# HICUM/L0 -

# Extraction results and experience

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Bipolar Arbeitskreis
Reutlingen, October 2005

# OUTLINE

- Introduction
- Temperature dependent model formulation
- High-current correction
- More experimental results
- Summary

# Introduction

## HICUM / Level0 - status overview

- Version 1.1
  - improved Verilog implementation
    - based on Level2 coding experience
    - equation extensions: avalanche current, rBi, self-heating, limitation for diode currents
  - simulator implementation via model compilers
    - Level0 (due to its simplicity) was initially used to set up model compilers (ADMS, Tiburon)
    - excellent help from Cadence to obtain consistent version at both sites

- Documentation
  - see new web-site
  - not as complete yet as for Level2 (lack of time, financial support)
  - see IEEE TED

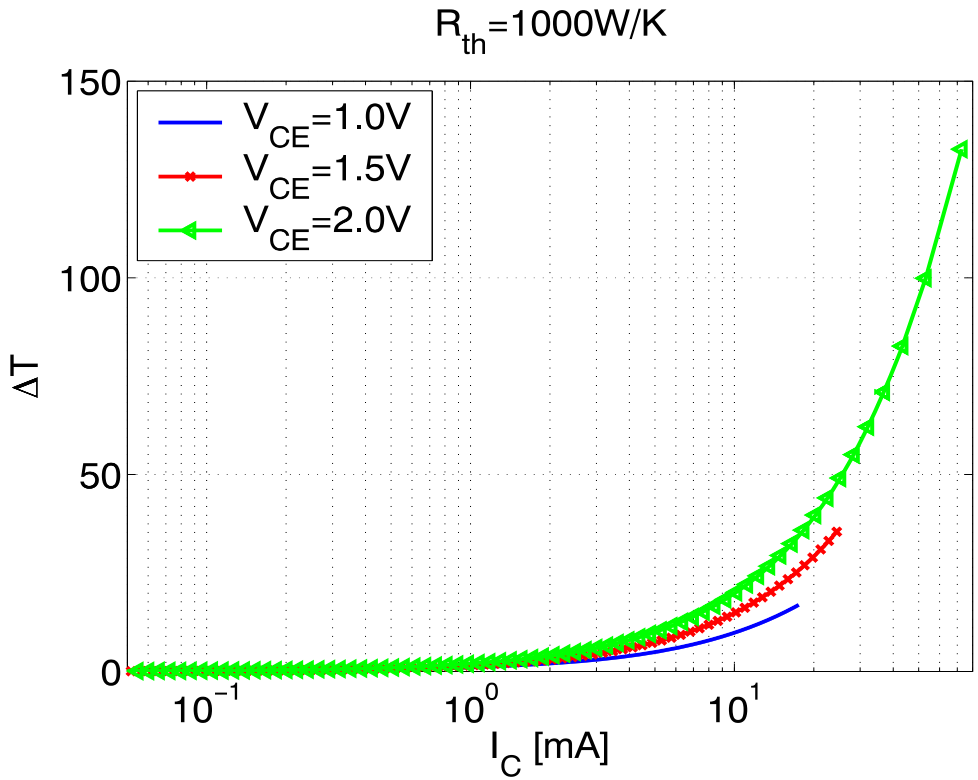
- Evaluations for a variety of process technologies
  - Atmel, Infineon, Jazz, ST, ...

This presentation: additional results

# Temperature dependent model formulation

## Self-heating

- simple single-pole network with thermal resistance and capacitance
- externally accessible thermal node




$$\Delta T = P_{th} R_{th}$$

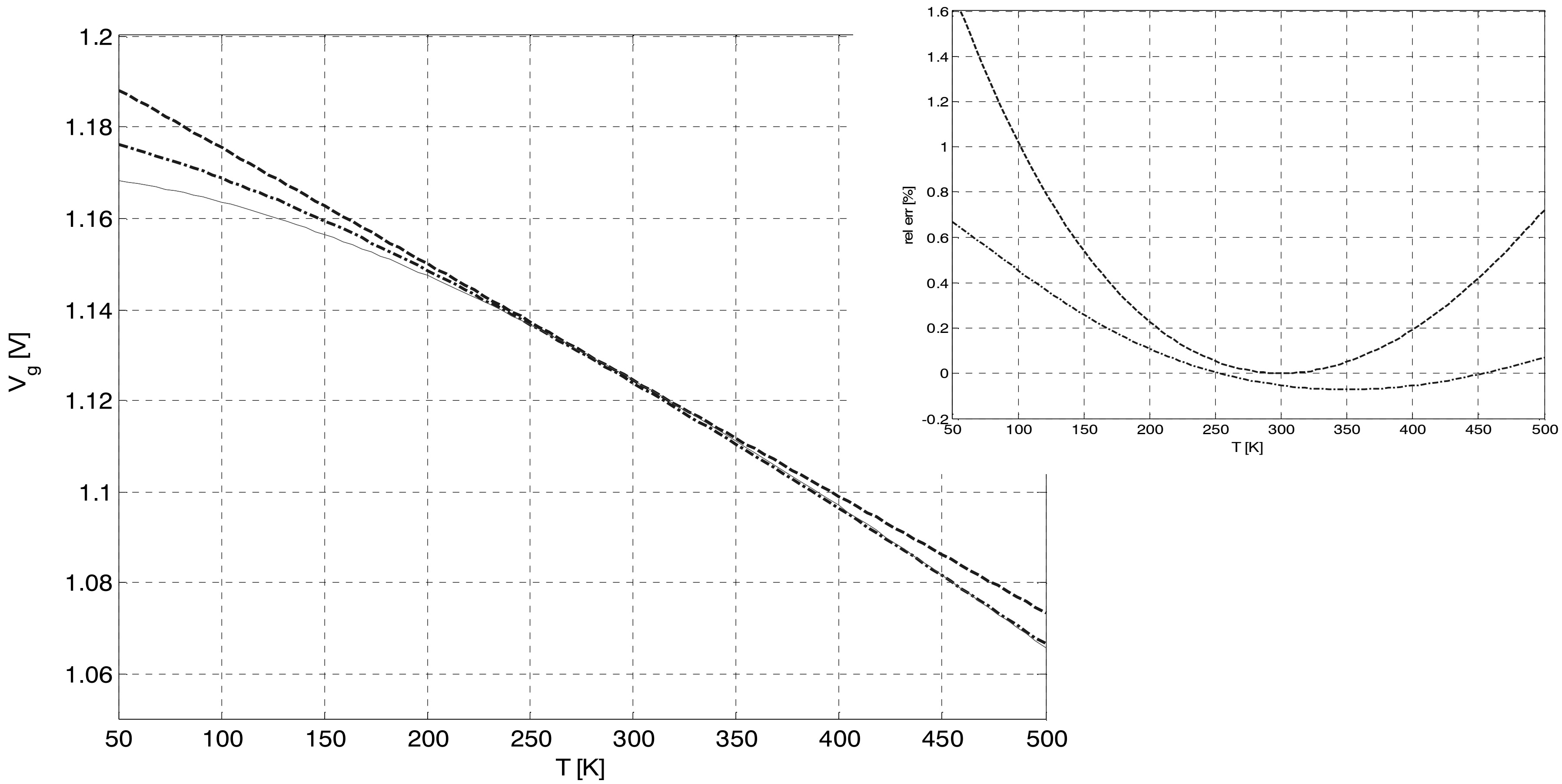
$$P_{th} = |i_T V_{C'E'}| + |i_{Avl} V_{C'B'}|$$

more terms?

=> still being debated

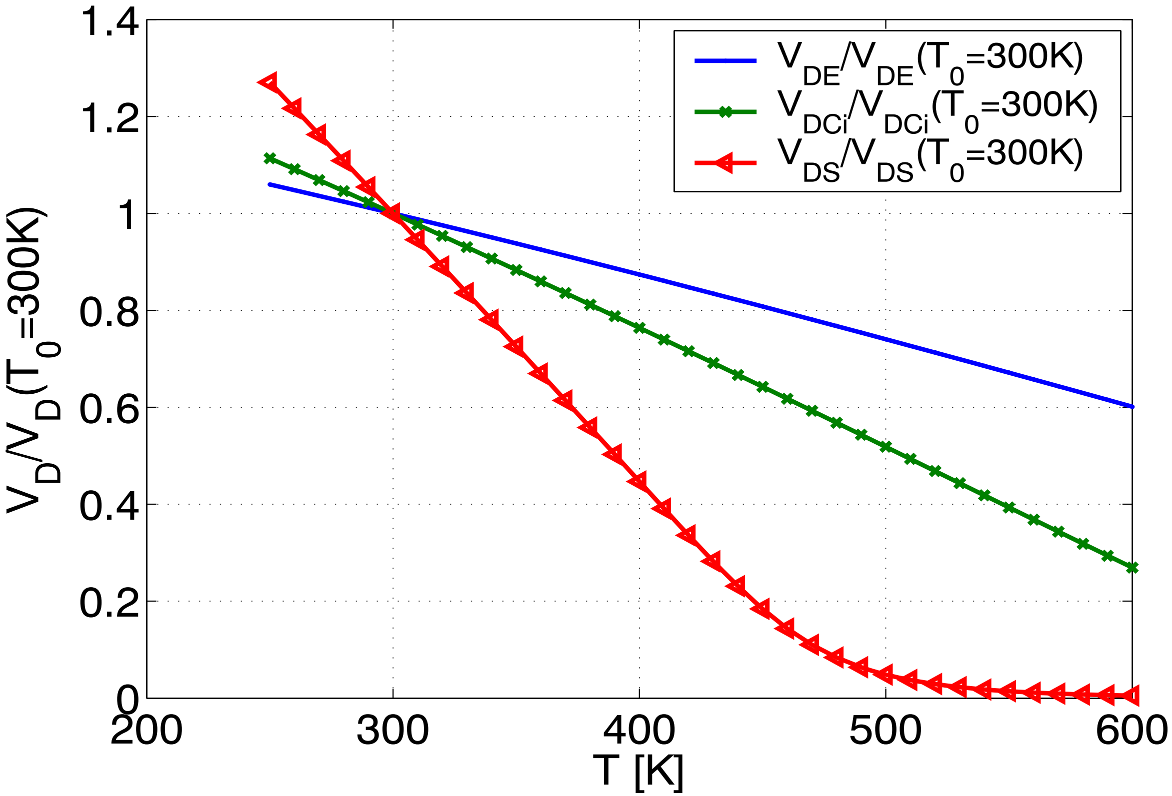
# Bandgap

$$V_g(T) = V_g(T_0) + k_1 \frac{T}{T_0} \ln\left(\frac{T}{T_0}\right) + k_2\left(\frac{T}{T_0} - 1\right)$$ , $T_0$ = reference temperature



# Depletion Capacitances: built-in voltage

$$V_D(T) = V_{Dj}(T) + 2V_T \ln\left(\frac{1 + \sqrt{1 + 4\exp\left(-\frac{V_{Dj}(T)}{V_T}\right)}}{2}\right)$$



# Depletion Capacitances: built-in voltage

$$V_{Dj}(T) = V_{Dj}(T_0)\left(\frac{T}{\mathbf{T_0}}\right) - V_{g(X,Y)eff}(0)\left(\frac{T}{T_0} - 1\right) - m_g V_T \ln\left(\frac{T}{T_0}\right)$$

with $V_{Dj}(\mathbf{T_0}) = 2V_T \ln\left[\exp\left(\frac{\mathbf{V_D}(\mathbf{T_0})}{2V_{T0}}\right) - \exp\left(-\frac{\mathbf{V_D}(\mathbf{T_0})}{2V_{T0}}\right)\right]$

thermal voltage at reference temperature: $V_{T0} = \frac{k\mathbf{T_0}}{q}$

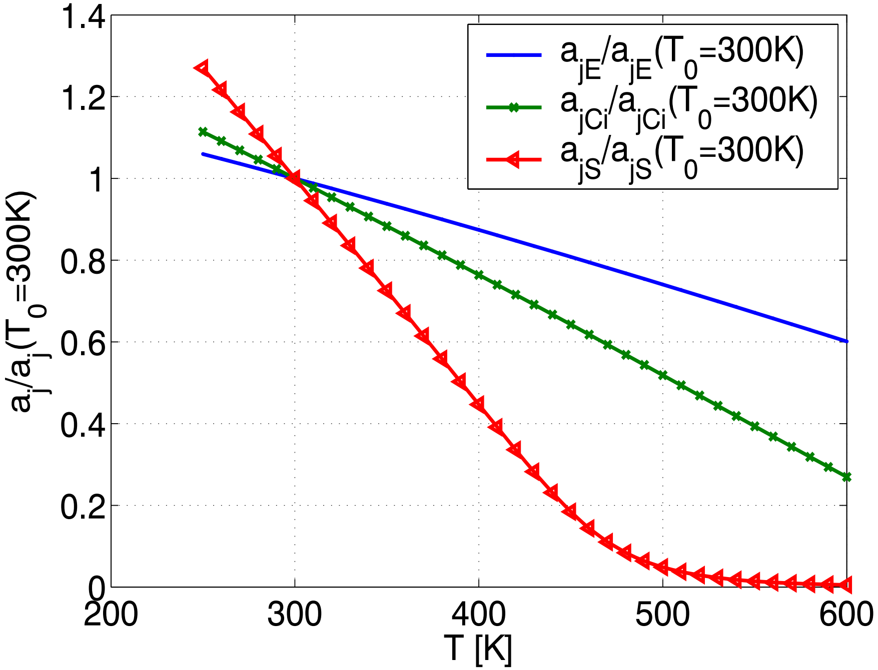
coefficient from T dependent bandgap: $m_g = 3 - \frac{q\mathbf{F_{1VG}}}{k_B}$

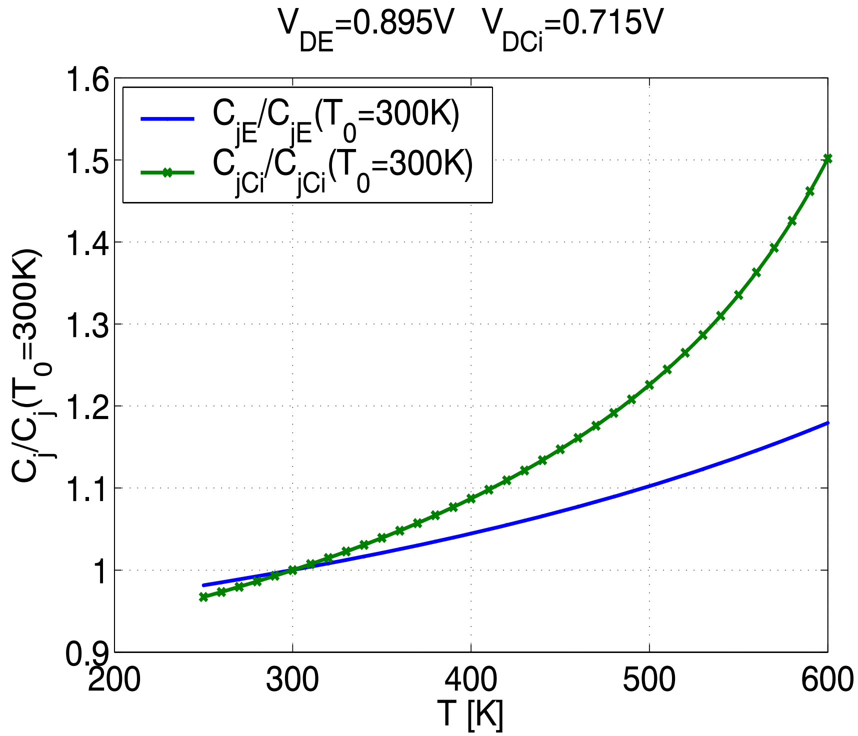
average junction bandgap voltage: $V_{g(X,Y)} = \frac{\mathbf{V_{gXeff}} + \mathbf{V_{gYeff}}}{2}$

(X,Y) = {BE, BC, SC}

# Depletion Capacitances

max. capacitance ratio $a_j(T)$ zero bias capacitance $C_{j0}(T)$




$$a_j(T) = \mathbf{a_j}(\mathbf{T_0})\left(\frac{V_D(T)}{\mathbf{V_D}(\mathbf{T_0})}\right)$$

$$C_{j0}(T) = \mathbf{C_{j0}}(\mathbf{T_0})\left(\frac{\mathbf{V_D}(\mathbf{T_0})}{V_D(T)}\right)^{\mathbf{z}}$$

# Saturation currents

- Transfer current

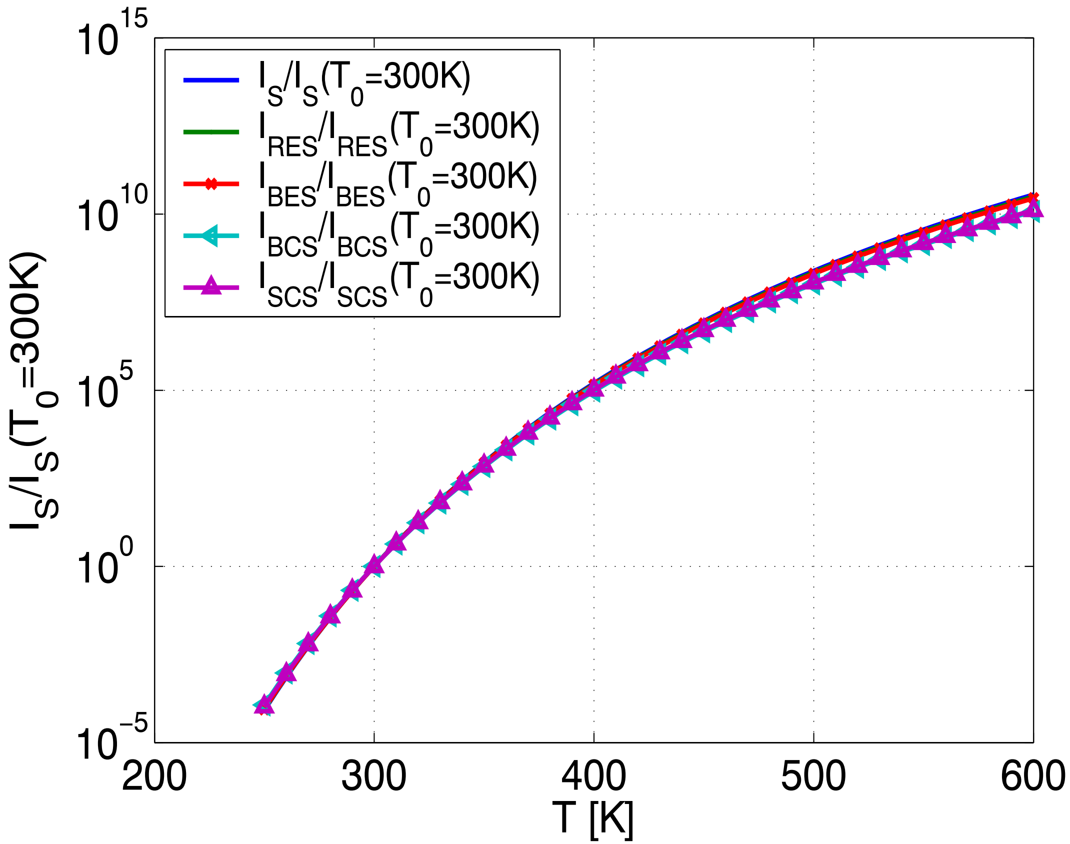
$$I_S^*(T) = \mathbf{I_S^*}(\mathbf{T_0})\left(\frac{T}{\mathbf{T_0}}\right)^{\zeta_{\mathbf{CT}}}\exp\left[\frac{\mathbf{V_{gB}}}{V_T(T)}\left(\frac{T}{\mathbf{T_0}}-1\right)\right]$$

- Diodes

$$I_{XX\mathrm{S}}(T) = \mathbf{I_{XXS}}(\mathbf{T_0})\left(\frac{T}{\mathbf{T_0}}\right)^{\zeta_{XXT}}\exp\left[\frac{V_{gXX}(0)}{V_T(T)}\left(\frac{T}{\mathbf{T_0}}-1\right)\right]$$

with BC current exponential factor $\zeta_{BCT} = m_g + 1 - \zeta_{\mathbf{Ci}}$ and substrate current exponential factor $\zeta_{SCT} = m_g + 1 - m_{\mu pS}$, assuming $m_{\mu pS} = 2.5$ .

# Saturation currents

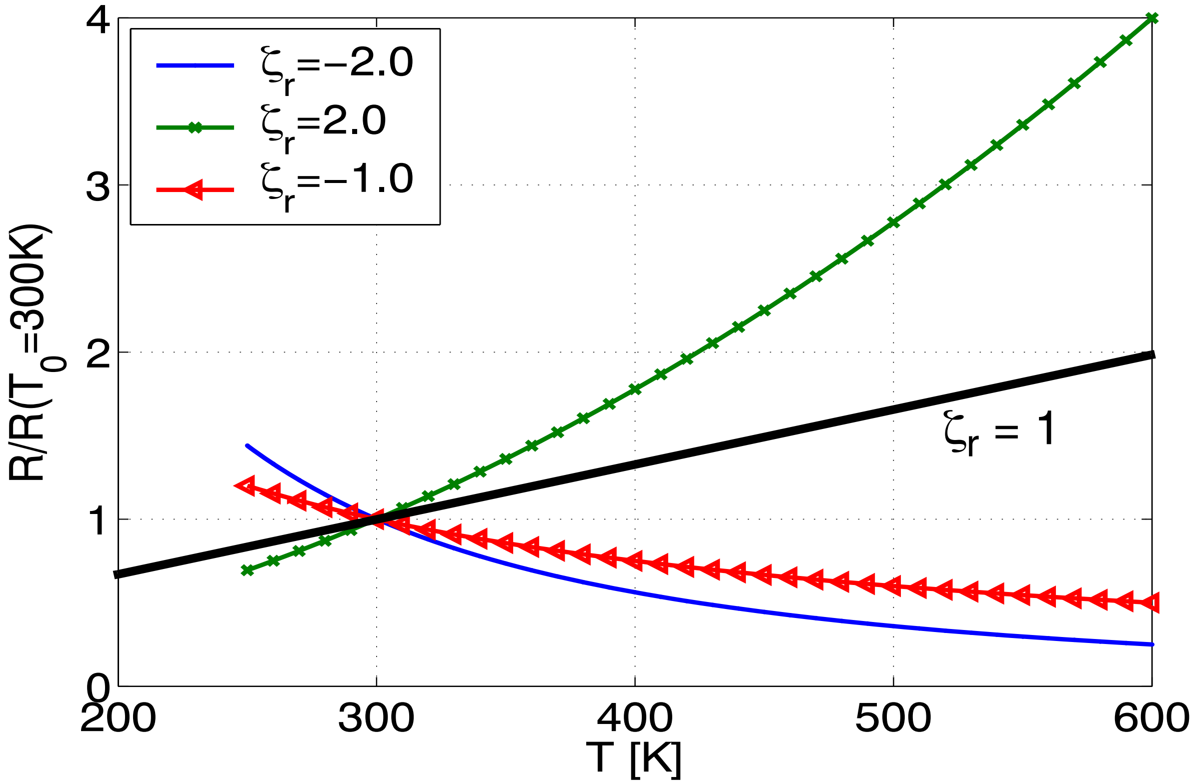



| component I | $\mathbf{I_{XXS}}$ | value |
|---|---|---|
| $I_{jBE}$ | $\mathbf{I_{BES}}$ | 7e-21 |
| $I_{jRE}$ | $\mathbf{I_{RES}}$ | 1e-30 |
| $I_{jBC}$ | $\mathbf{I_{BCS}}$ | 9.8e-20 |
| $I_{jSC}$ | $\mathbf{I_{SCS}}$ | 1e-18 |
| component I | $V_{gXX}$ | |
| $I_{jBE}$ | $\mathbf{V_{gEeff}}$ | 1.139 |
| $I_{jRE}$ | $V_{gBE}$ | calculated |
| $I_{jBC}$ | $\mathbf{V_{gCeff}}$ | 1.114 |
| $I_{jSC}$ | $\mathbf{V_{gSeff}}$ | 1.15 |
| component I | $\zeta_{XXT}$ | |
| $I_{jBE}$ | $\zeta_{\mathbf{BET}}$ | 2.97 |
| $I_{jRE}$ | $\zeta_{\mathbf{BET}}$ | 2.97 |
| $I_{jBC}$ | $\zeta_{BCT}$ | calculated |
| $I_{jSC}$ | $\zeta_{SCT}$ | calculated |

# Series resistances

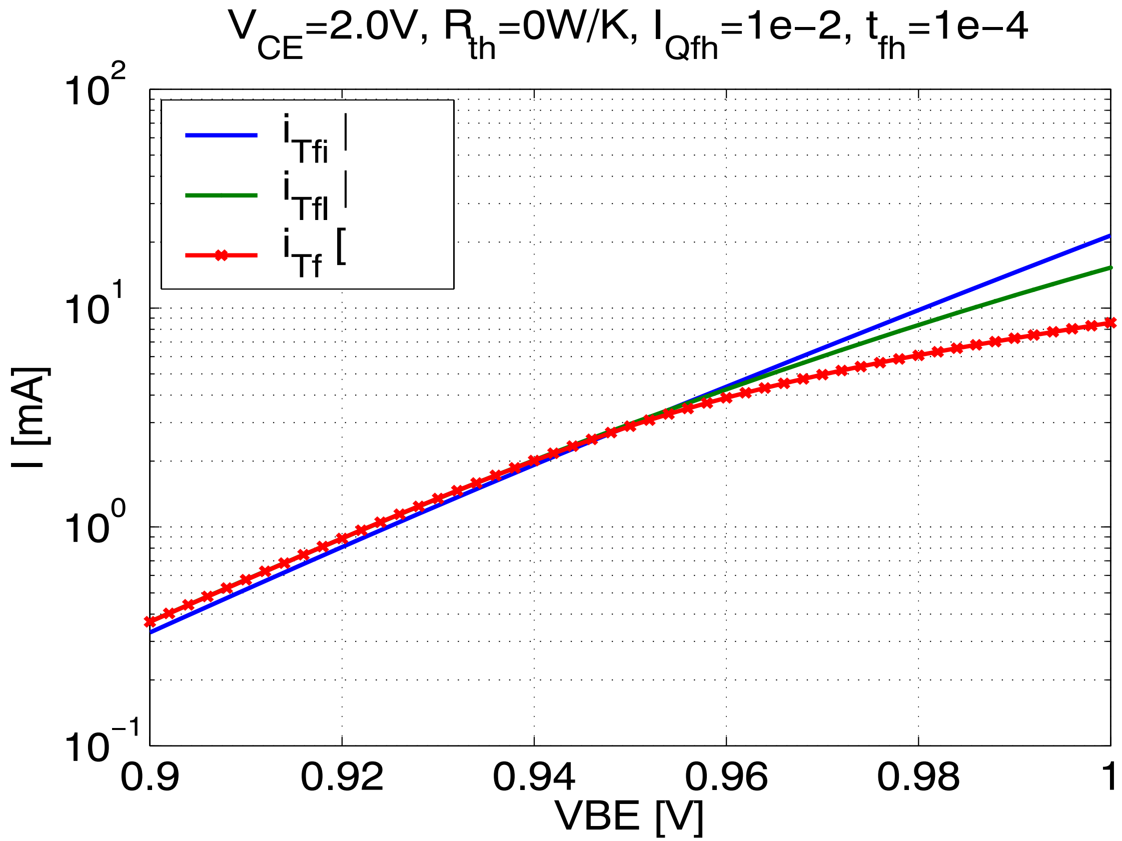
- same formulation for all series resistances:

$$r(T) = \mathbf{r}(\mathbf{T_0})\left(\frac{T}{\mathbf{T_0}}\right)^{\zeta_r}, \qquad \zeta_r = \text{temperature coefficient}$$



# High-current correction

$$i_{Tf} = \frac{i_{Tfl}}{1 + \frac{\Delta q_{fh}}{q_{p,T}}} \quad \text{with} \quad i_{Tfl} = \frac{i_{Tfi}}{q_{p,T}} \quad \text{and} \quad i_{Tfi} = \mathbf{I_S^*} \exp\frac{V_{B'E'}}{\mathbf{m_{Cf}} V_T}$$

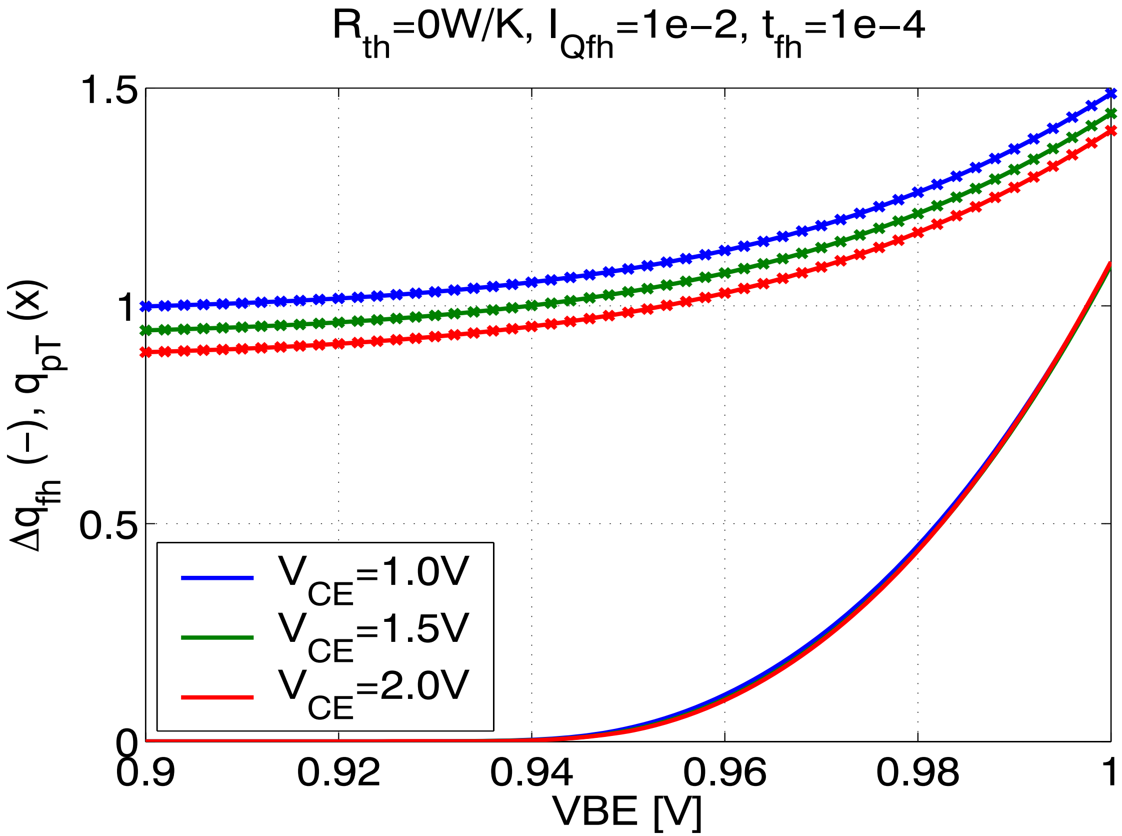


# Correction charge $\Delta q_{fh}$

## comparison with normalized hole charge

$$\Delta q_{fh} = \left(w_{low}^2 + \mathbf{t_{fh}}\frac{i_{Tfl}}{I_{CK}}\right)\frac{i_{Tfl}}{\mathbf{I_{Qfh}}} \approx \frac{\int_0^{I_{Tf}}\tau_f dI}{\tau_{f0} I_{Tf}} - 1 \quad \text{with} \quad w_{low} = \frac{w_i(i_{Tfl})}{w_C} = \frac{i_l + \sqrt{i_l^2 + \mathbf{a_{hc}}}}{1 + \sqrt{1 + \mathbf{a_{hc}}}}$$

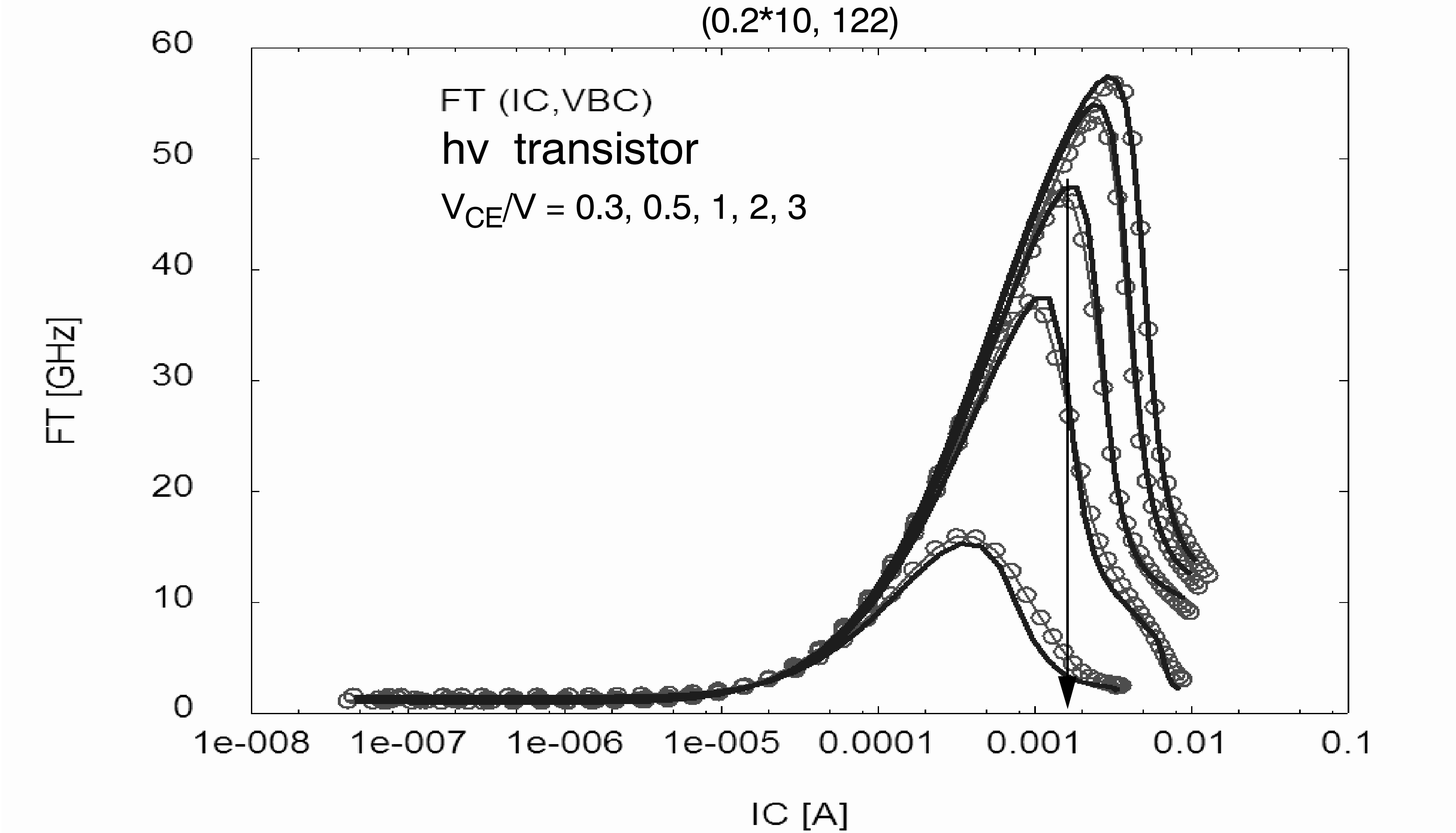
$$i_l = 1 - \frac{I_{CK}}{i_{Tfl}}$$



# More experimental results

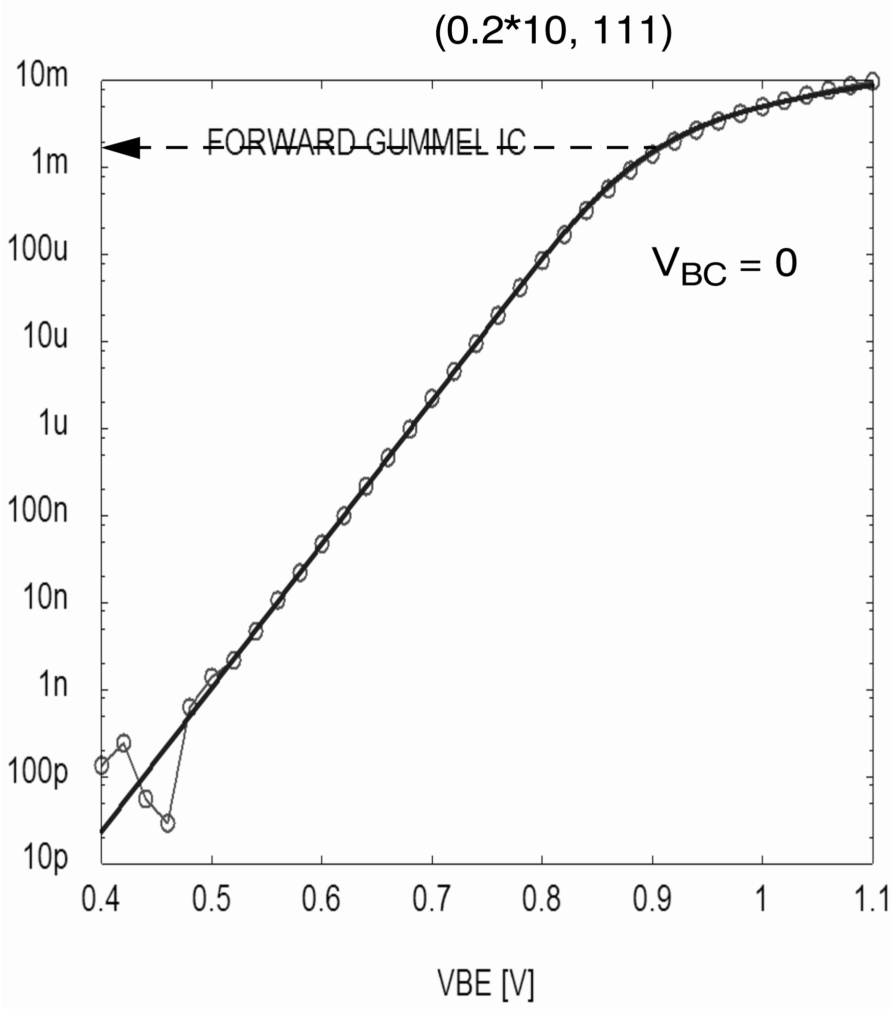
## 0.18μm foundry BiCMOS process

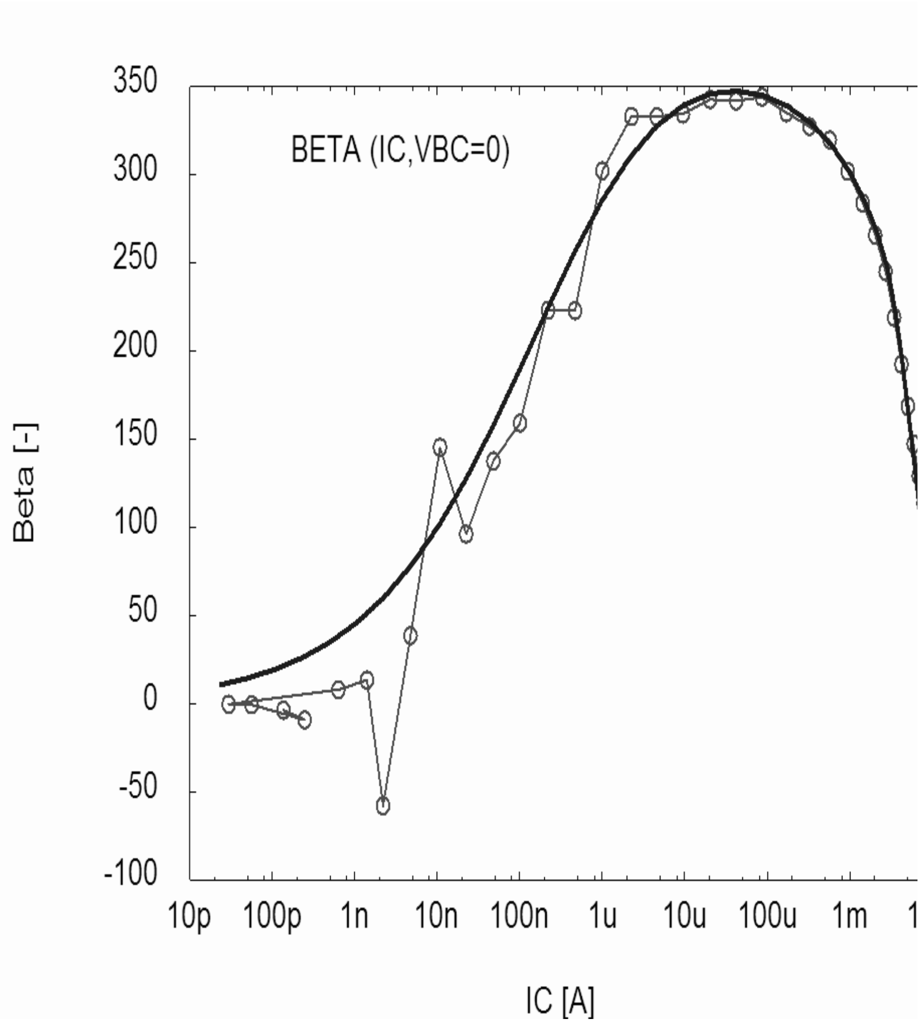
data comparison: measurement (symbols), model (lines)



# Forward Gummel characteristics

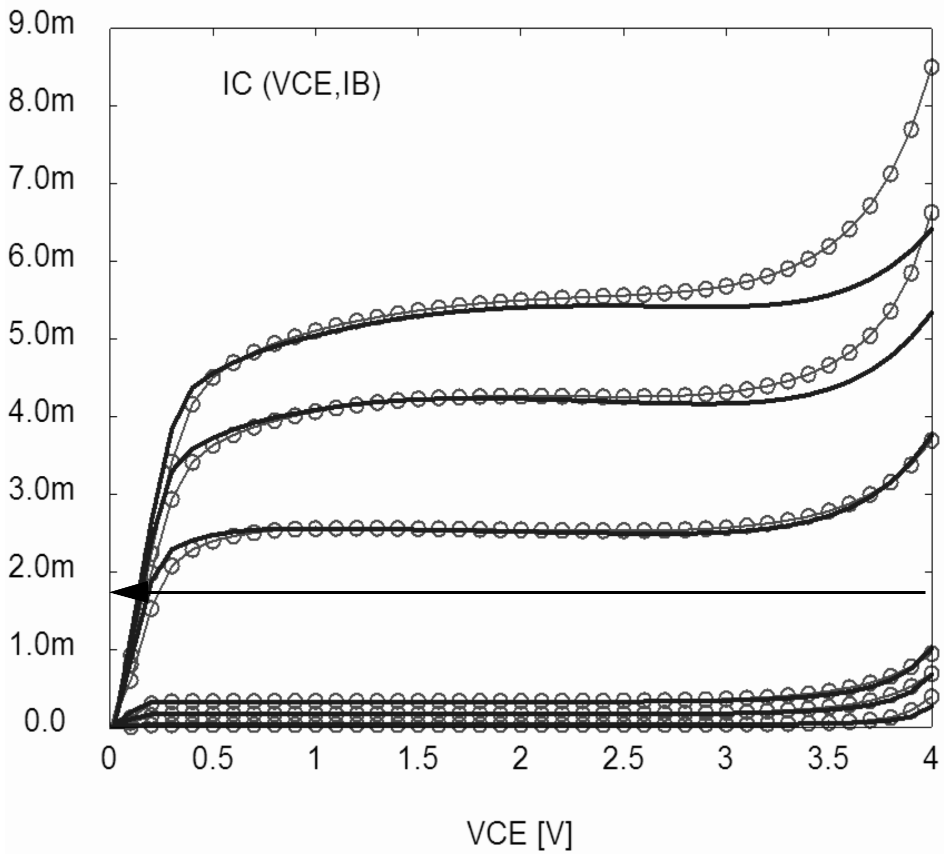
data comparison: measurement (symbols), model (lines)

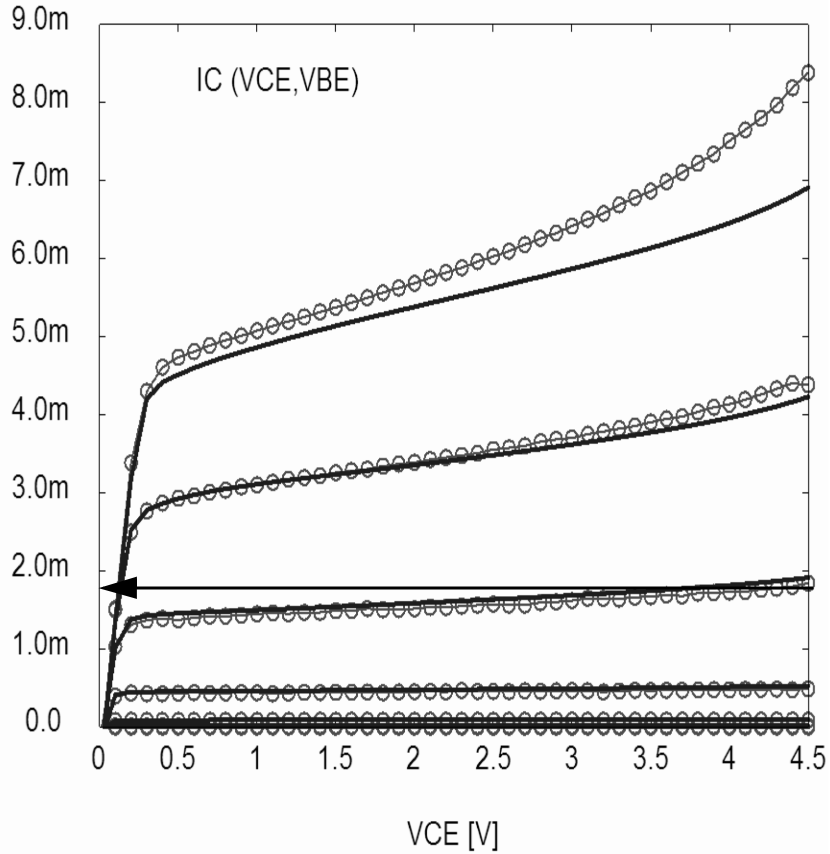


# Forward output characteristics

(0.2*10, 111)



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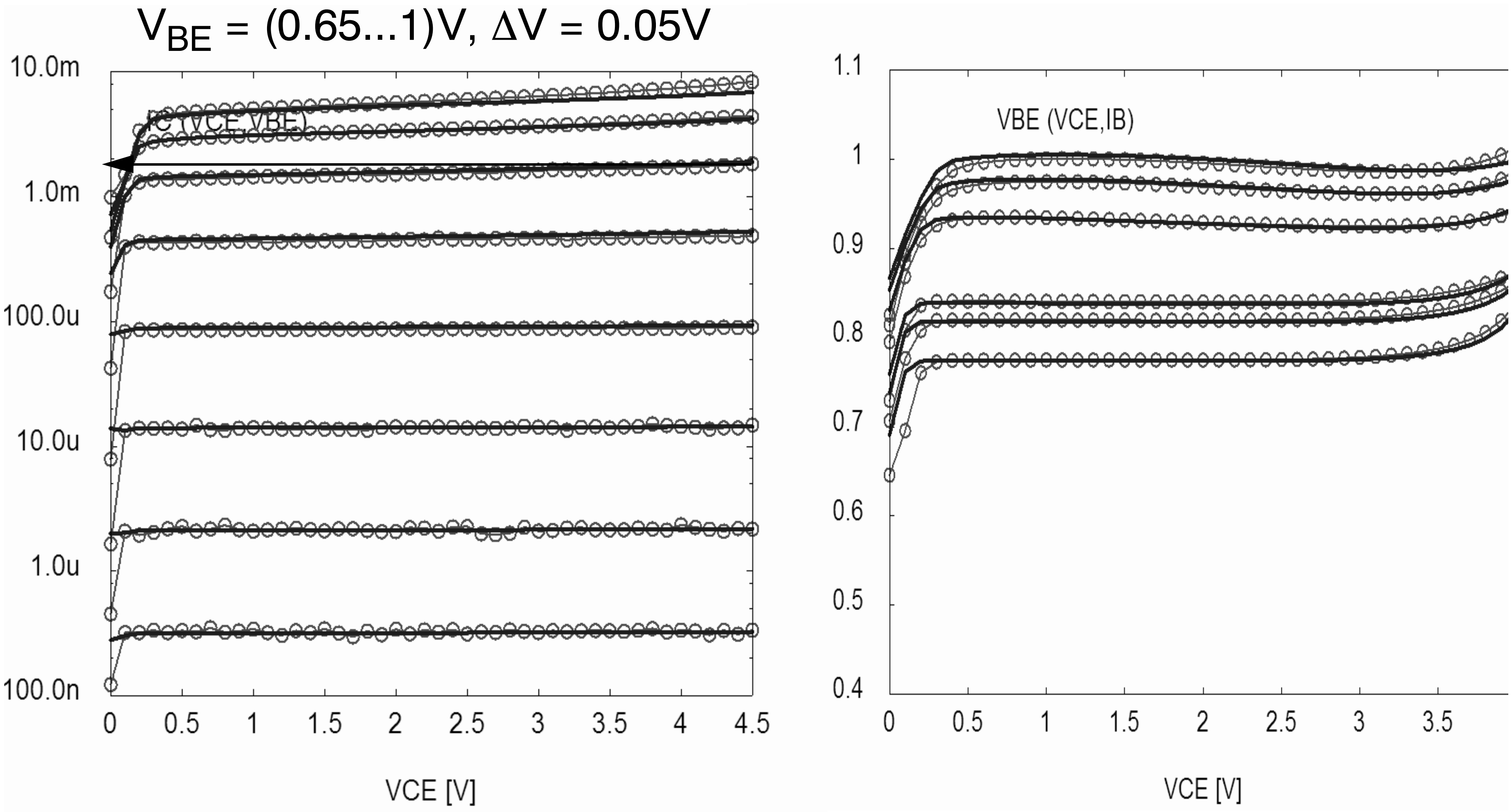
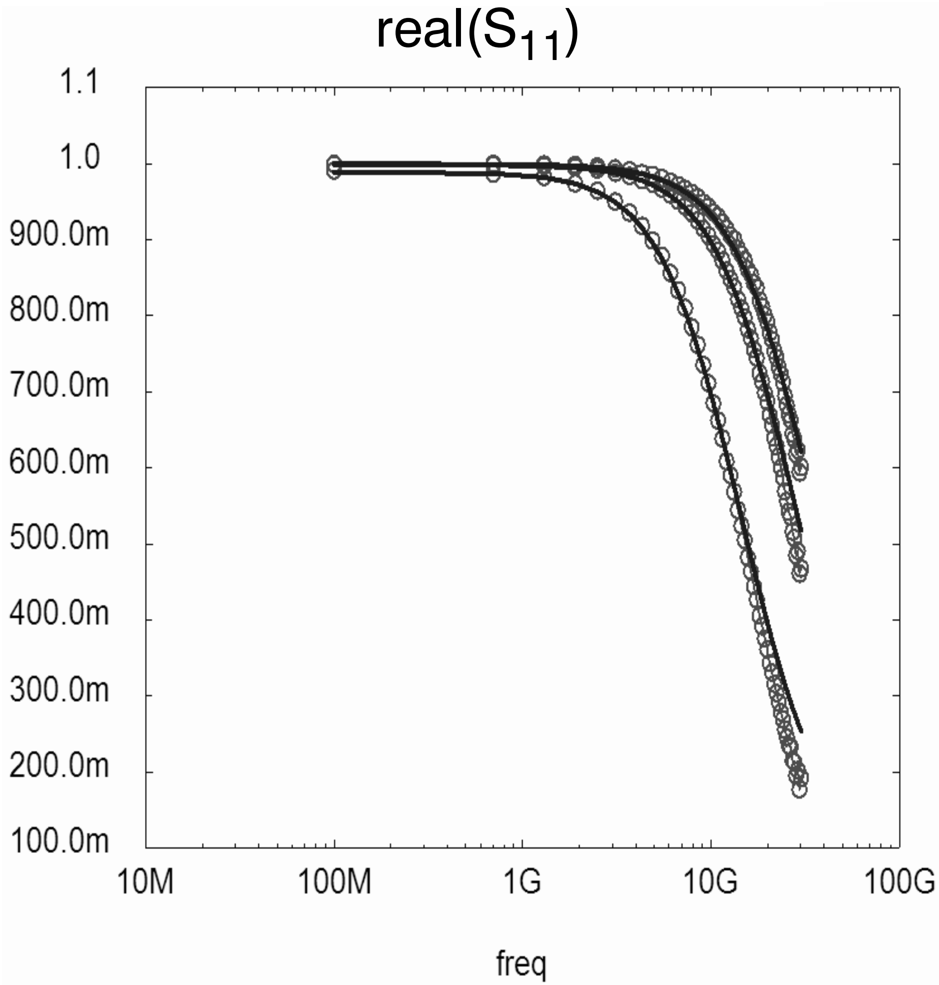
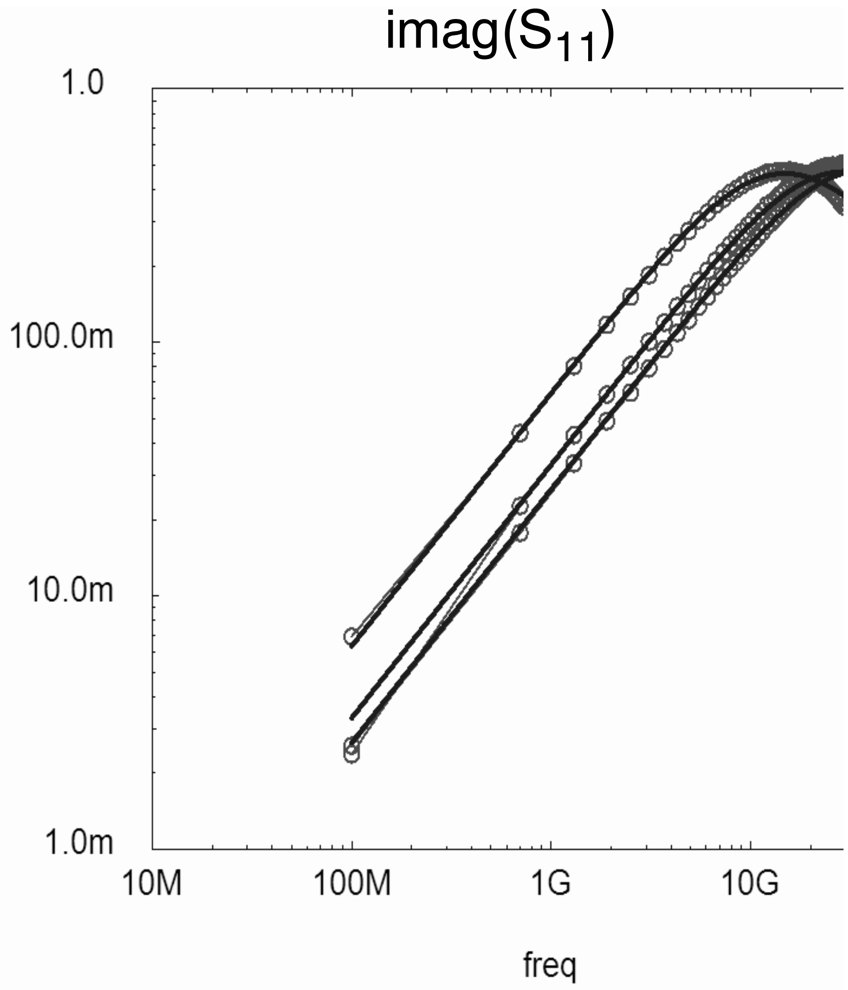


# Frequency dependence

S-parameter comparison: measurement (symbols), model (lines)



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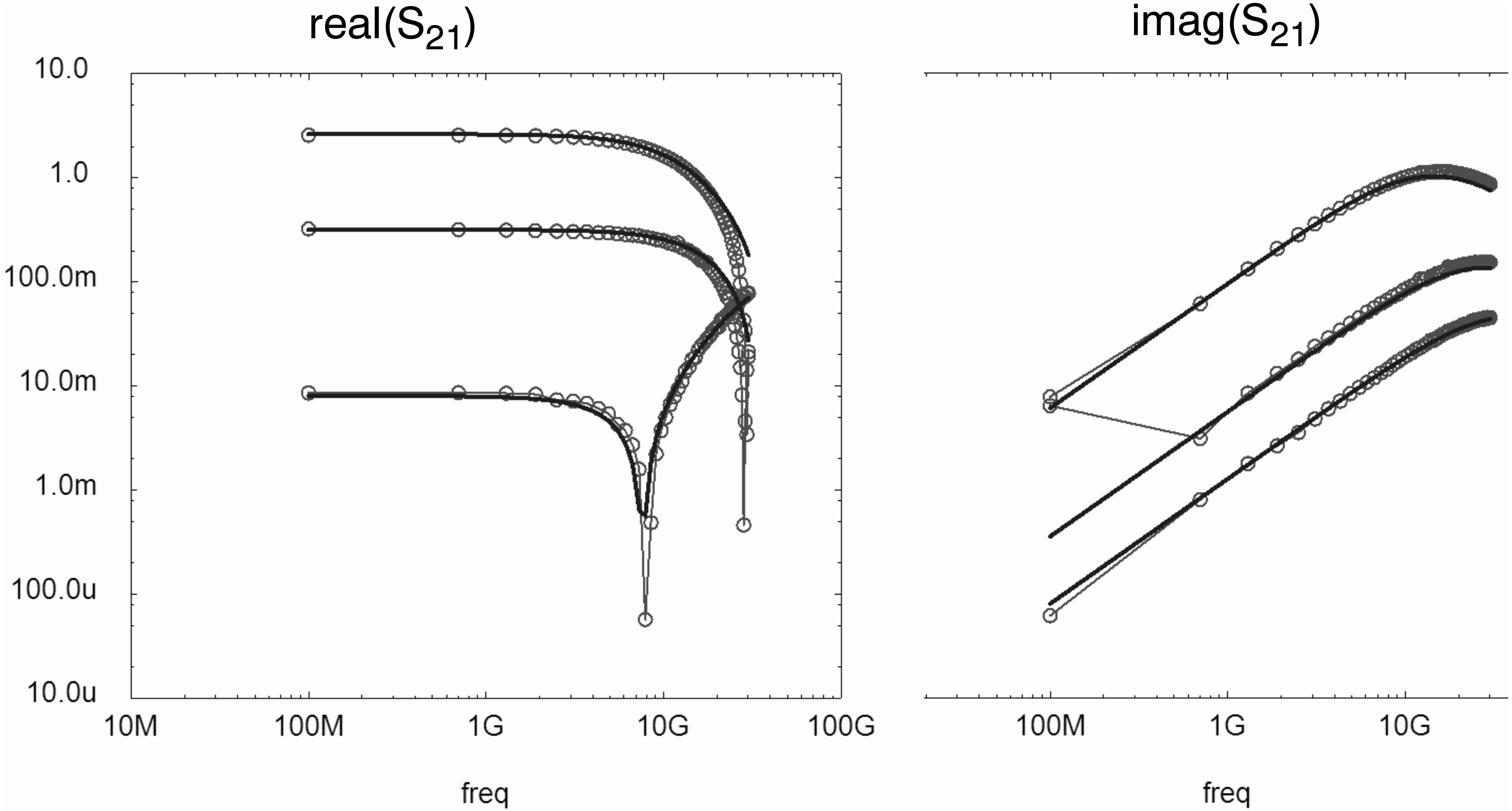

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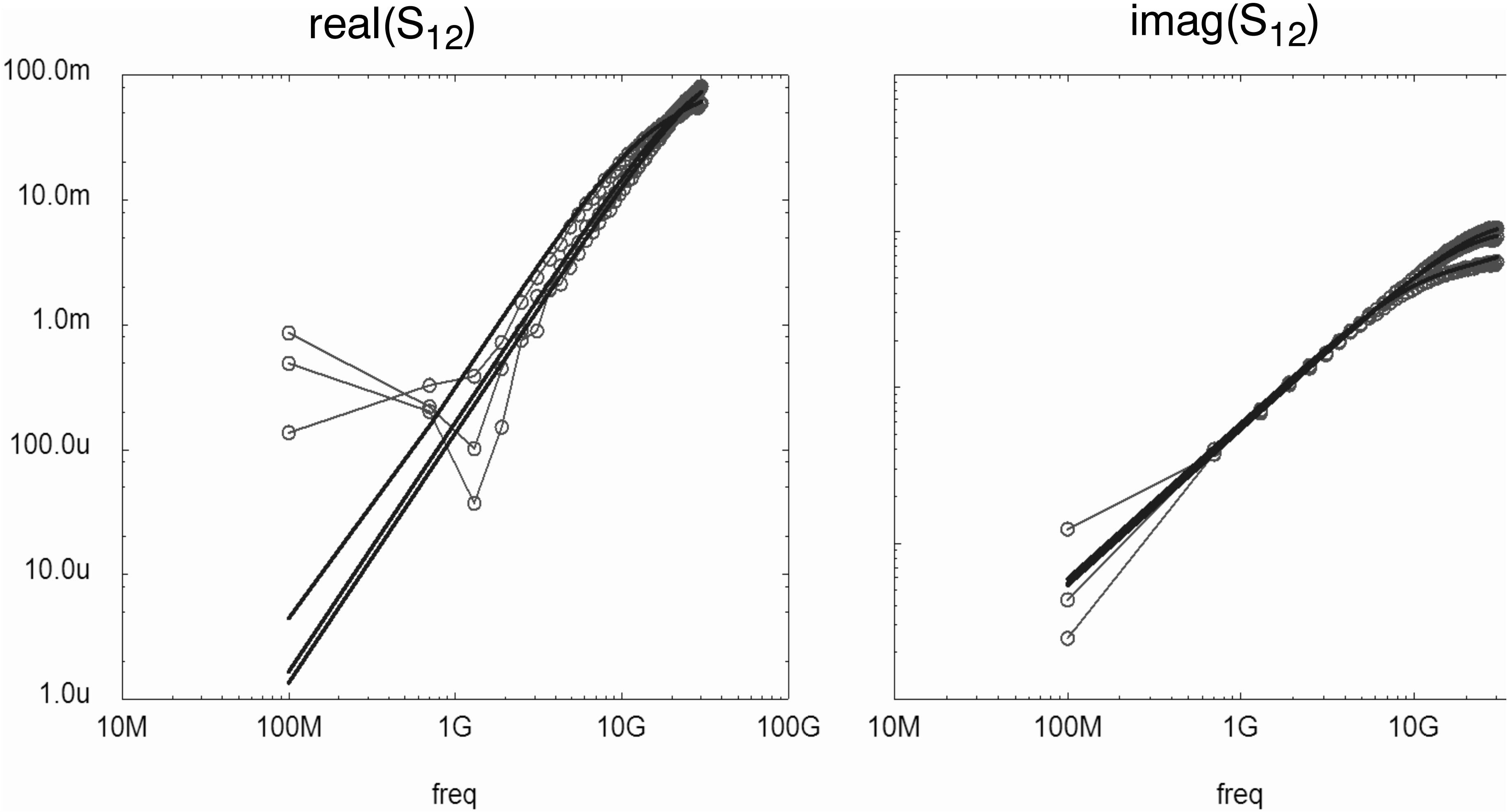

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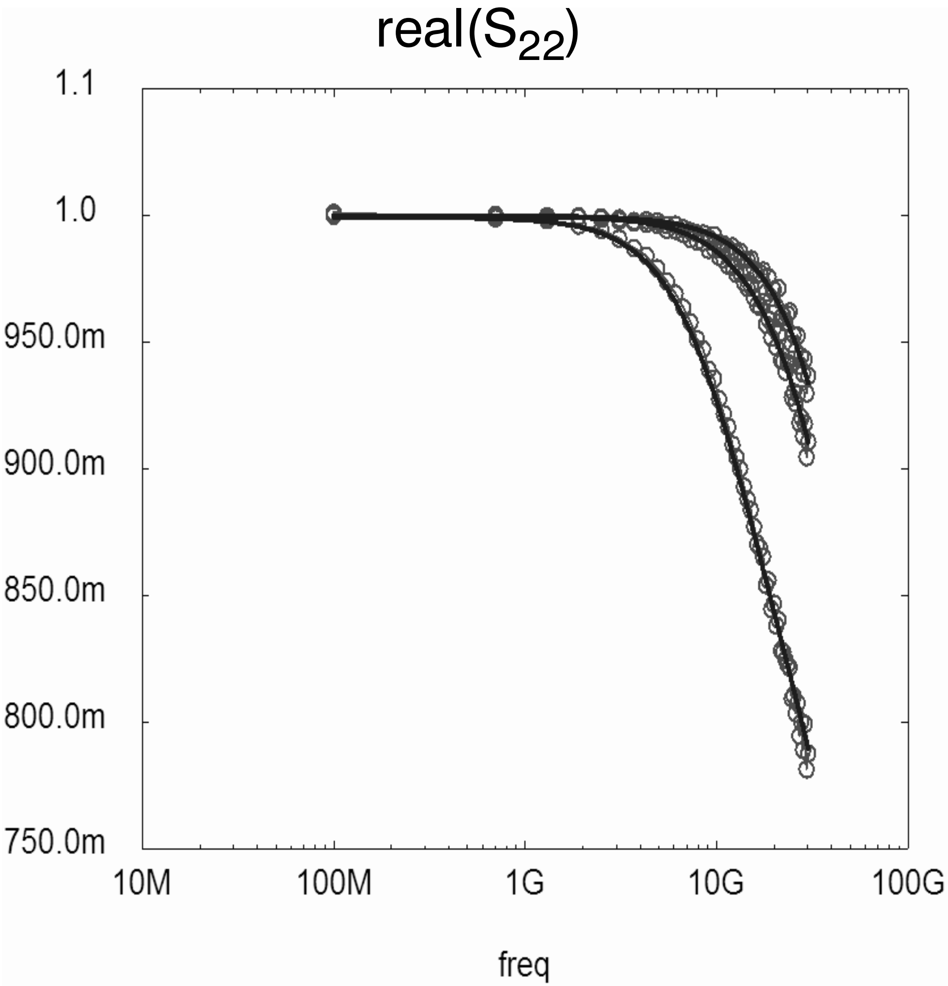


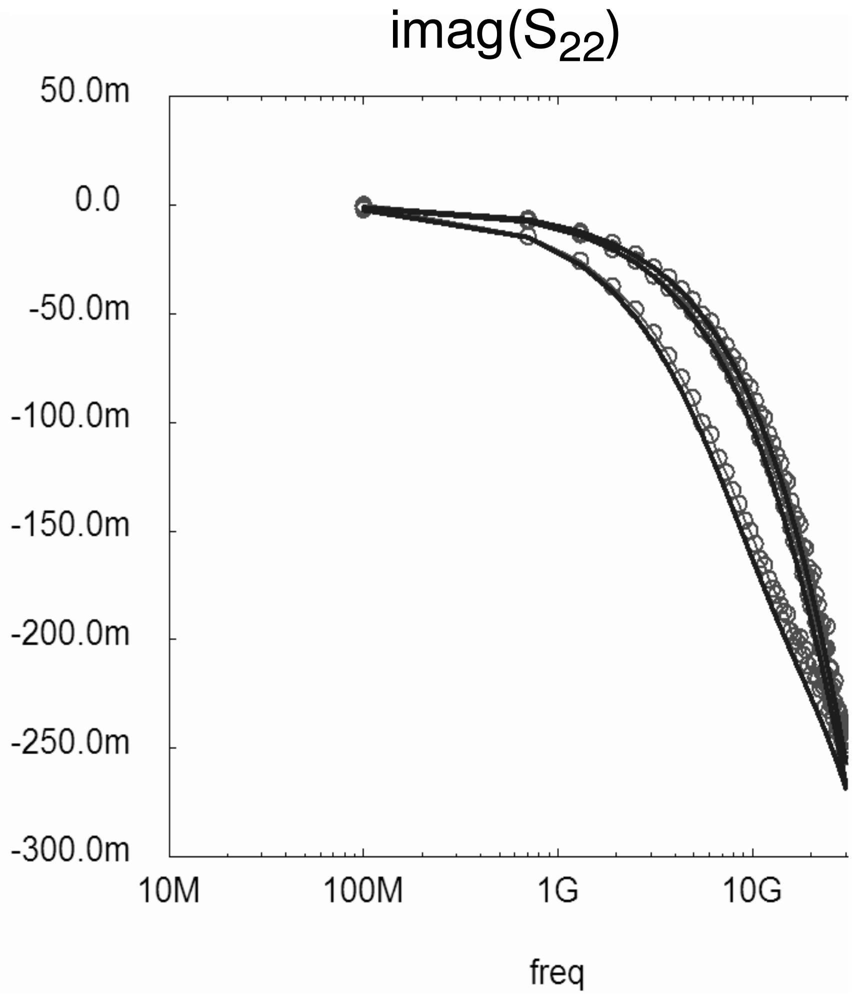

# Summary

- overview on temperature dependent formulation
  => available model parameters, feeling for the characteristics

- comparison with latest data of state-of-the-art 0.18μm BiCMOS process
  => good agreement of all standard device characteristics
  (within the expected validity range of the model)

- apparently high interest in Level0 model
  => implemented already in various commercial simulators
  (see EDA vendors web-sites for present status)

- 2-part IEEE TED paper accepted
  - model background and equations
  - parameter extraction procedure (single geometry)
  - comparison to experimental results with from different technologies

# HICUM Workshop

- 2006
  - location: Heilbronn
  - proposed date: June 12 (Mo) & 13 or 13 & 14

- future plans/options
  - moving across continents (Europe, US, Asia)
  - still once a year
  - attach to a conference ?
    - US: MTT/RFIC in June, ICMTS in ?
    - Europe: ?
    - Asia: ?
  - steering committee ?
  - other ideas ?