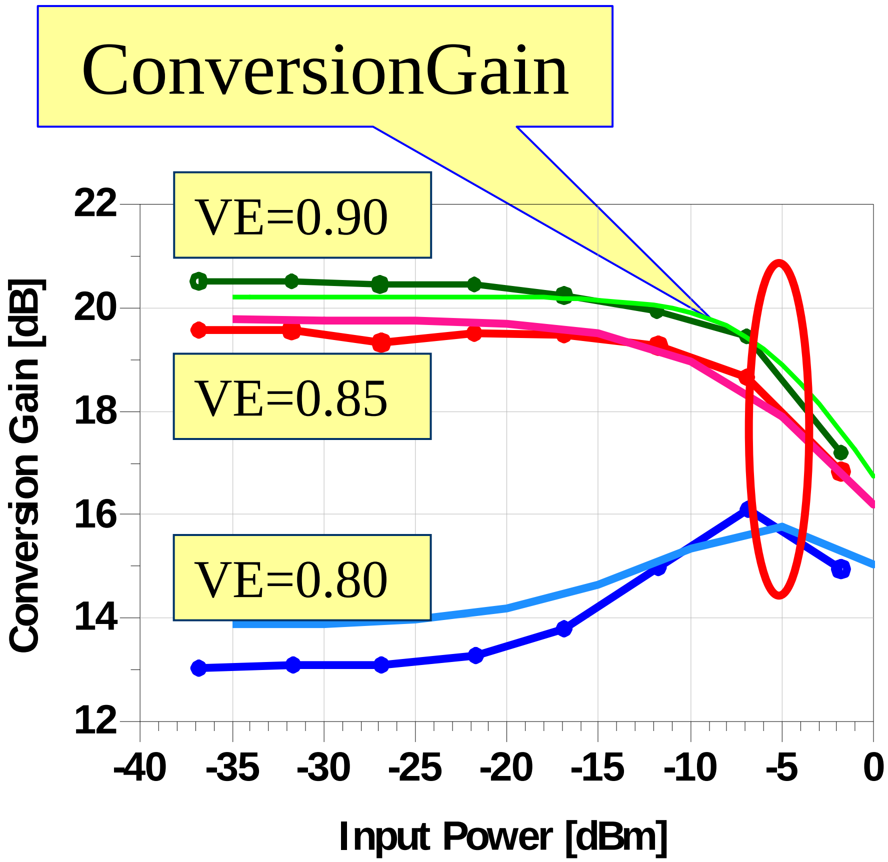
Power Amplifier for PHS applications

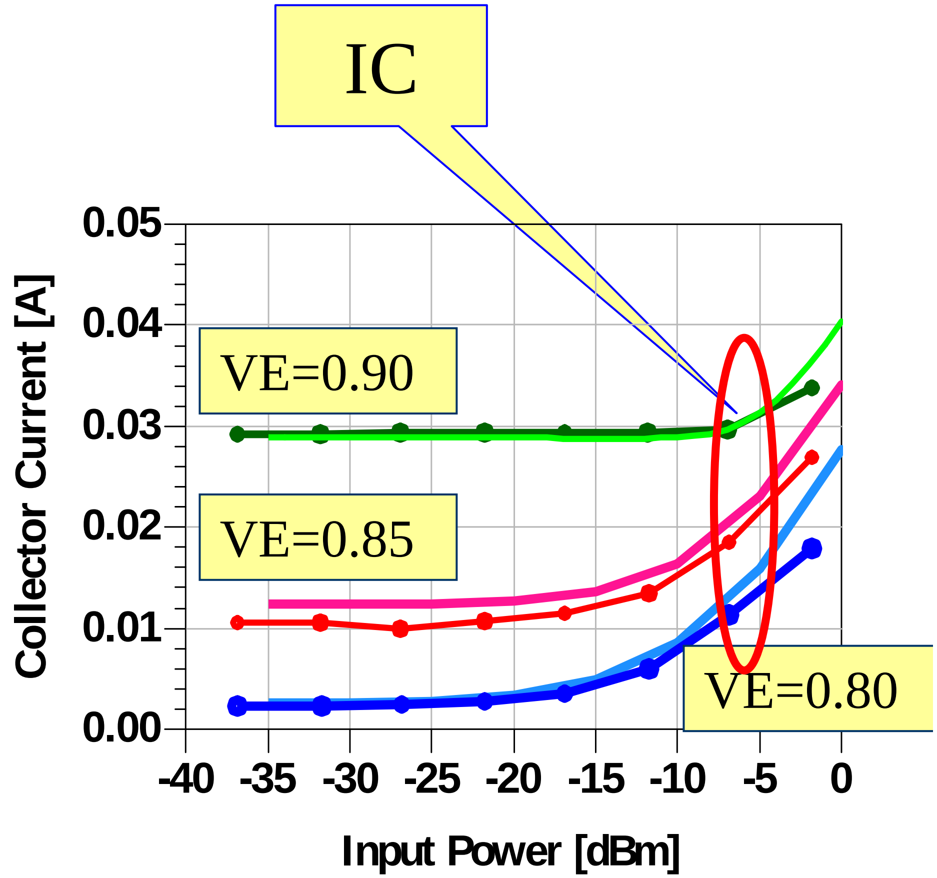




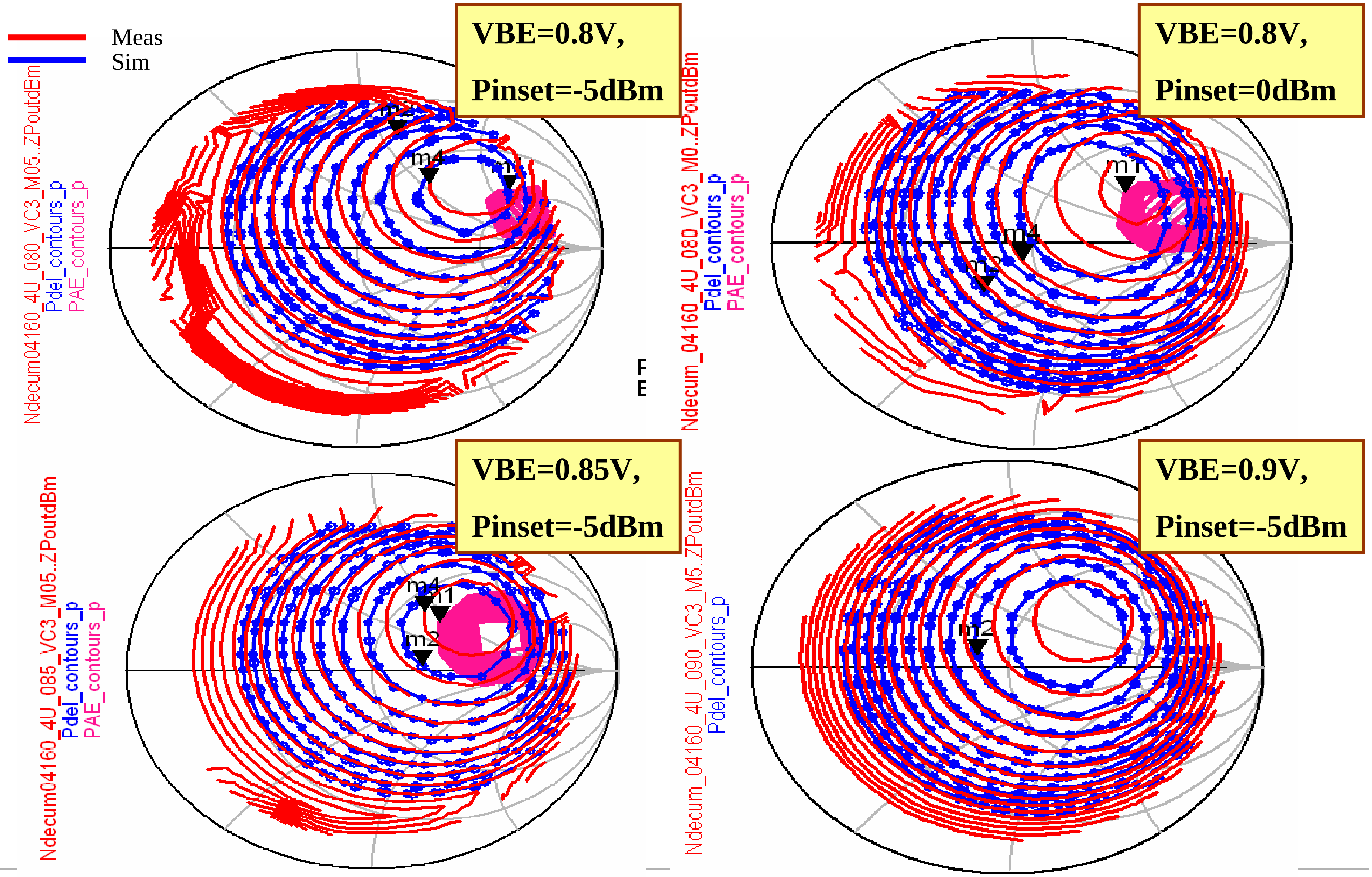
HiCUM Pin-Pout modelling result (0.4um*16um*4unit)

Pin=2.4 GHz





LoadPull modelling result (0.4um*16um*4unit)

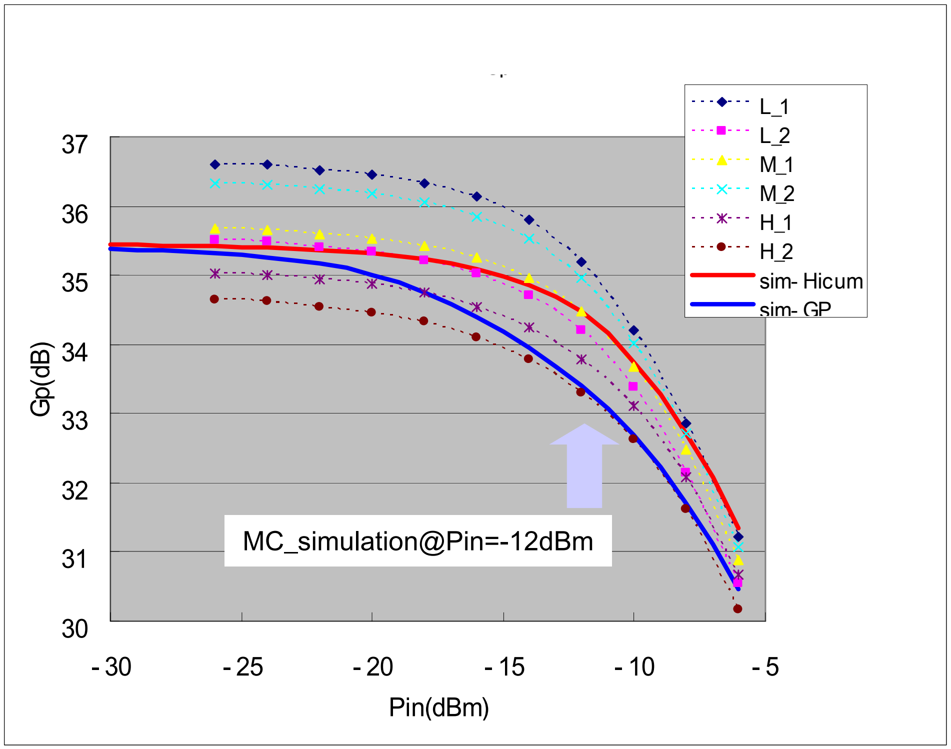


Comparison with the measurement (1)

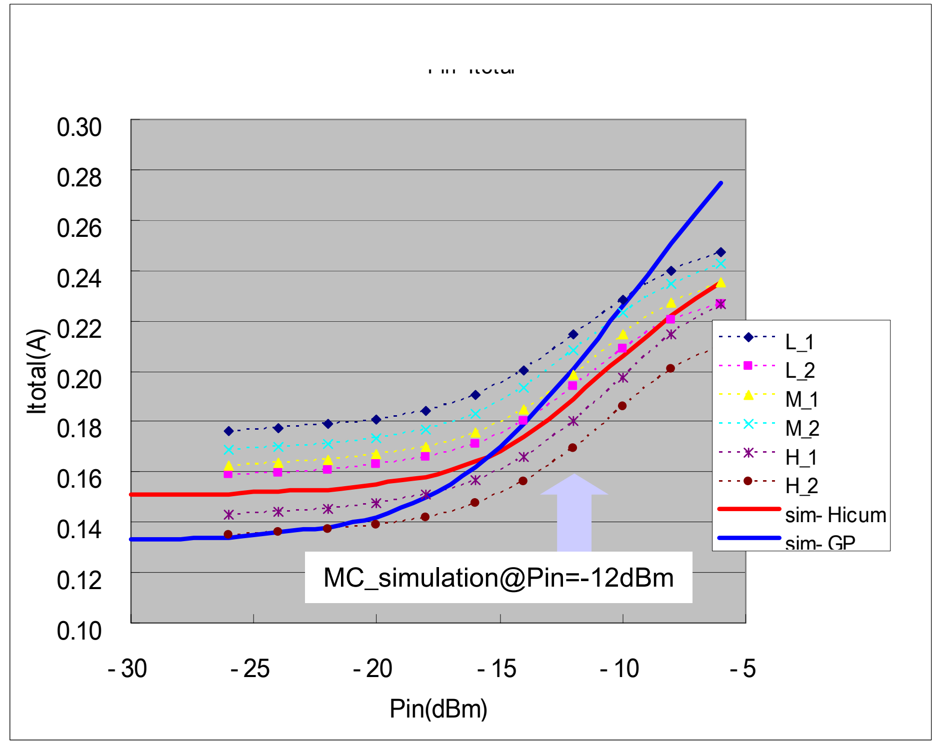
Split samples (R±10%) Plus 3 different evaluation boards (3states*2)
HiCUM model (nominal parameters)

GP model
Hicum
Measureme
nt

Pin - Gp



Pin - Itotal

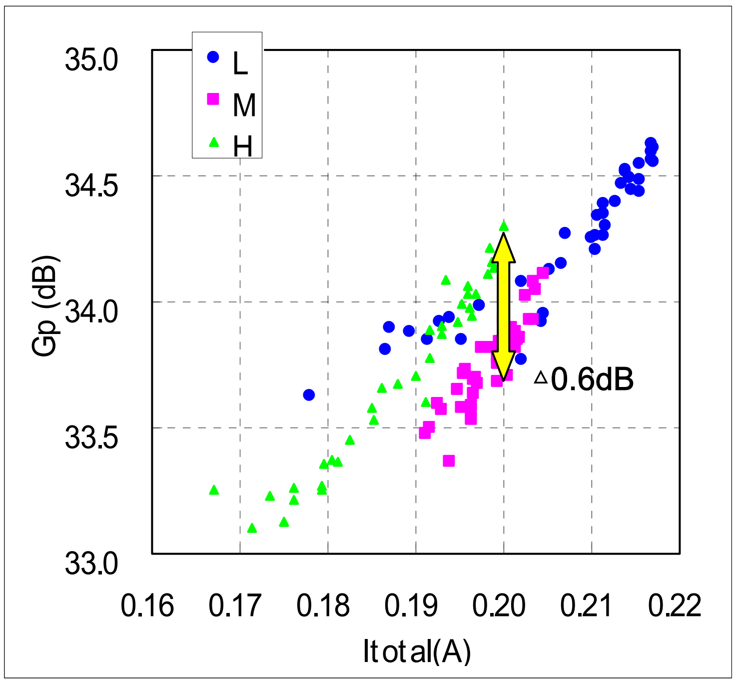


Comparison with the measurement (2)

Good Match between MonteCarlo simulation and measurement

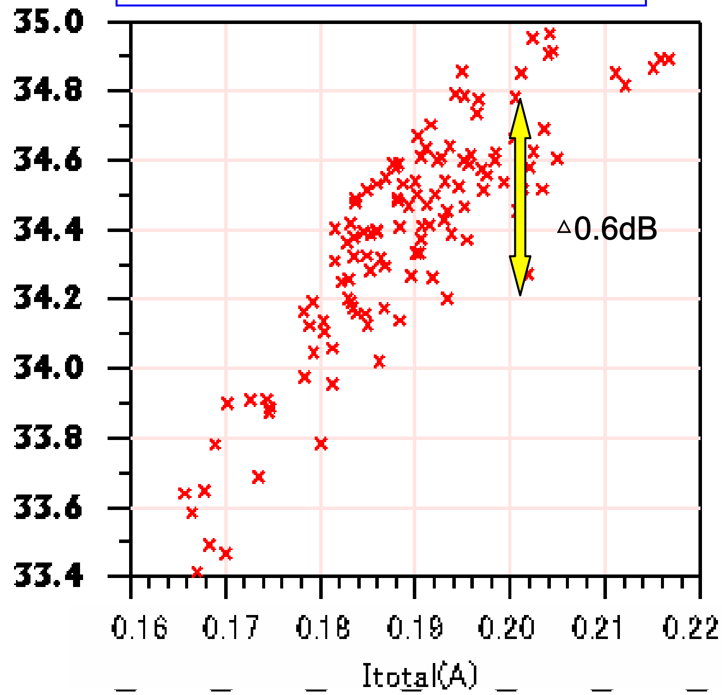
CW @Pin=-12dBm
R±10%(3 R conditions) 120 samples

Measurement
120 samples



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

Monte-Carlo simulation by
the BJT physical model card



Summary

- Proposed “BJT physical model card” provides
  - Simple structure
    - 9 process variables
      - **N_b,W_b,d_EG,Rpinch, A_e,N_e,W_e N_sic, W_sic**
    - Formulae by the use of mobility, bulk resistance, Diffusion coefficients.
  - Rreasonable prediction of the device and circuits’ statistics without going through fabrication process.

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