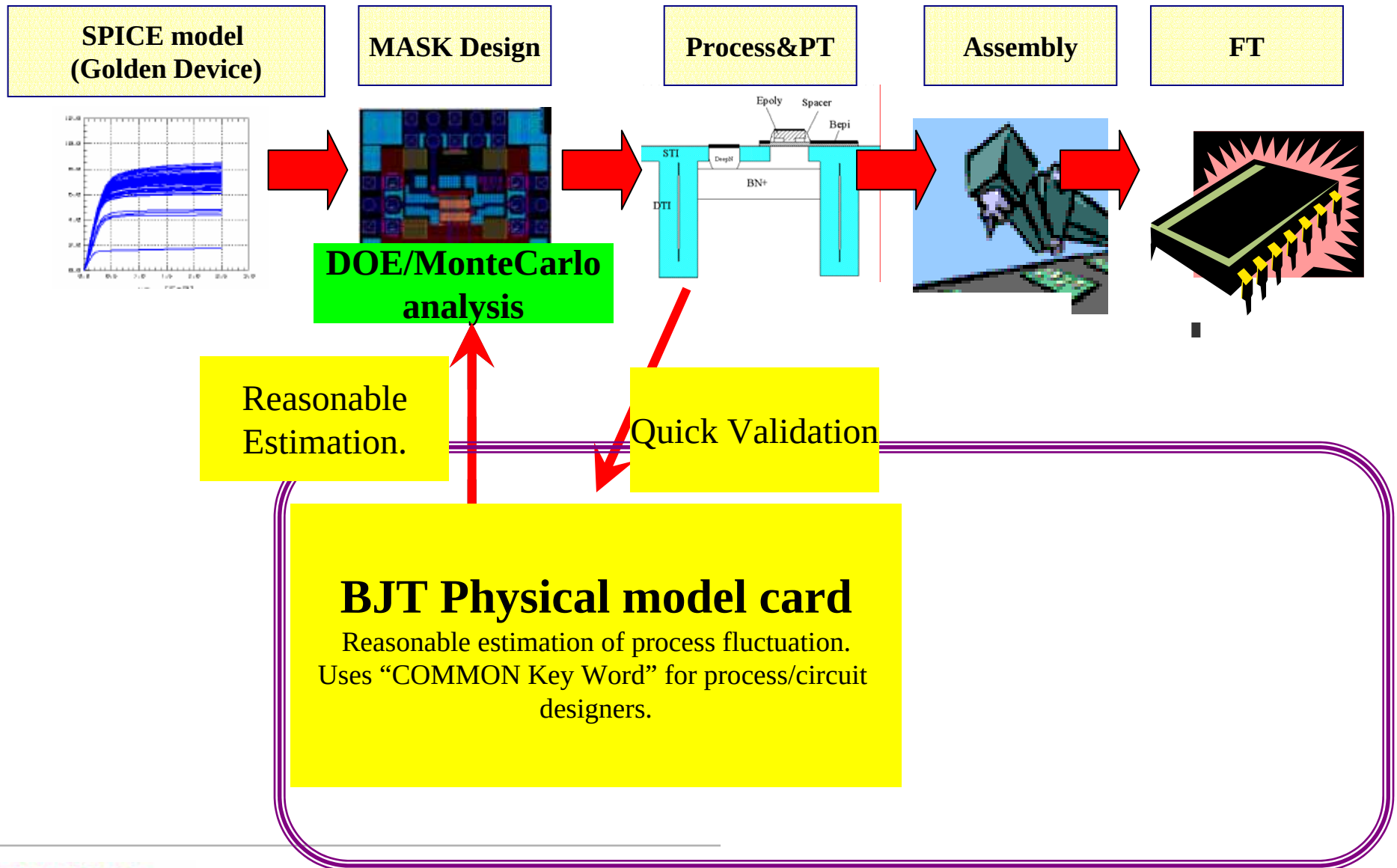


*Modification of HiCUM and G-P model card for DFM  
(Design For Manufacturing) Applications*

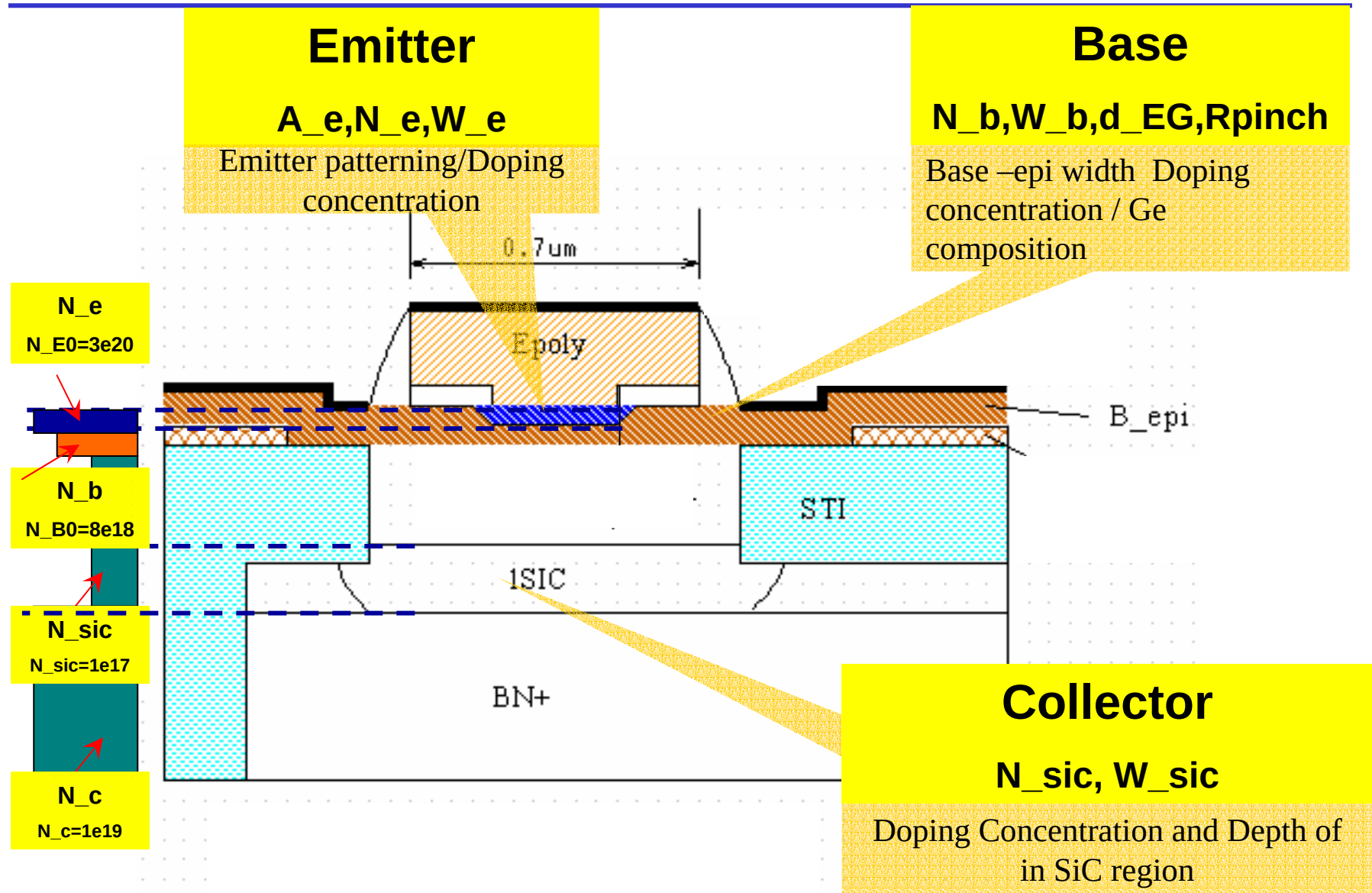
**Sadayuki Yoshitomi**

Toshiba Corp, Semiconductor Company

# Objective of this work



# Key Process variables for Bipolar Transistors' Fabrication



# Structure of BJT Physical Model Card

## 2 : DFM Functions

```

VAR
Fluctuation_Ratio_for_HICUM
K_c10=
K_hje=
K_hjc=
K_hfc=
K_hfc=(ueNB*N_b**2)/(ueNB_def*N_b**2)
K_qp0=(ueNB_def*N_b*N_b)/(ueNB_def*N_b**2)
K_tauf0=(W_b**2*D_e*(-1))/(W_b0**2*D_e0*(-1))
K_rbi0=(pb/W_b)*(W_b0/pb_def)
K_rbx=(pb/W_b)/(pb_def/W_b0)
K_VDEI0=ln((N_e*N_b)/N_i**2)/ln((N_e*N_b0)/N_i**2)
K_VDCI0=ln((N_c*N_b)/N_i**2)/ln((N_sic0*N_b0)/N_i**2)
K_CJCI0=sqrt(N_b/N_b0/K_VDEI0)
K_CJCI0=sqrt(N_b/N_b0/K_VDCI0)
K_RCI=(pc/pc_def)*(W_c-T_depc)/(W_c-T_depc0)
K_tbfvs=((W_b*W_c)/(W_b0*W_c_sic))*(ueNC_def/ueNC)
    
```

```

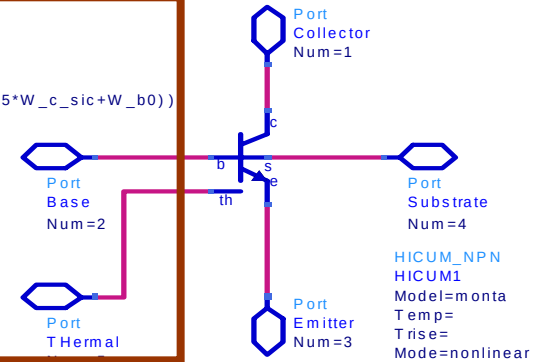
K_fthc=(W_c/W_c_sic)*(W_c_sic+2*W_b0)/(W_c+2*W_b)
K_tef0=(1/K_hfe)*(W_e/W_e0)**2*(uhNE/uhNE_def)
K_Vpt=(N_c/N_sic0)*(W_c/W_c_sic)**2
K_thcs=(W_c/ueNC)*(ueNC_def/W_c_sic)*((0.5*W_c+W_b)/(0.5*W_c_sic+W_b0))
    
```

```

VAR
GeometryParams1
W_c=W_c_sic
W_c_sic=145u
W_b0=7.0u
W_e0=3.0u
W_e=W_e0
    
```

```

VAR
GeometryParams_for_Debug
W_n=W_b0
W_c=W_c_sic
W_c_sic=145u
W_b0=7.0u
    
```



## 1 : Model paramter list

|                         |                         |                    |                |                    |                   |                 |                   |
|-------------------------|-------------------------|--------------------|----------------|--------------------|-------------------|-----------------|-------------------|
| HICUM_Model             | Cjci0=28.15e-15*K_CJCI0 | Vpt=1.951          | Fcrbi=0.000    | Zcx=270.0m         | Tsf=0.000         | Kt0=57.49u      | SelfheatingModel= |
| monta                   | Vdci=637.7 mV*K_VDCI0   | Vces=113.2m        | Latb=0.000     | Vptcx=1.00000E+020 | Cjs0=23.68 fF     | Alces=9.669m    | AIIParams=        |
| NPN=yes                 | Zci=270.0m              | Tr=58.08p          | Latl=0.000     | Ccox=49.36 fF      | Vds=1.933         | Zetarbi=-73.50m |                   |
| PNP=no                  | Vptci=1.00000E+020      | Ibeis=9.91339E-021 | Cjep0=253.9 fF | Fbc=0.000          | Zs=500.0m         | Zetarb=-2.284m  |                   |
| C10=K_c10*6.49578E-029  | T0=K_tauf0*2.643p       | Ireis=3.509p       | Vdep=930.4 mV  | Ibcxs=50.14a       | Vpts=1.00000E+020 | Zetarc=-221.5m  |                   |
| Qp0=K_qp0*34.62f        | Dt0h=436.3 fsec         | Mrei=4.331         | Zep=335.0m     | Mbcx=1.097         | Rsu=1.000 GOhm    | Zetare=314.9m   |                   |
| Ich=1.00000E+020        | Tbvl=3.215 psec         | Ibcis=1.00000E-023 | Aljep=2.500    | Ccox=58.74 fF      | Csu=1.000a        | Alfav=5.413u    |                   |
| Hfe=1.000*K_hfe         | Tef0=599.1 fsec         | Mbci=1.022         | Ibeps=2.328a   | Rbx=K_rbx*4.47     | Kf=0.000          | Alqav=1.000u    |                   |
| Hjei=4.918*K_hjei       | Gtfe=174.5m             | Mbep=1.066         | Mbep=1.066     | Re=2.047           | Af=2.000          | Tnom=27.00      |                   |
| Hjci=8.715m*K_hjci      | Thcs=5.222 psec         | Favl=112.4m        | Ireps=395.2 fA | Rcx=5.683          | Krbi=1.000        | Trise=          |                   |
| Mcf=992.0m              | Alhc=150.0 msec         | Qavl=463.5f        | Mrep=2.550     | Itss=1.147a        | Vgb=1.134         | Rth=100         |                   |
| Alit=47.56m             | Fthc=0.000              | Rbi0=16.17*K_rbi0  | Ibets=0.000    | Msf=1.006          | Alb=-2.833m       | Cth=0.000       |                   |
| Cjei0=157.7e-15*K_CJCI0 | Alqf=1.000m             | Fdqr0=1.000m       | Abet=40.00     | Msr=1.000          | Zetaci=0.000      | Imax=           |                   |
| Vdei=930.4m*K_VDEI0     | Rci0=6.806*K_RCI        | Fgeo=655.7m        | Cjcx0=3.510 fF | Iscs=0.000         | Alvs=6.015m       | Imelt=          |                   |
| ZeI=335.0m              | Vlim=156.5 mV           | Fqi=1.000          | Vdcx=637.7 mV  | Msc=1.000          | Alt0=3.994m       | AcModel=        |                   |
| Aljei=2.500             |                         |                    |                |                    |                   |                 |                   |

## 3 : Formulae of carrier's mobility and bulk resistances

```

VAR
LayoutP
N_i=145
N_b=tes
N_c=N_sic0
N_e=N_e0
m=2.0
D_e=(4688000)*N_b*(-0.322)
D_e0=(4688000)*N_b0*(-0.322)
D_h=(boltzmann*300/qelectron)*uhNB
N_e0=3.0e20
N_sub=1e15
N_b0=8e18
N_sic0=1.0e17
N_buried=3.0e19
pe=10**(-0.699*log(N_e)+11.28)
pc=10**(-0.699*log(N_c)+11.28)
    
```

Example of Agilent's ADS

# Concepts of the DFM functions

## (1) Static Characteristics

Ignoring recombination current

$$I_B \approx I_{pe} = -\frac{qA_e D_{p\_e} n_i^2}{L_{pe} N_{\_e}} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$I_C \approx I_{nc} = \frac{-qA_c D_{n\_b} n_i^2}{W_{\_b} N_{\_b}} \exp\left(\frac{qV_{BE}}{kT}\right) \equiv I_S \cdot \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$= C10/Qb0$$

$$BF \equiv \frac{I_C}{I_B} = \frac{\left(\frac{qA_c D_{n\_b} n_i^2}{W_{\_b} N_{\_b}}\right)}{\left(\frac{qA_b D_{p\_e} n_i^2}{W_{\_e} \cdot N_{\_e}}\right)} = \frac{D_{n\_b} W_{\_e} N_{\_e}}{D_{p\_e} W_{\_b} N_{\_b}}$$

• $n_i$  (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

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

$V_A \cdot C_{JC} = Q_B = A_C \cdot N_b \cdot W_b$  Accounts for a equivalent voltage for minority carriers needed to fully-charge  $Q_B$  (base charge) via CJC

## (3) Transit time

TF0

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

$m = 2$

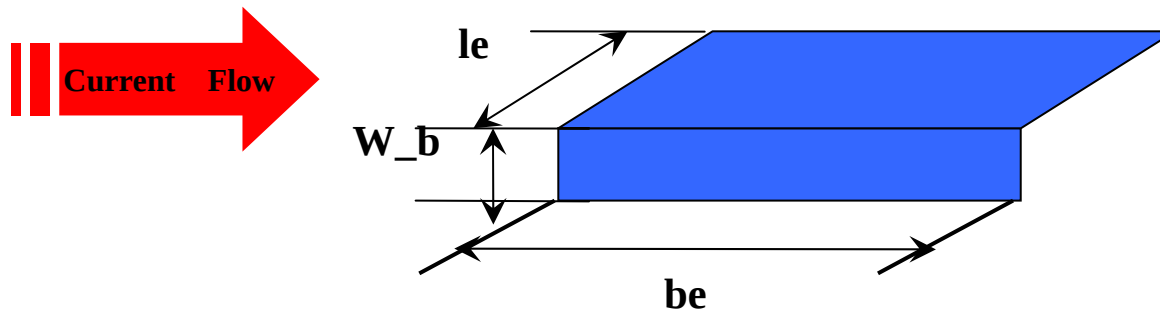
Accounts for the transit time of minority carriers traveling in the intrinsic base region with distance of  $W_B$

# Concepts of the DFM functions

## (4) Intrinsic base resistance

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

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

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

$$r_{Ci0} = \frac{w_c}{q\mu_n(N_c)N_c A_E} \cdot \frac{1}{f_{cs}}$$

$$V_{lim} = \frac{v_{sn}}{\mu_n(N_c)} w_c$$

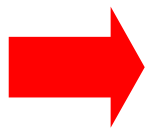
$$V_{PT} = \frac{q \cdot N_{sic}}{2\epsilon_{si}} W_{sic}^2$$



# Formulae of carrier's mobility and bulk resistances

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

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



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

| Parameter                                                       | A-As     | P        | B        |
|-----------------------------------------------------------------|----------|----------|----------|
| $\mu_{\max}$ (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ) | 1417.0   | 1414.0   | 470.5    |
| $\mu_{\min}$ (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ) | 52.2     | 68.5     | 44.9     |
| $\mu_l$ (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> )      | 43.4     | 56.1     | 29.0     |
| $N_{\text{ref}1}$ (cm <sup>-3</sup> )                           | 9.68E+16 | 9.20E+16 | 2.23E+17 |
| $N_{\text{ref}2}$ (cm <sup>-3</sup> )                           | 3.43E+20 | 3.41E+20 | 6.10E+20 |
| $\alpha 1$                                                      | 0.68     | 0.711    | 0.719    |
| $\alpha 2$                                                      | 2.0      | 1.98     | 2.0      |

## Resistivity

$$\rho_i = 10^{(C1 \cdot \log_{10}(N_i) + C2)}$$

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

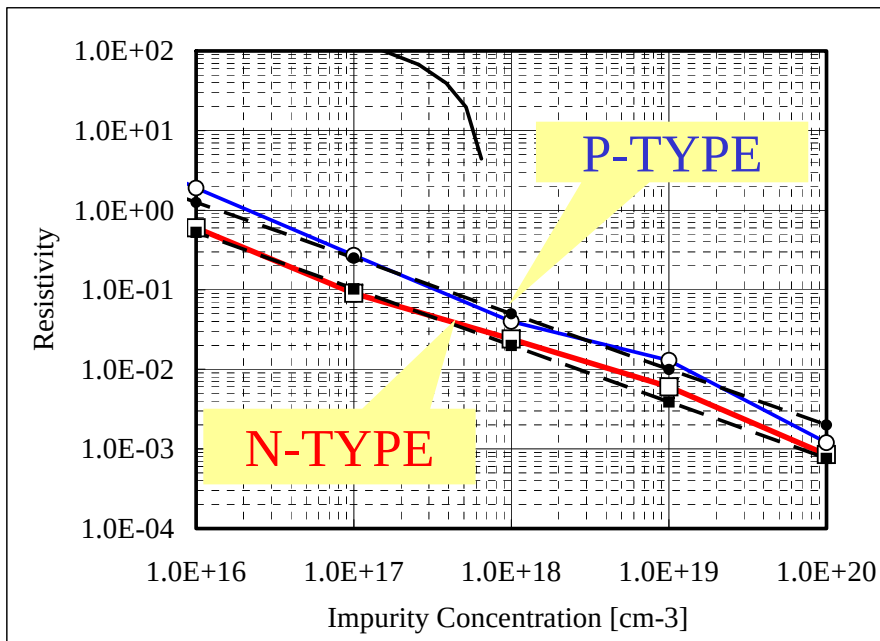
For n-type: C1=-0.710, C2=11.08

Formula for minority carriers

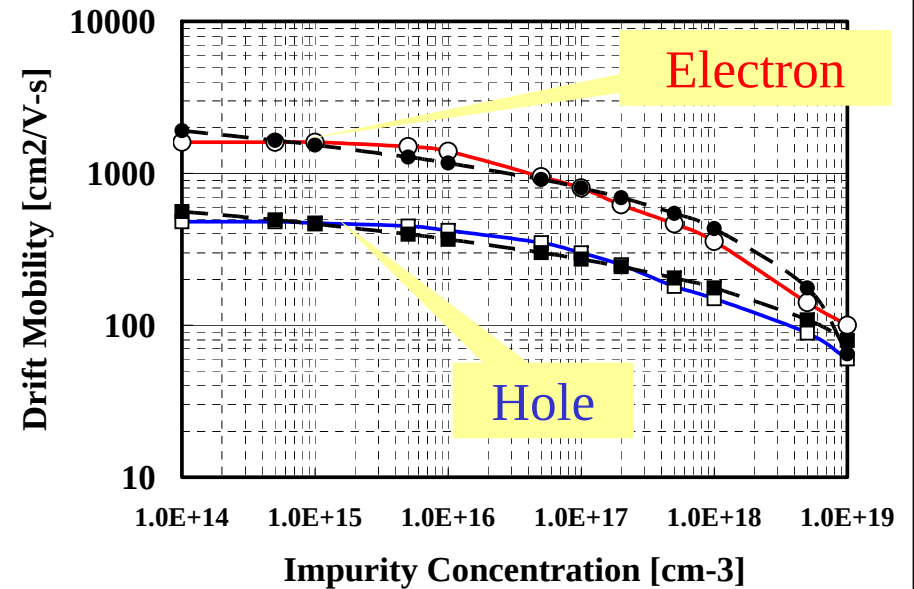
$$\mu_i^m = \frac{\mu_i}{G(m, c, T)}$$

# Fitting with experimental data

Resistivity [11]



Mobility [6,7,12]



# Creation of the DFM function and its implementation

$$C10 = (qA_E)^2 V_T \mu_B (N\_b) N\_b^2 = C10(A_E, N\_b)$$


$$\begin{aligned} KC10 &\equiv \frac{c10(A_E, N\_b)}{c10(A_{E0}, N\_b0)} \\ &= \frac{(qA_E)^2 V_T \mu_B (N\_b) \cdot N\_b^2}{(qA_{E0})^2 V_T \mu_B (N\_b0) \cdot N\_b0^2} \\ &= \frac{A_E^2}{A_{E0}^2} \frac{\mu_B (N\_b) \cdot N\_b^2}{\mu_B (N\_b0) \cdot N\_b0^2} \\ &= (K\_AE)^2 \cdot \frac{\mu_B (N\_b) \cdot N\_b^2}{\mu_B (N\_b0) \cdot N\_b0^2} \end{aligned}$$

$$New\_C10 = c10(\text{extracted value}) \cdot K\_C10$$

## List of DFM functions (1)

| Name           | DFM function                                                                                                                                                  | HiCUM        | Gummel-Poon |
|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|-------------|
| <b>K_c10</b>   | $(K_{-}Ae)^2 \cdot \frac{\mu_B(N_{-}b) \cdot N_{-}b^2}{\mu_B(N_{-}b0) \cdot N_{-}b0^2}$                                                                       | <b>C10</b>   | <b>IS</b>   |
| <b>K_hjci</b>  | $\exp\left(\frac{a_G}{V_T}(W_{-}b0 - W_{-}b)\right)$                                                                                                          | <b>Hjci</b>  | <b>(VA)</b> |
| <b>K_hjei</b>  | $K_{-}Ac \cdot \frac{N_{-}b \cdot W_{-}b}{N_{-}b0 \cdot W_{-}b0} \cdot \frac{1}{K_{cjci}}$                                                                    | <b>Hjei</b>  | <b>(VA)</b> |
| <b>K_hfe</b>   | $\frac{\mu_n(N_{-}b)N_{-}b^2}{\mu_n(N_{-}b0)N_{-}b0^2} \cdot \frac{\mu_n(N_{-}e)N_{-}e^2}{\mu_n(N_{-}e0)N_{-}e0^2}$                                           | <b>Hfe</b>   | --          |
| <b>K_hfc</b>   | $\frac{\mu_n(N_{-}b)N_{-}b^2}{\mu_n(N_{-}b)N_{-}b0^2} \cdot \frac{\mu_n(N_{-}sic)N_{-}sic^2}{\mu_n(N_{-}sic)N_{-}sic0^2}$                                     | <b>Hfc</b>   | --          |
| <b>K_Qp0</b>   | $K_{-}Ae \cdot \frac{N_{-}b \cdot W_{-}b}{N_{-}b0 \cdot W_{-}b0}$                                                                                             | <b>Qp0</b>   | --          |
| <b>K_tauf0</b> | $\frac{W_{-}b^2 \cdot De(N_{-}b)^{-1}}{W_{-}b0^2 \cdot De(N_{-}b0)^{-1}}$                                                                                     | <b>Tauf0</b> | <b>TF</b>   |
| <b>K_thcs</b>  | $\frac{W_{-}sic}{\mu_n(N_{-}sic)} \cdot \frac{\mu_n(N_{-}sic0)}{W_{-}sic0} \cdot \frac{\frac{W_{-}sic}{2} + \frac{W_{-}b}{G}}{W_{-}sic0 + \frac{W_{-}b0}{G}}$ | <b>Thcs</b>  | --          |
| <b>K_fthc</b>  | $\frac{W_{-}sic}{W_{-}sic0} \cdot \frac{W_{-}sic0 + 2 \cdot W_{-}b0}{W_{-}sic + 2 \cdot W_{-}b}$                                                              | <b>Fthc</b>  | --          |
| <b>K_Vpt</b>   | $\frac{N_{-}sic}{N_{-}sic0} \left( \frac{W_{-}sic}{W_{-}sic0} \right)^2$                                                                                      | <b>Vpt</b>   | --          |

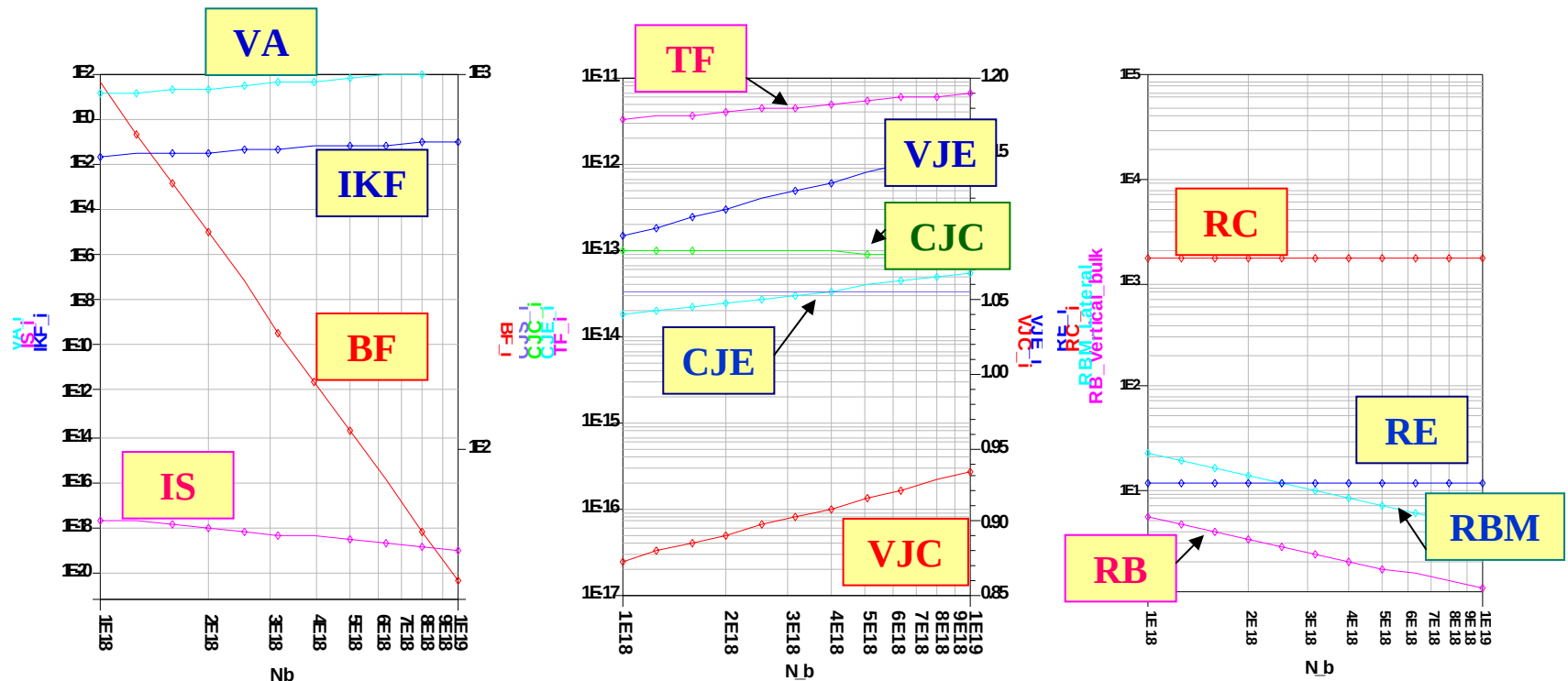
## List of DFM functions (2)

| 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    | $\frac{W\_e \cdot N\_e \cdot D_n(N\_B)}{W\_e0 \cdot N\_e0 \cdot D_n(N\_B0)} \cdot \frac{W\_b \cdot N\_b \cdot D_p(N\_b)}{W\_b0 \cdot N\_b0 \cdot D_p(N\_b0)}$ | ---   | BF          |
| K_rbi0  | $\frac{K\_BE}{K\_Le} \cdot \frac{W\_b}{p\_b0} \cdot \frac{p\_b}{W\_b0}$                                                                                       | Rbi0  | RB          |
| K_rbx   | $\frac{p\_b}{p\_b0} \cdot \frac{W\_b}{W\_b0}$                                                                                                                 | Rbx   | RBM         |
| K_rci   | $\frac{pc}{pc\_def} \cdot \frac{W\_sic - T\_depc}{W\_sic0 - T\_depc0}$                                                                                        | Rci   | RC          |
| K_CJxi0 | $K\_Ax \cdot \sqrt{\frac{N\_b}{N\_b0} \cdot \frac{1}{KVdxi0}}$                                                                                                | 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         |

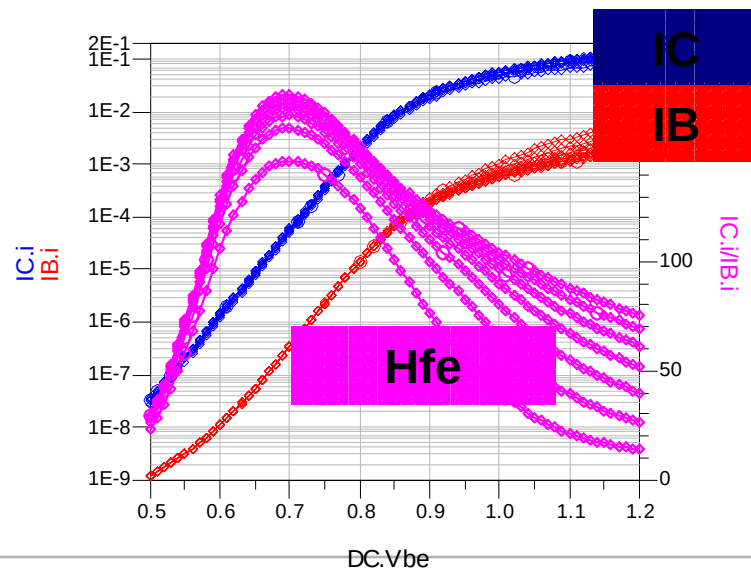
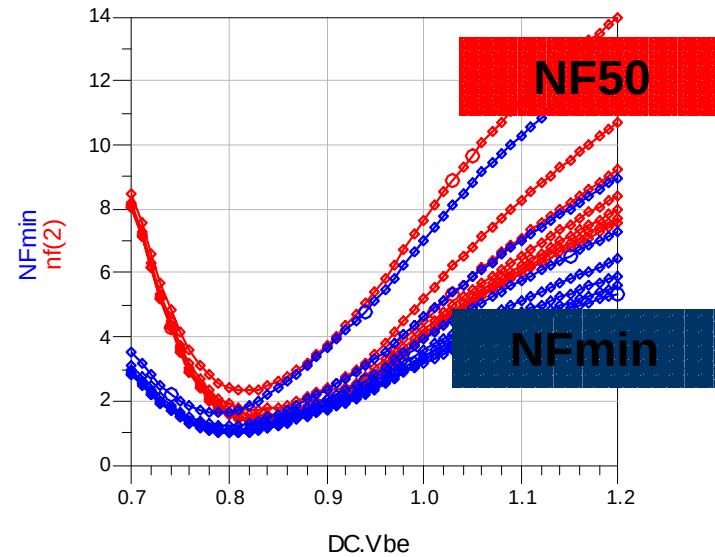
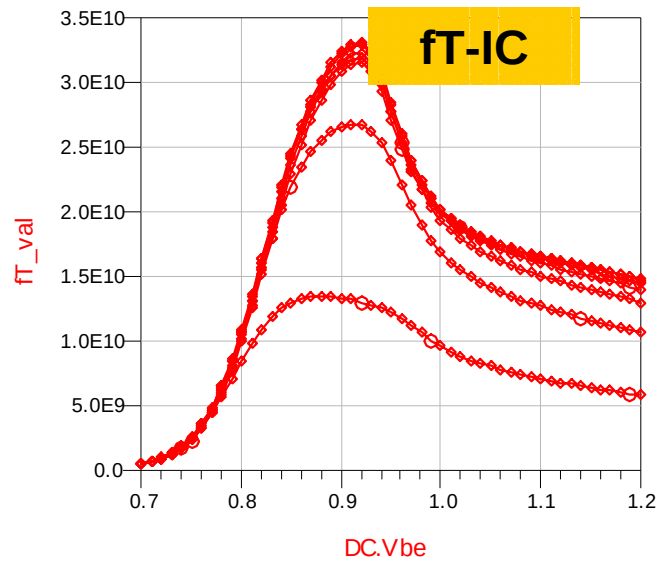
# Function of BJT physical model card (1)

## SPICE model parameters: Function of ( $N_b$ )

$N_b$ :doping concentration in the base



# Function of BJT physical model card

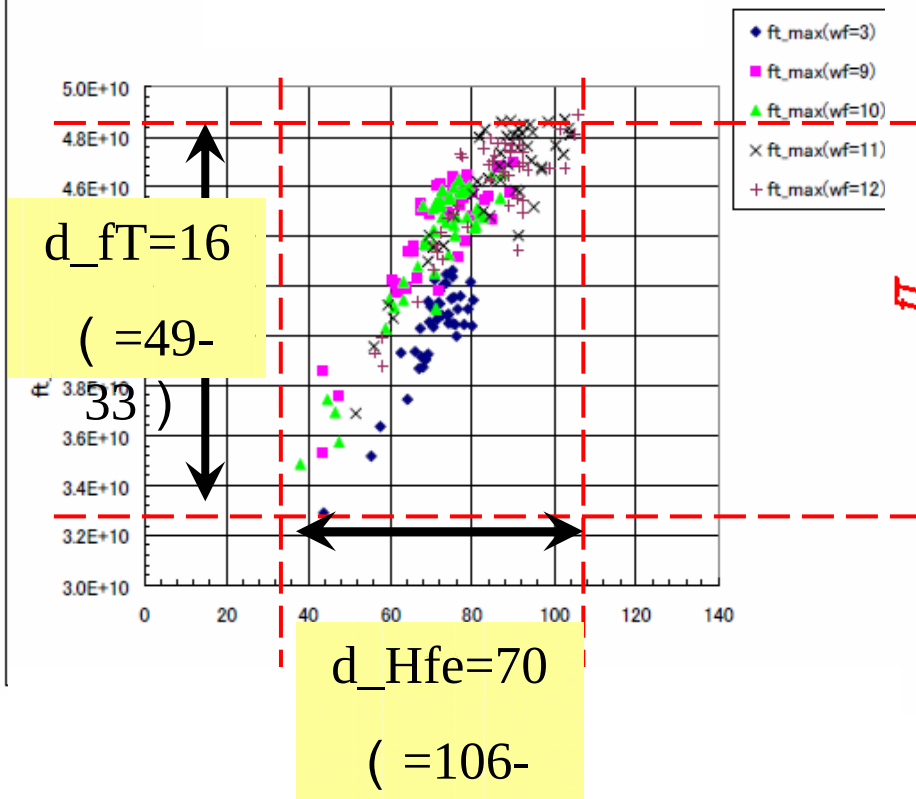


**$N_B$  : 2e18 to 1.4e19 cm<sup>-3</sup>  
by 2e18 cm<sup>-3</sup>**

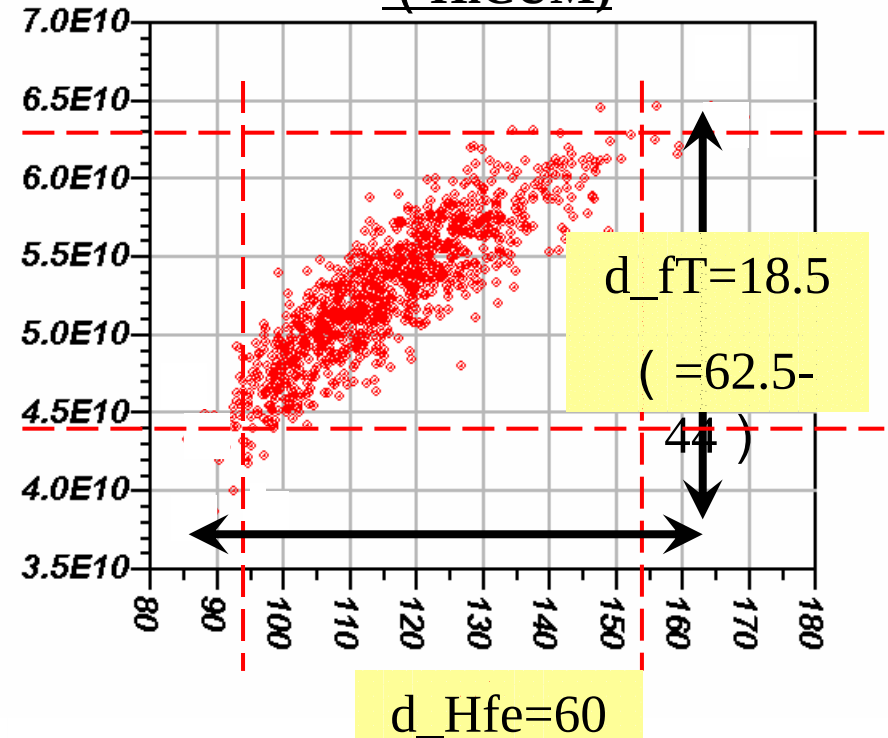
# fT vs. Hfe Scattering Plot

VBE=0.92V, VC=3V

Measurement data (230 points)



BJT Physical model card  
( HiCUM )

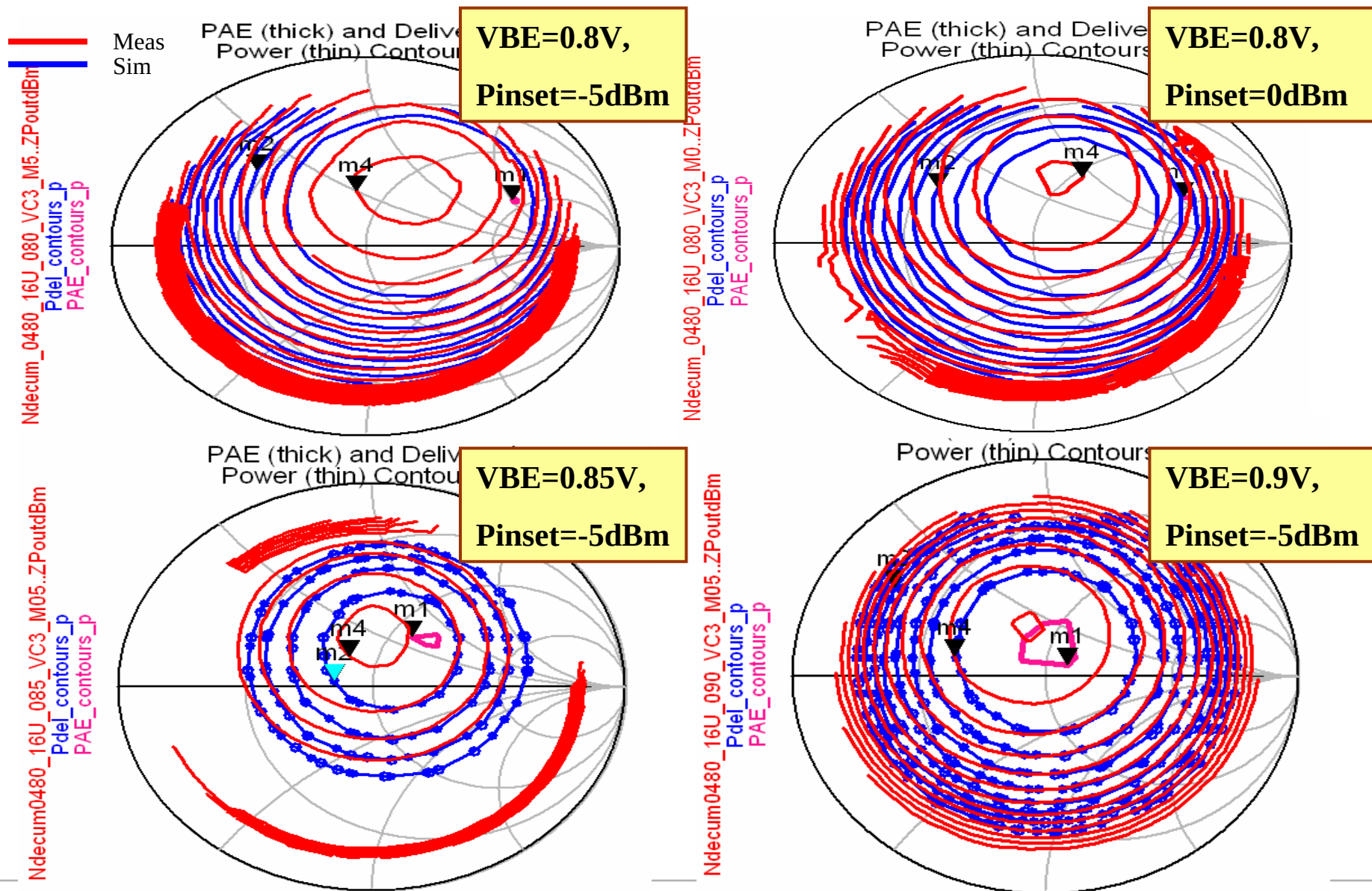


N<sub>B</sub> Gaussian Nominal value=8e18  $\pm 10\%$

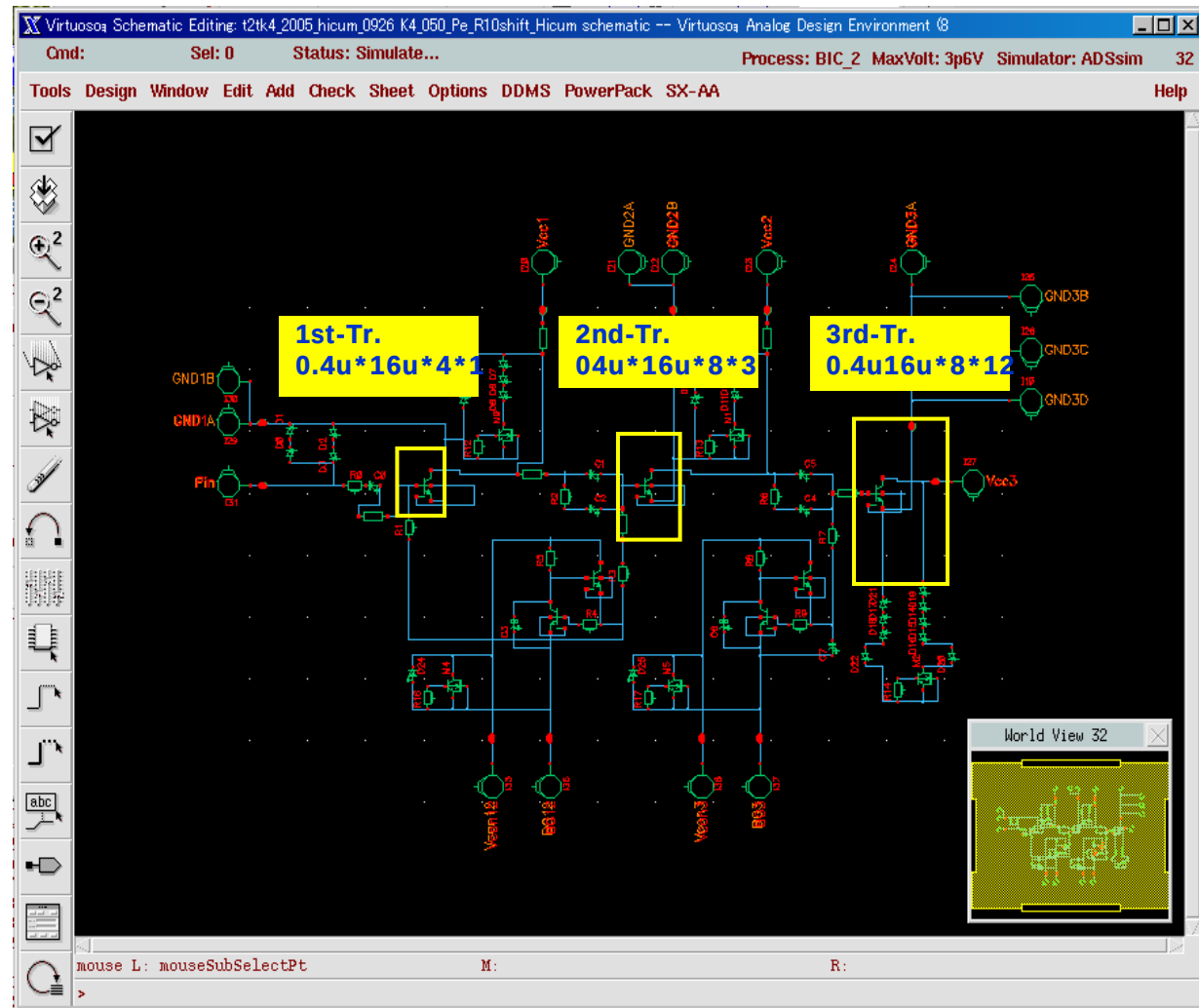
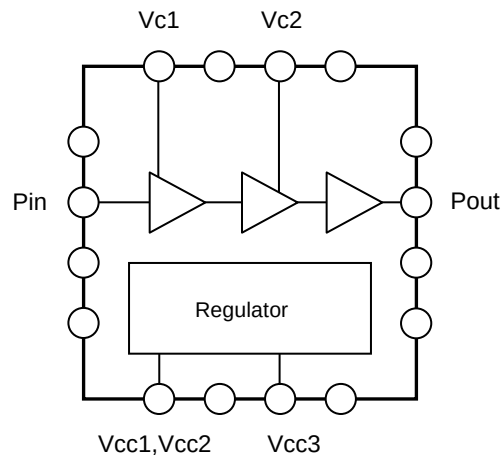
W<sub>B</sub> Gaussian Nominal value=7ucm  $\pm 10\%$



# GainCircles modelling result (0.4um\*8um\*16unit)



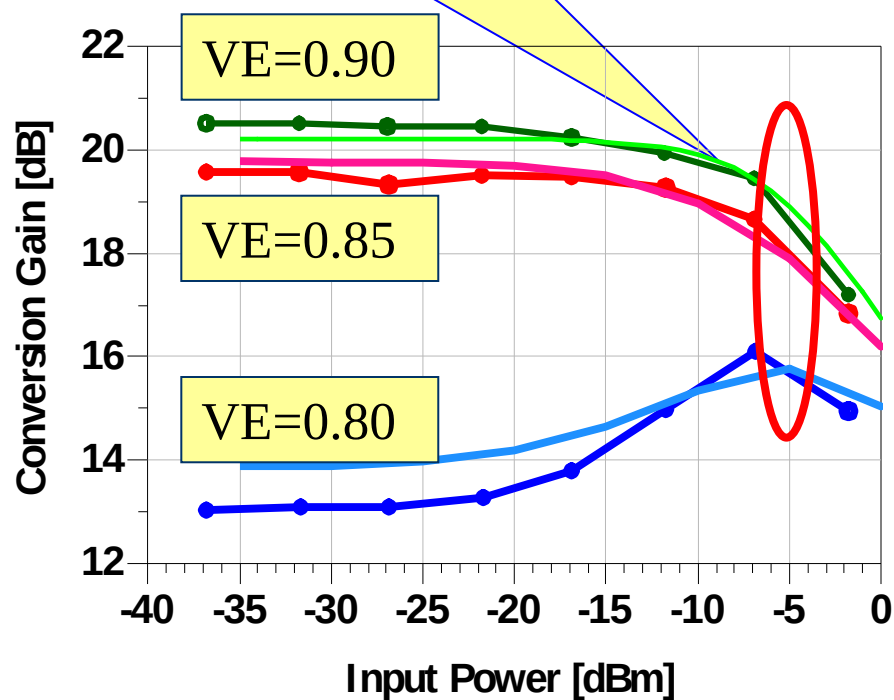
# Power Amplifier for PHS applications



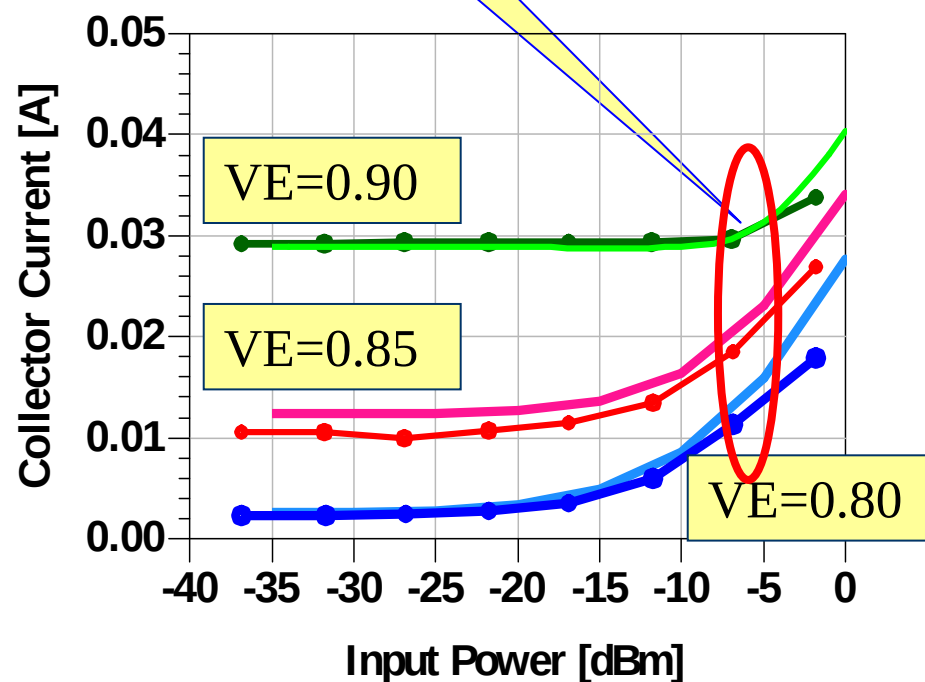
# HiCUM Pin-Pout modelling result (0.4um\*16um\*4unit)

Pin=2.4 GHz

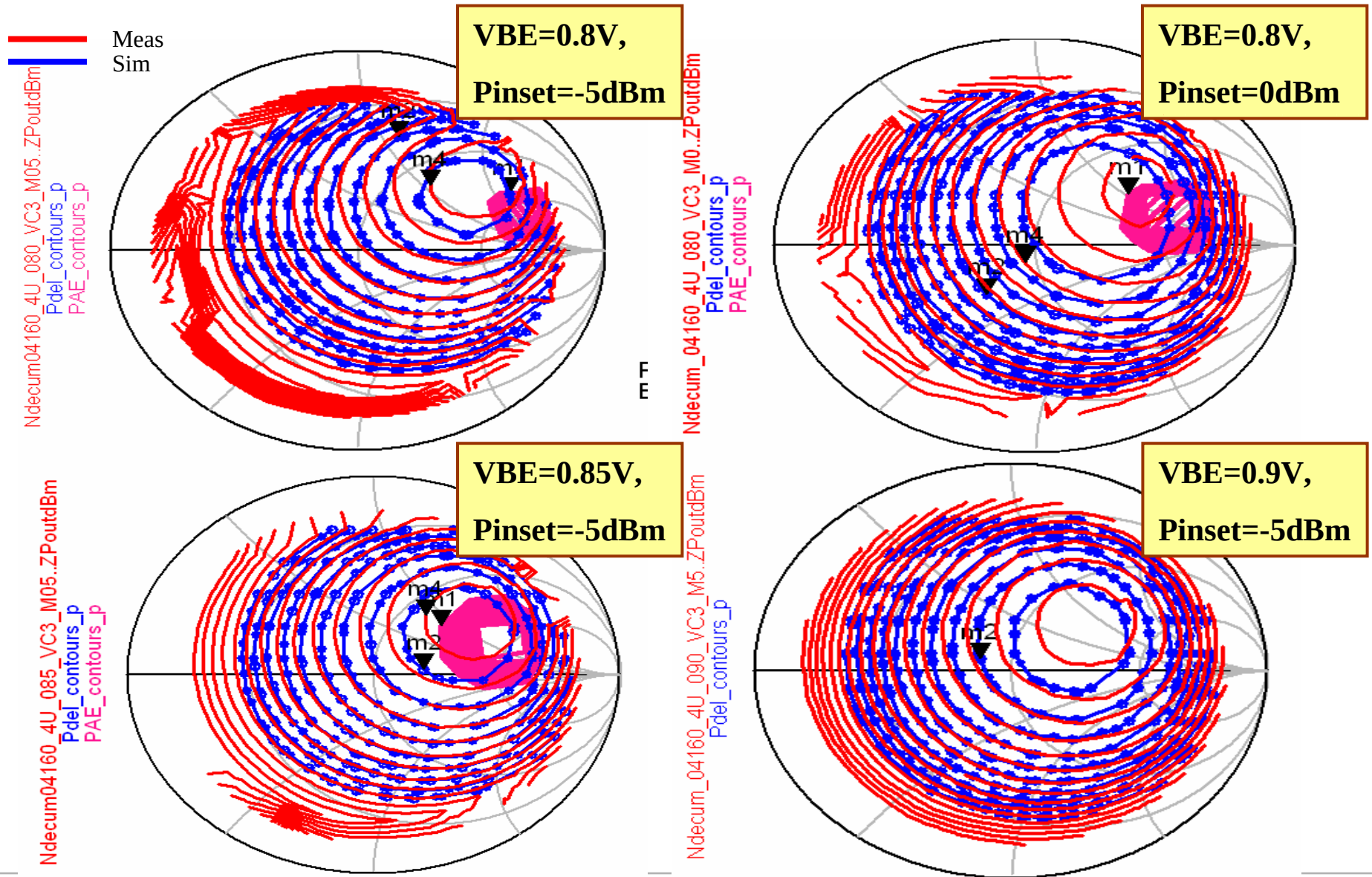
ConversionGain



IC



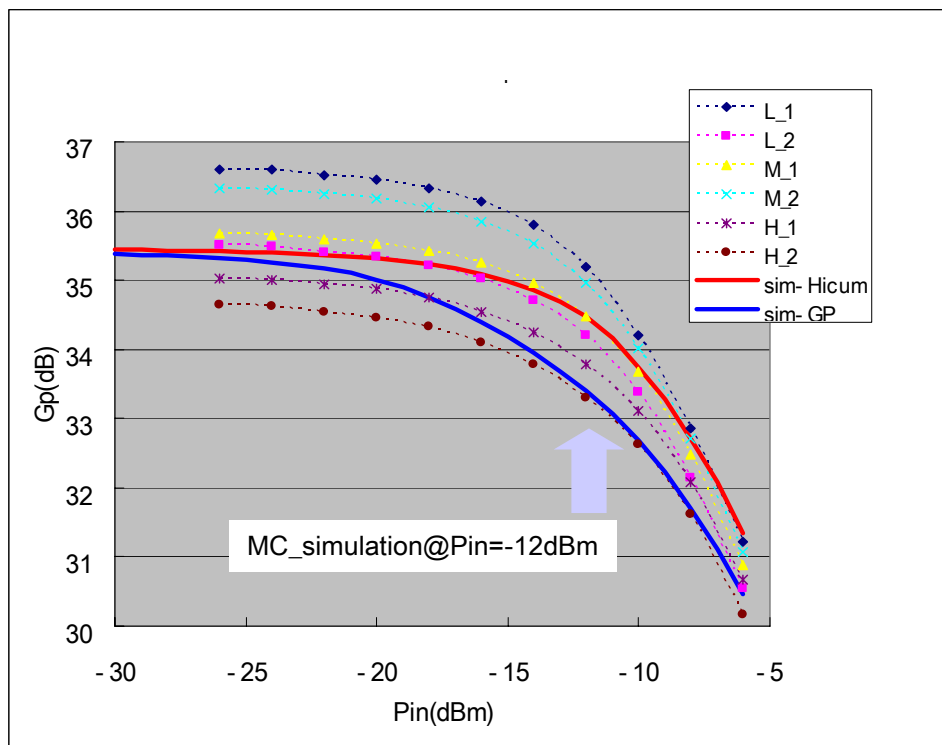
# LoadPull modelling result (0.4um\*16um\*4unit)



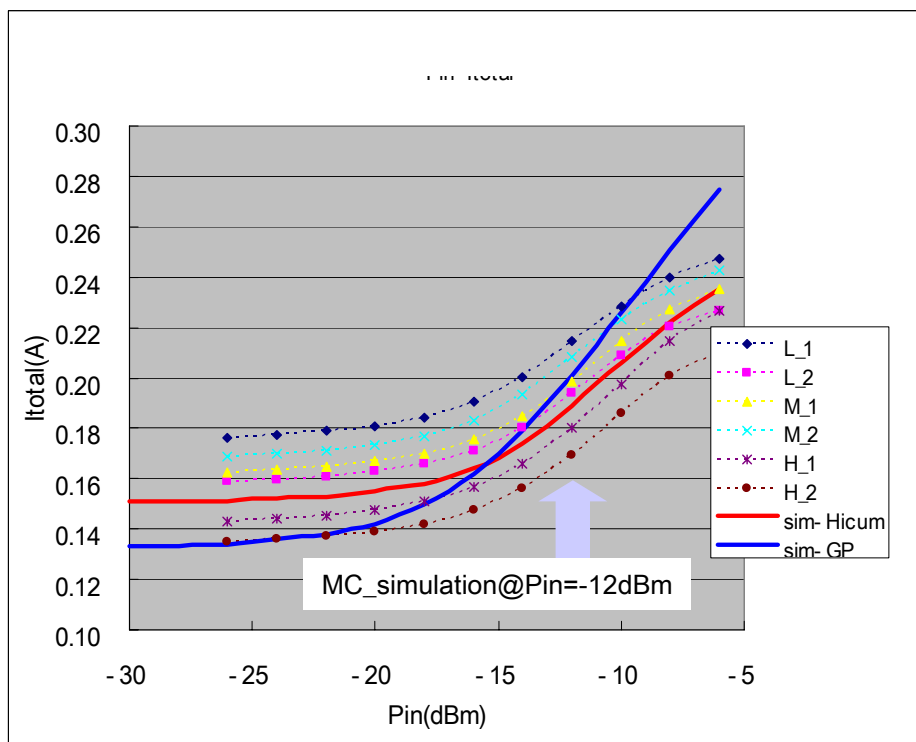
# Comparison with the measurement (1)

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

Pin - Gp



Pin - Itotal

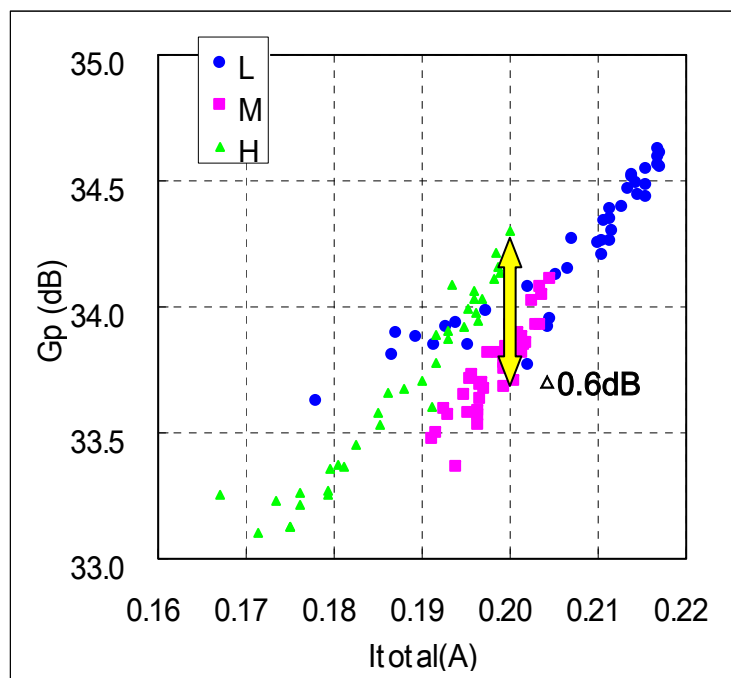


## Comparison with the measurement (2)

Good Match between MonteCarlo simulation and measurement

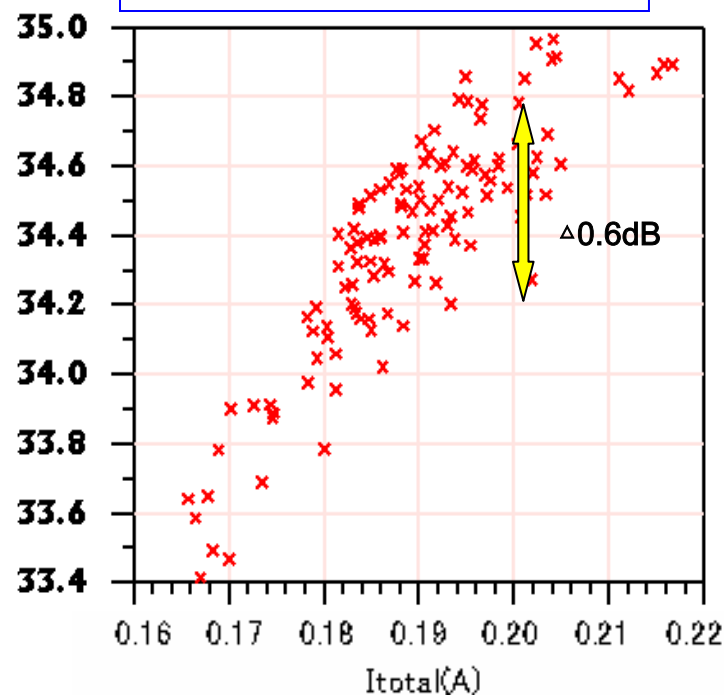
CW @Pin=-12dBm  
**R±10%(3 R conditions )** 120 samples

Measurement  
120 samples



Amp\_1Tone\_NF\_MC @Pin=-12dBm  
Hicup Physical model card  
**NB, WB±10%, R±10%** 120 trials

Monte-Carlo simulation by  
the BJT physical model card



# Summary

---

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



# References

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