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Thermal Capacitance cth – its Determination and Influence on Transistor and Circuit Performance

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Overview

- Motivation
  - D/A Converter Issues
  - Previous Assumptions
- Thermal Time Constant τ_{TH} = rth x cth
  - Definition
  - Measurement Methods
- Simulation Results for Output Admittance
- cth Extraction for Different IHP HBT Types
- Summary

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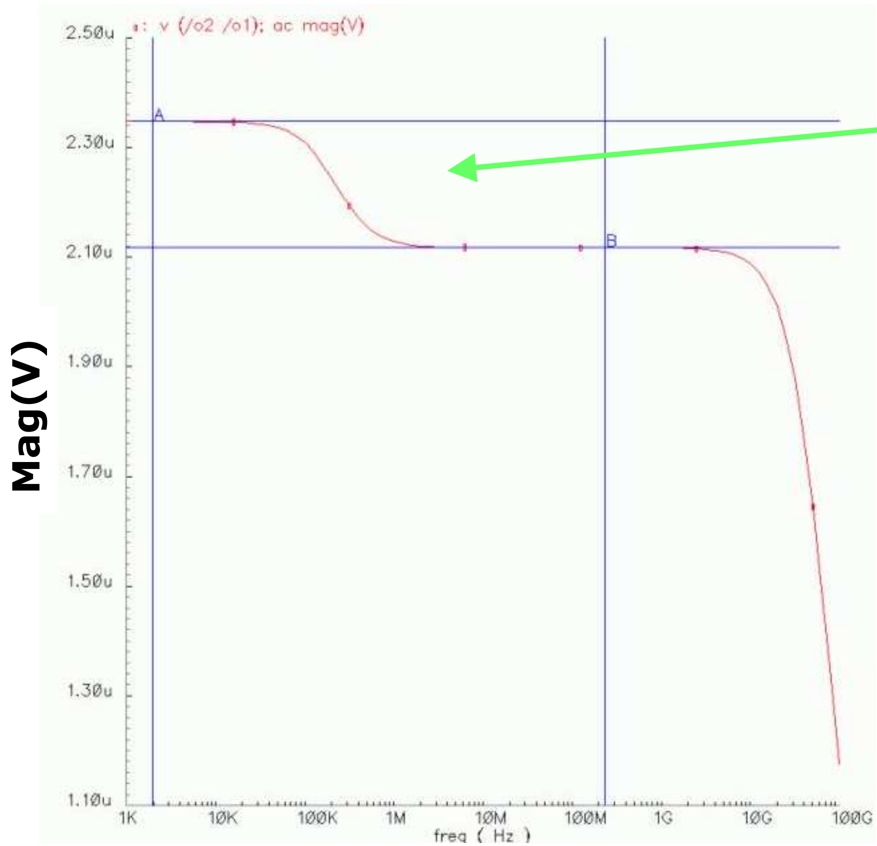
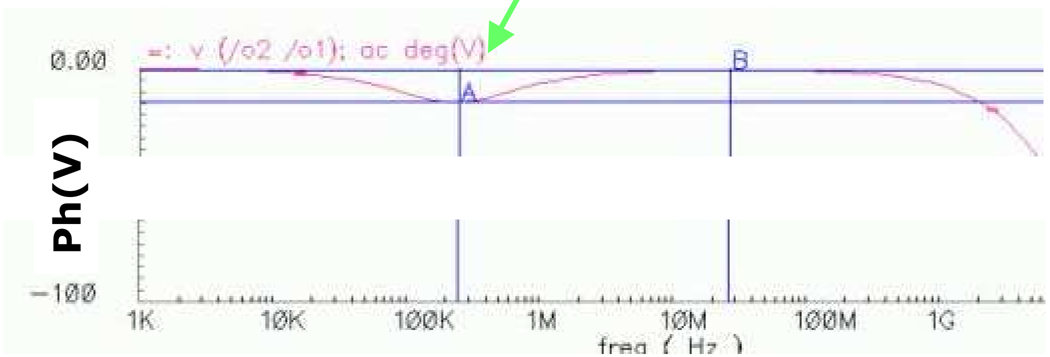
Motivation

- Fast A/D converters are currently a “hot topic” for IHP customers
  - I received similar questions from different designers
  - main issue: “particular behavior of ac response of bipolar differential pair”



“Step” in magnitude and “sink” in phase of frequency response.
Cause? cth ?!
How accurate is model for cth ?



Previous Assumptions

- For all IHP HBT VBIC models cth > 0.
  - Based on pulsed measurements of thermal time constant

    $$\tau_{TH} = rth \cdot cth$$

    (F. Korndörfer, AK Bipolar 2006):

    cth ~ 400 pJ/K for H1-HS HBT with emitter number NX=8
  - Assumption: τ_{TH} ~ 850 ns = constant for NX=1 – 8
  - For all other HBT we chose

    $$cth \sim 100 \text{ pJ/K and } rth \cdot cth = \text{const.}$$
  - Therefore, if rth ~ $NX^{-0.8}$ → cth ~ $NX^{0.8}$
- But: one customer complained that τ_{TH} must be function of HBT size

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Self Heating I

- Power dissipation p(t) leads to increase of HBT junction temperature:

$$p(t) = \frac{dW_{th}(t)}{dt} + p_{th}(t) = CTH\,\frac{d\Delta T(t)}{dt} + \frac{\Delta T(t)}{RTH}$$

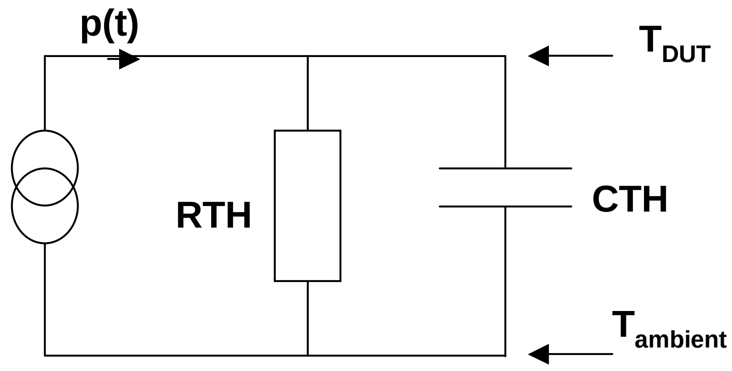
$$\Delta T = T_{DUT} - T_{ambient}$$

- Transient temperature response is determined by thermal time constant :

$$\Delta T(t) = P(t \to \infty) \cdot RTH \cdot \left(1 - \exp\left[-\frac{t}{\tau_{TH}}\right]\right),$$

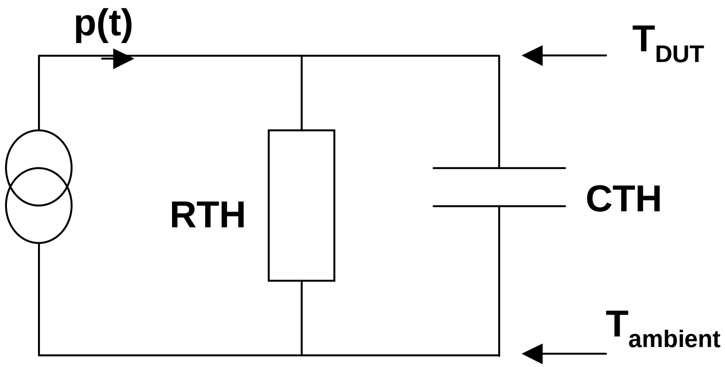
$$\tau_{TH} = RTH \cdot CTH$$

[K/W] • [J/K]



Self Heating II

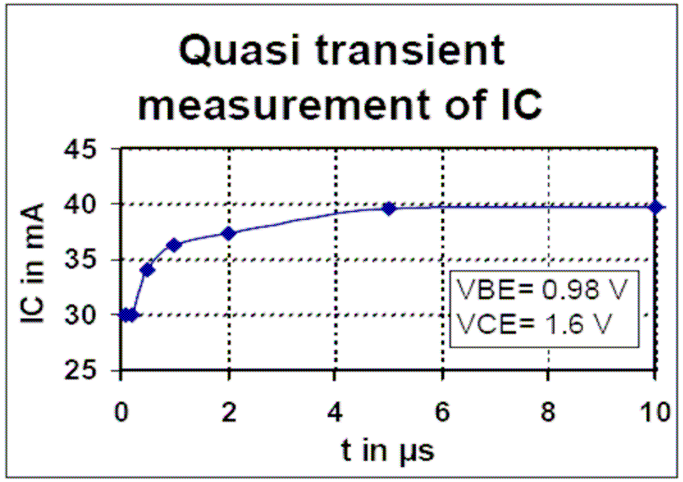
- In compact models ΔT is calculated by using a simplified thermal network with only one thermal time constant

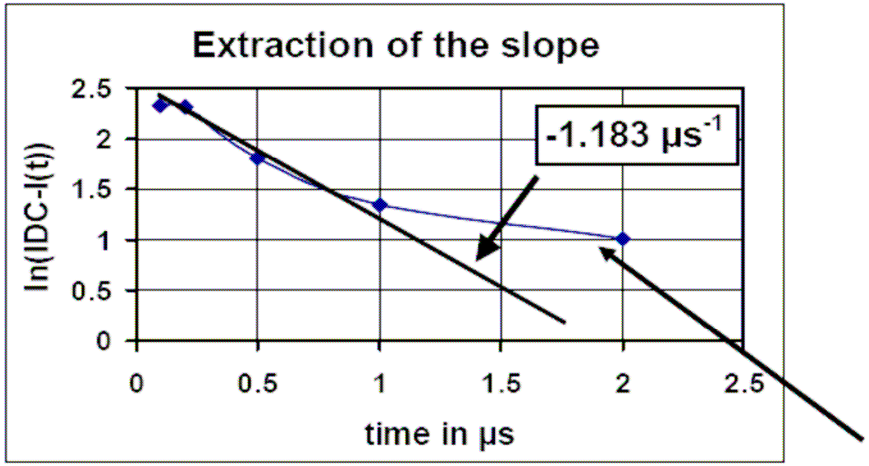


- Thermal resistance rth can easily be measured with DC analyzer

1st Approach: Pulsed Measurements

- Concept presented at 2006 AK Bipolar (F. Korndörfer)
  - dynamic I(V) analyzer → 100ns – 1ms pulse width
  - DUT: SG25H1 HS-HBT (f_T = 180 GHz)





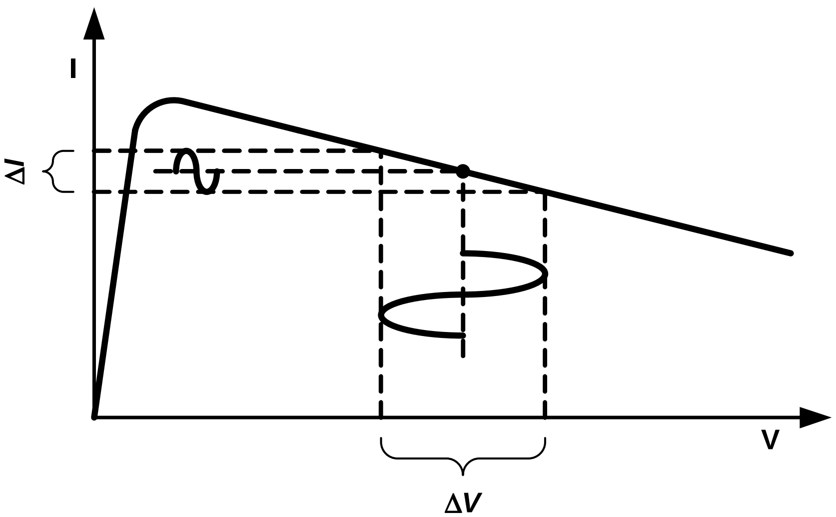
second time constant is visible

$$\tau_{TH} = -\frac{1}{m} \approx 0.85\mu s$$

With given rth this lead to cth ~ 400 pJ/K for largest DUT with 8 emitter in BEC configuration.

2^{nd} Approach: Impedance Analyzer

- Output characteristic with fixed IB
  - Based on concept by Bruce et al., Electronics Letters 33(2), 1997

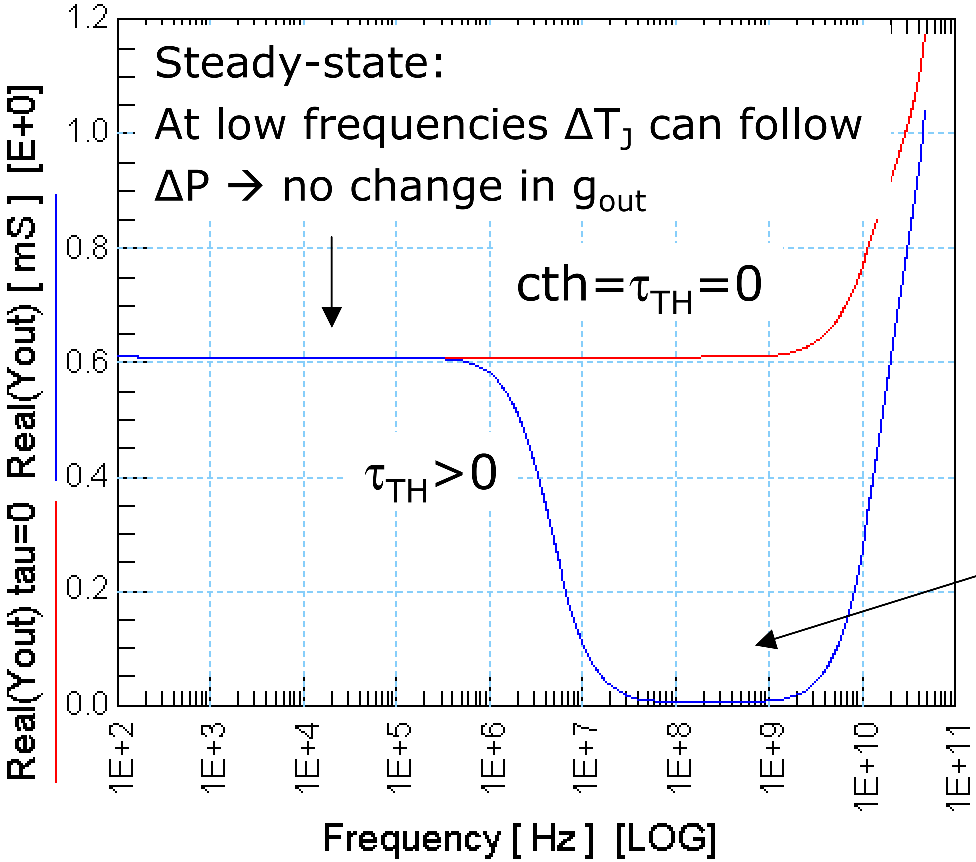


$$g_{\mathrm{OUT}} = \Re\{Y_{\mathrm{OUT}}\} = \frac{\mathrm{d}I}{\mathrm{d}V} \approx \frac{\Delta I}{\Delta V}$$

Approach:
Use impedance analyzer to measure Real(Y_{out}) as function of frequency and find the transition between steady-state and transient mode.

Y_{out} Transient Behavior (Simulation)

VBIC simulation example for g_{out} = Re(Y_{out}) = Re(Y_{22} + Y_{12}) with fixed I_B

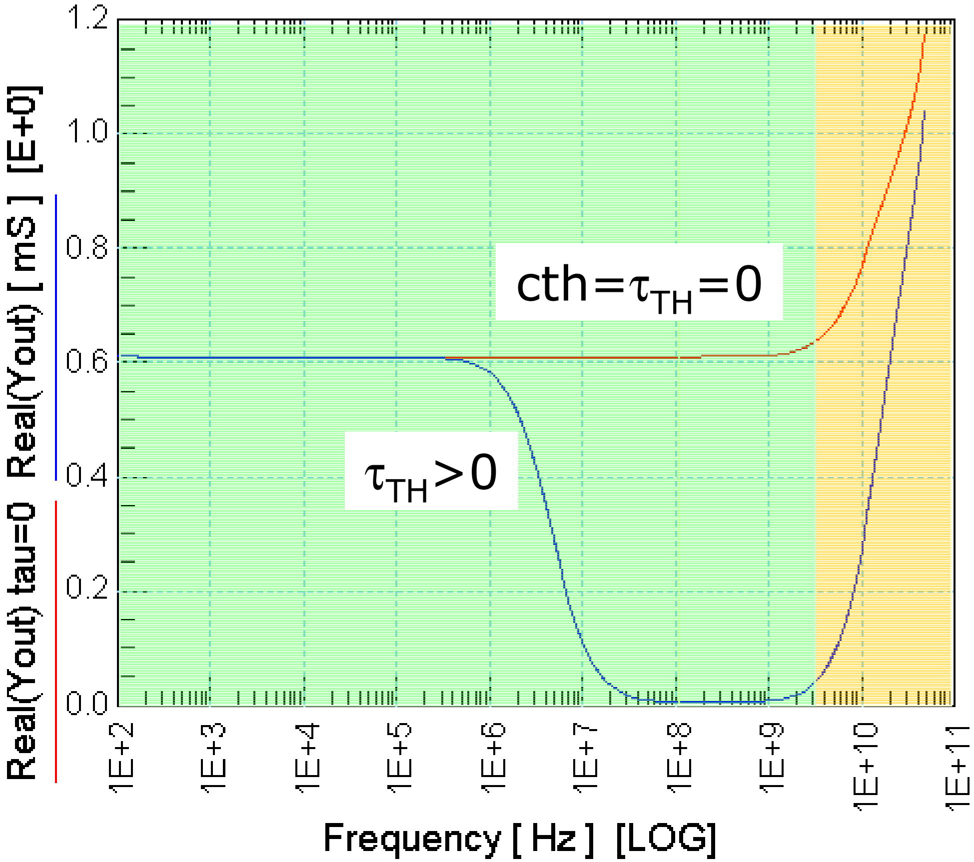


- Measurement of g_{out}
  - from slope of Y_{out} in MHz range extraction of τ_{TH} possible

Transient mode:
At high frequencies ΔT_J cannot follow
→ g_{out} reaches its intrinsic value

Y_{out} Transient Behavior (Simulation)

VBIC simulation example for $g_{out} = Re(Y_{out}) = Re(Y_{22} + Y_{12})$ with fixed I_B



- Measurement of g_{out}
  - Frequency range < 3 GHz: Impedance analyzer
    ➔ Ongoing work not yet to be published
  - Frequencies > 100MHz: Network analyzer

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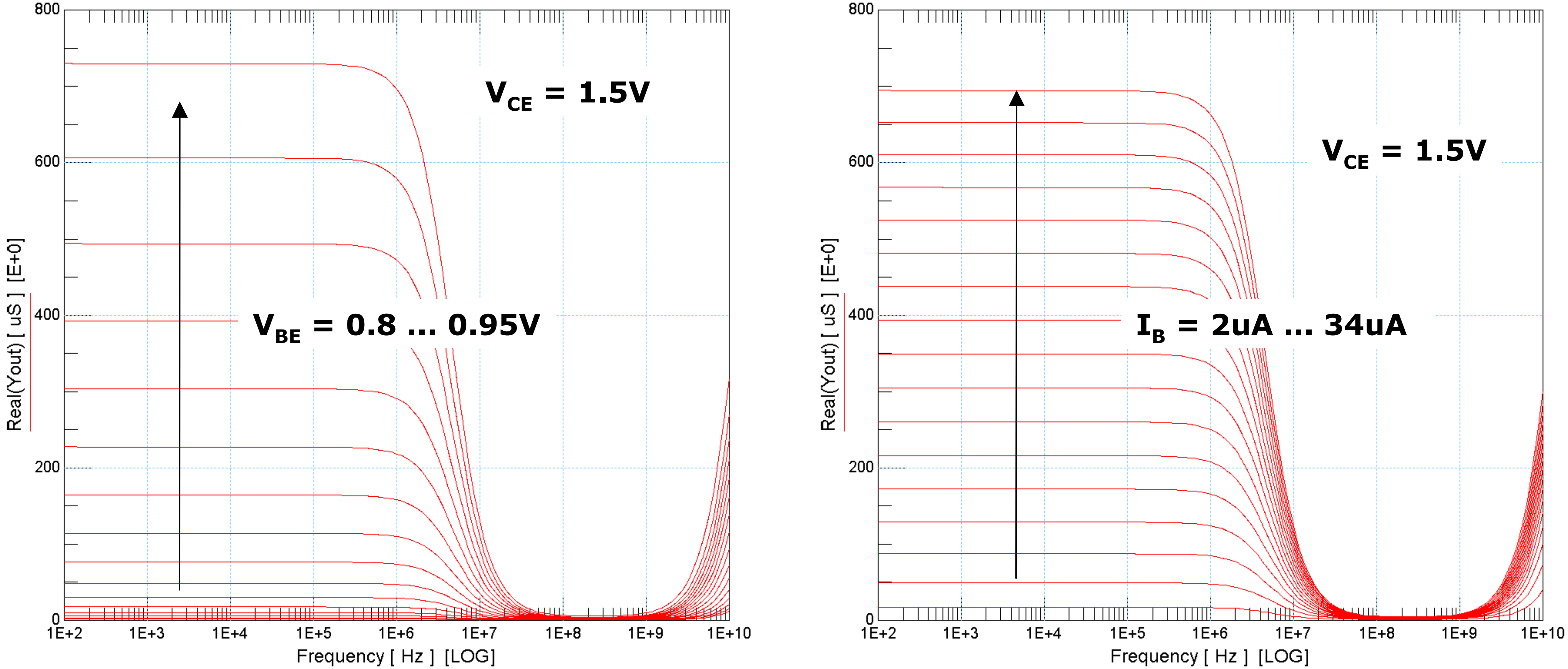
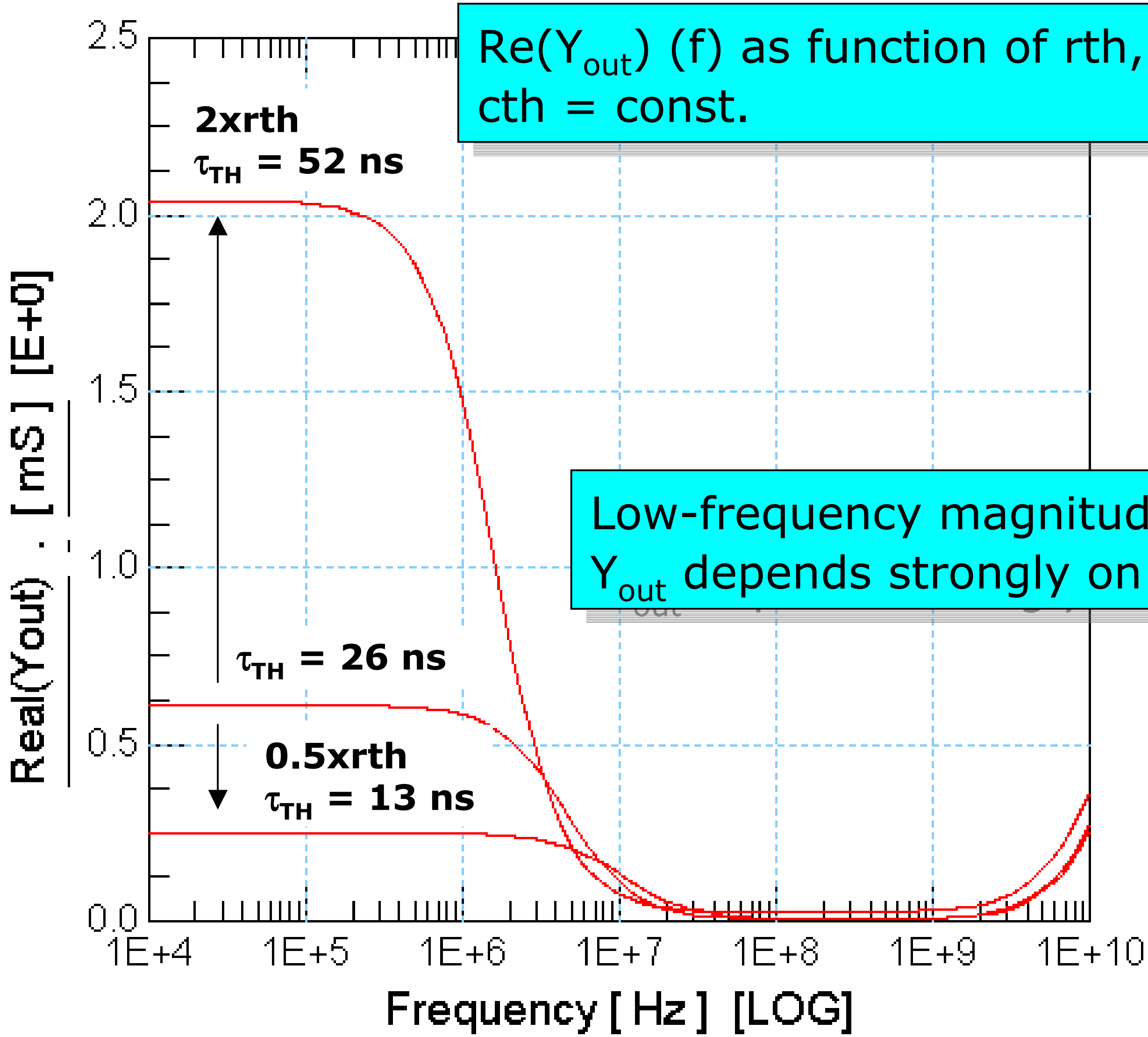
Output Admittance Simulations I

Re(Y_{out}) (f) as function of operating point



HBT SGB25V-HS (f_T=80GHz)
$A_{Emitter}$ = 0.42x0.87µm²; rth=3.900K/W, cth = 6.7pJ/K → τ_{TH}=26ns

Output Admittance Simulations II



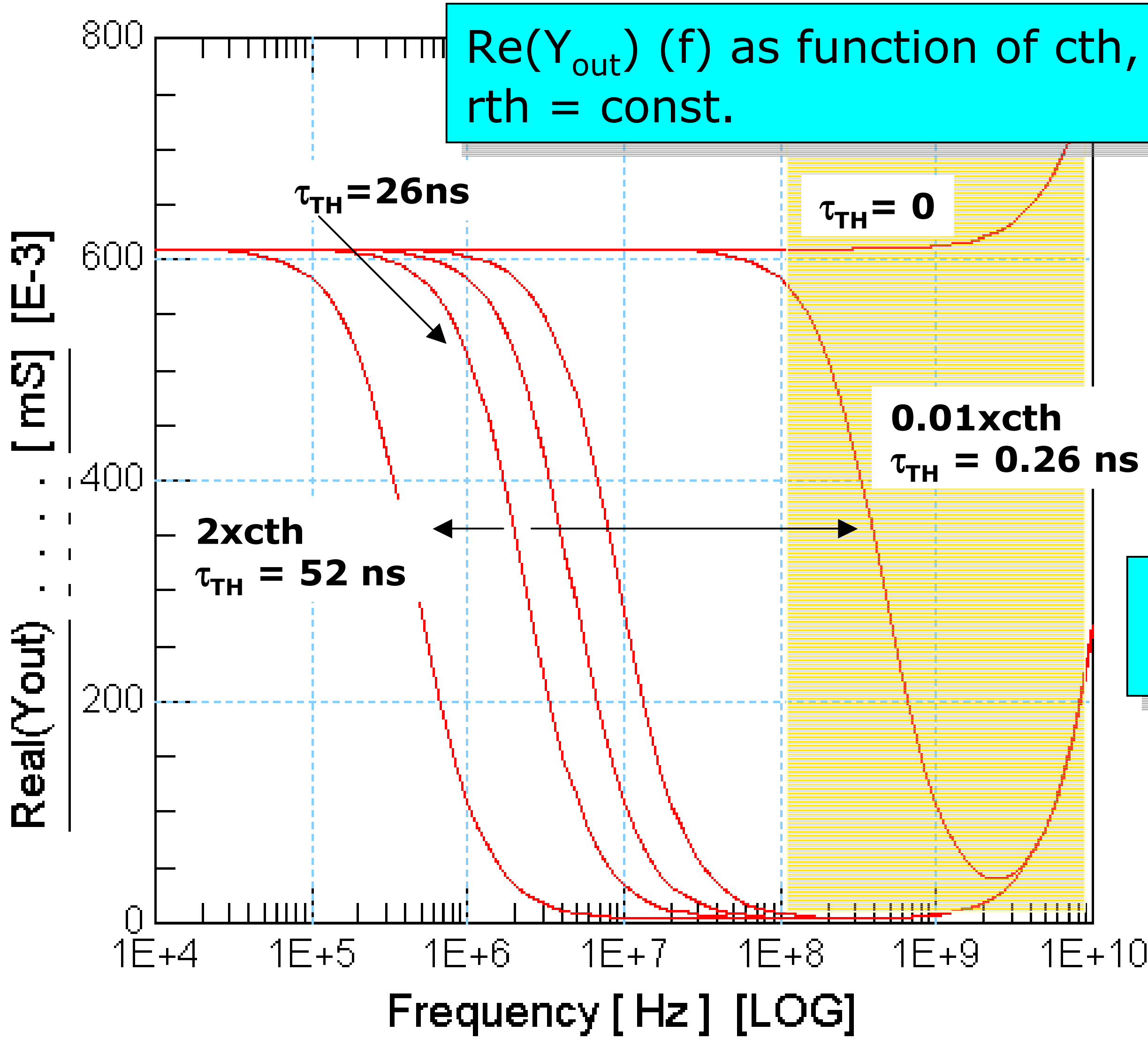
Re(Y_{out}) (f) as function of rth, cth = const.

Low-frequency magnitude of Y_{out} depends strongly on rth.

V_{CE} = 1.5V, IB=30µA

HBT SGB25V-HS (f_T=80GHz)
$A_{Emitter}$ = 0.42x0.87µm²

Output Admittance Simulations III



Re(Y_{out}) (f) as function of cth, rth = const.

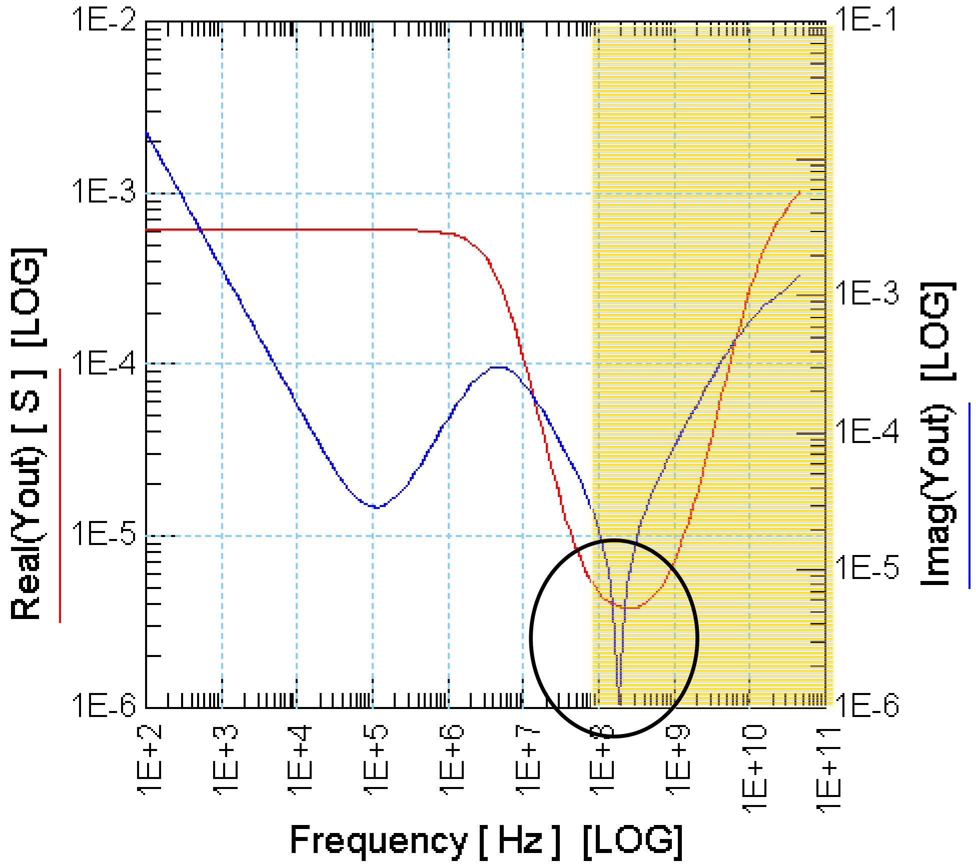
V_{CE} = 1.5V, IB=30µA, rth=const.

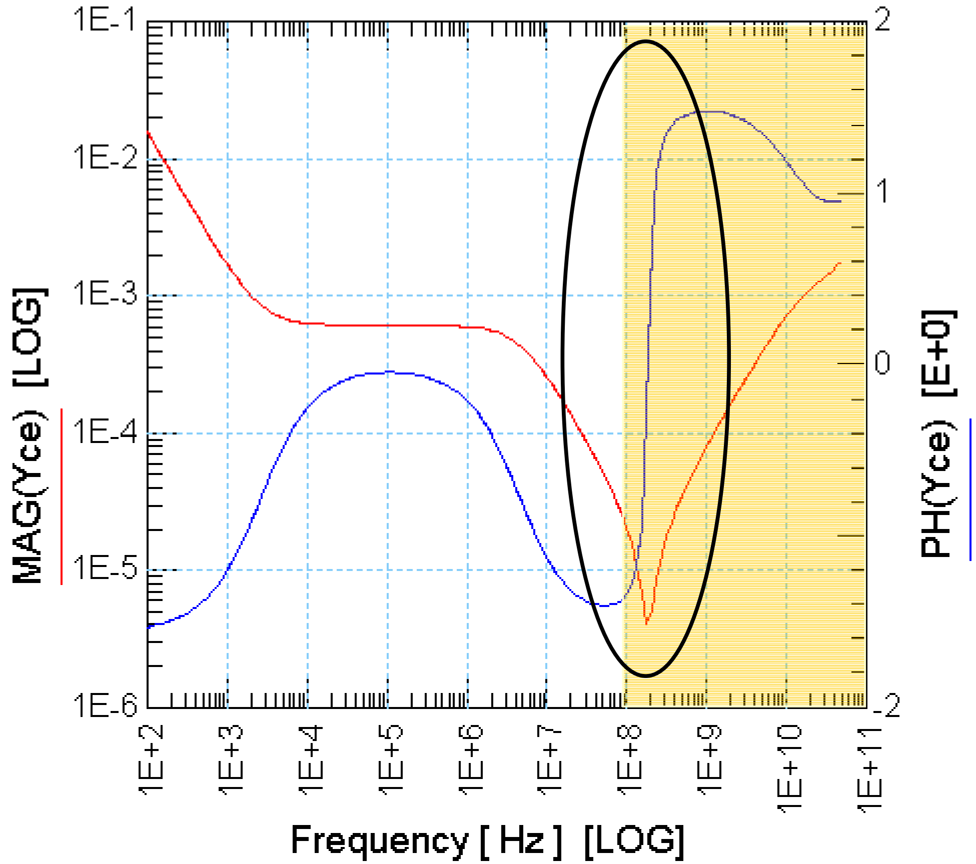
With τ_{TH} < 1ns Y_{out} step shifts into in NWA frequency range !

HBT SGB25V-HS (f_T=80GHz)
$A_{Emitter}$ = 0.42x0.87µm²

Output Admittance Simulations IV

Real/Imag Y_{out} vs. Mag/Phase Y_{out}





HBT SGB25V-HS (f_T=80GHz)
$A_{Emitter}$ = 0.42x0.87µm²
V_{CE} = 1.5V, IB=30µA, τ_{TH} =26ns

(Oder) Germ

Because of minimum of Mag(Y_{out}) and phase shift of Ph(Y_{out}) at f > 100MHz extraction of cth with NWA possible ?!

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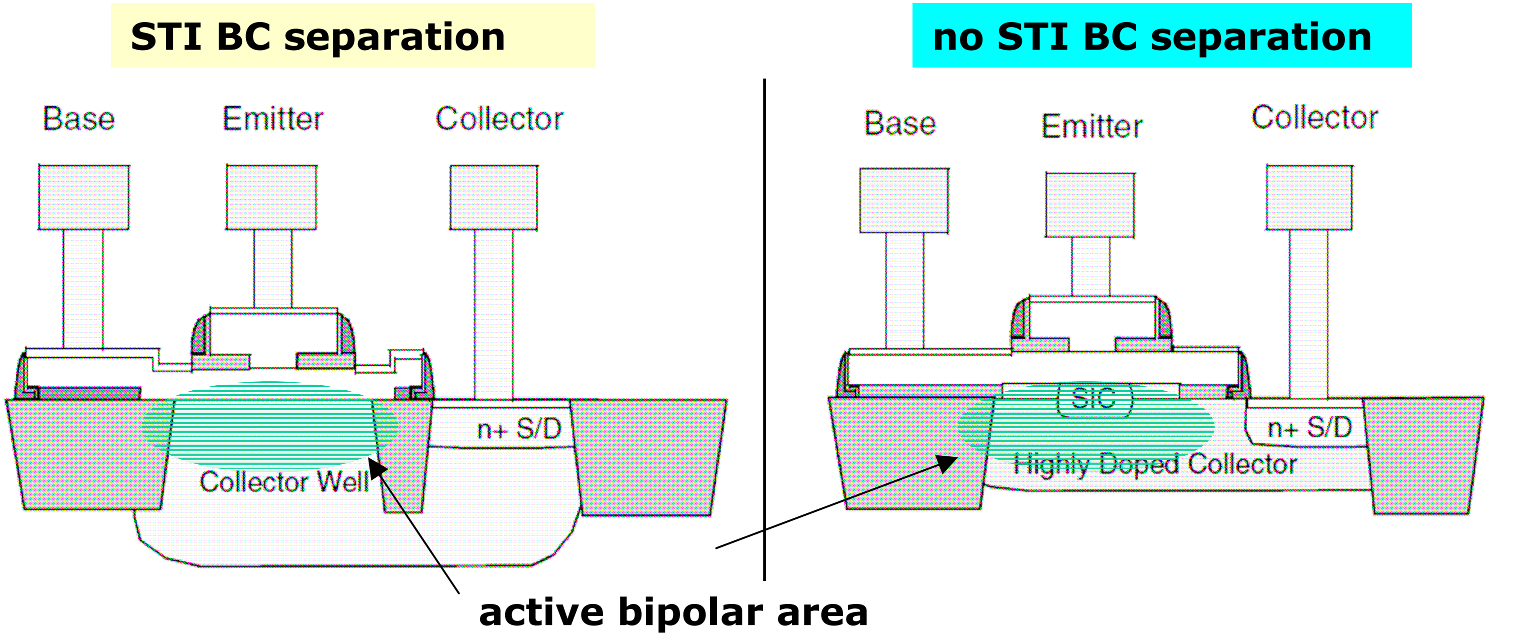
Simulation Results – Test Devices

- Comparison of 5 different IHP HS-HBT types.

HBT-Type	Technology	fT [GHz]	BVCE0 [V]	Layout	Minimum Emitter Size [µm²]		Active Bipolar Area [µm²]
SGB25V-HS	0.25µm BiCMOS	80	2.4	BEC	0.42x0.87	0.37	1.32
SG25H3-HS	0.25µm BiCMOS	110	2.2	BEC	0.3x0.92	0.28	0.81
SG25H1-HS-B	0.25µm BiCMOS	180	1.9	BEC	0.26x0.92	0.24	0.55
SG13-HS-CBEBC	0.13µm BiCMOS	250	1.75	CBEBC	0.16x1.04	0.17	0.44
SG13-HS-BEC	0.13µm BiCMOS	250	1.75	BEC	0.16x0.52	0.08	0.26



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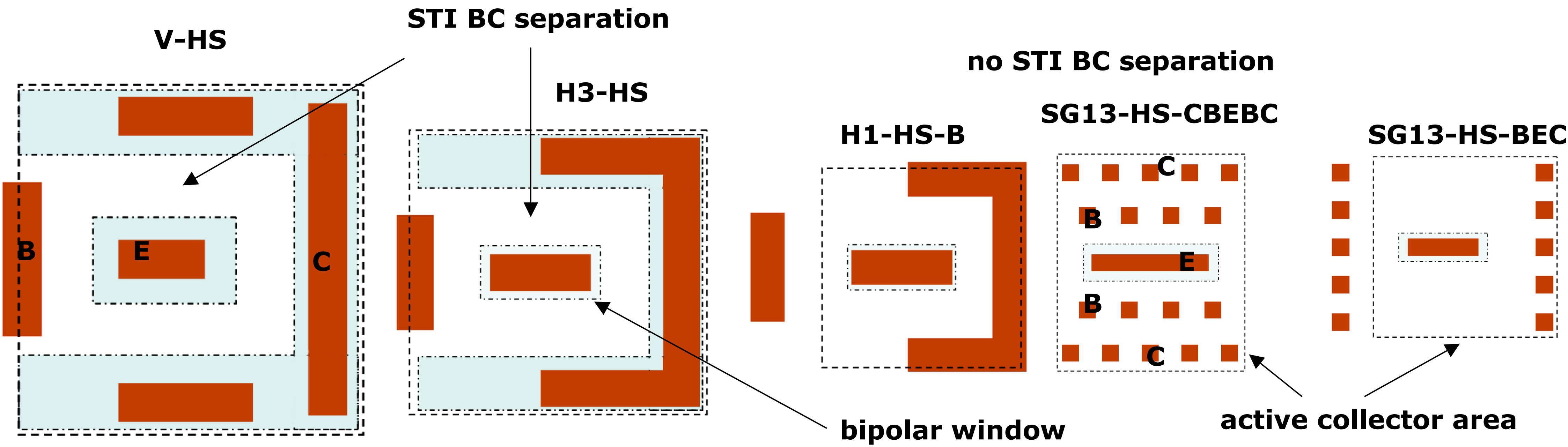
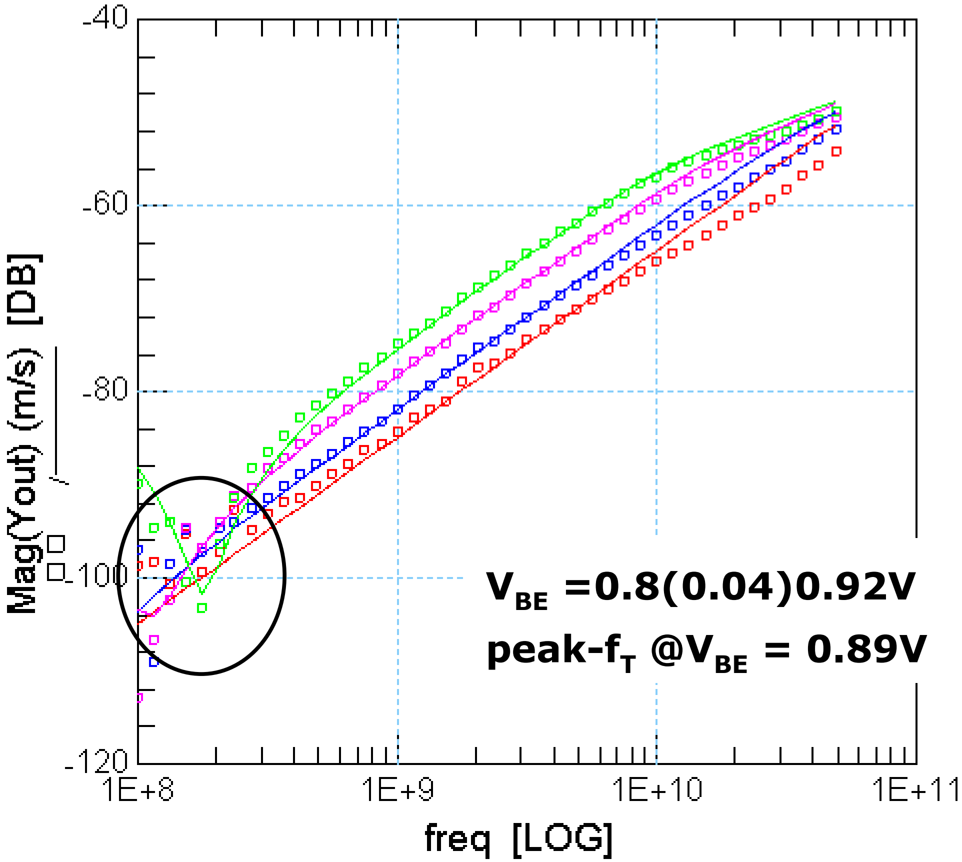
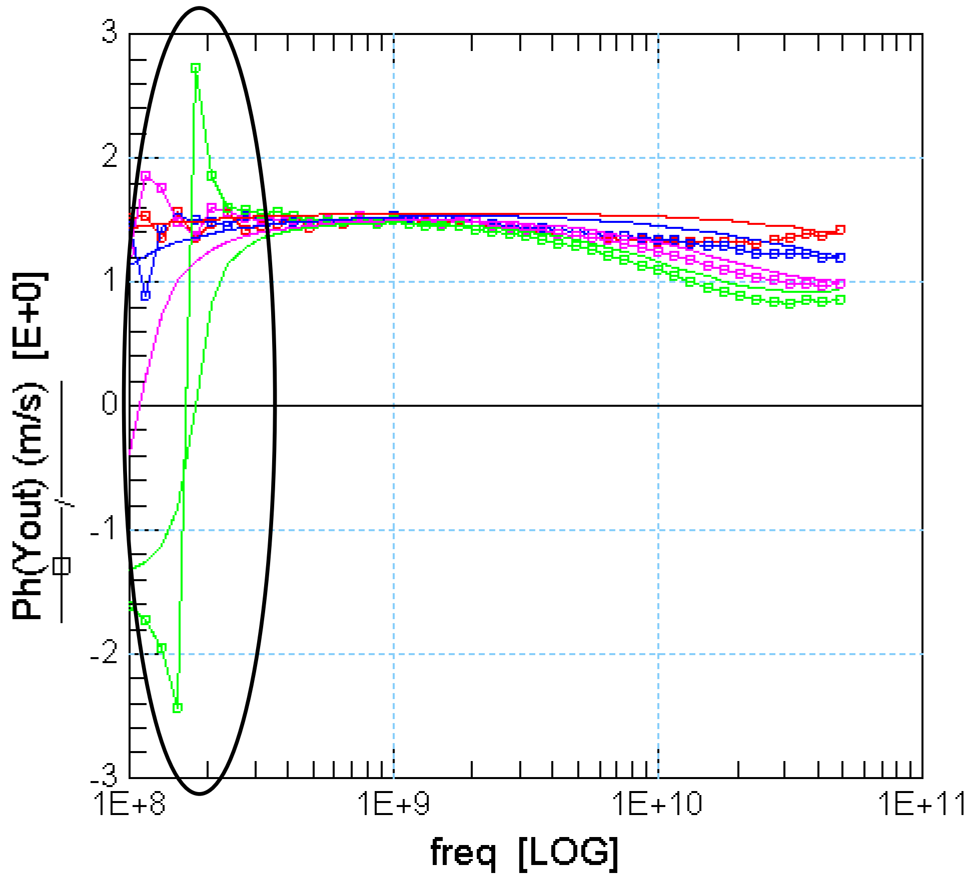
SG25H1-HS-B	0.25µm BiCMOS	180	1.9	BEC	0.26x0.92	0.24	0.55
SG13-HS-CBEBC	0.13µm BiCMOS	250	1.75	CBEBC	0.16x1.04	0.17	0.44
SG13-HS-BEC	0.13µm BiCMOS	250	1.75	BEC	0.16x0.52	0.08	0.26



SGB25V – HS-HBT





HBT SGB25V-HS (f_T=80GHz)
2 DUT parallel
$A_{Emitter}$ = 0.42x0.87µm²
V_{CE} = 1.5V, τ_{TH} =26ns

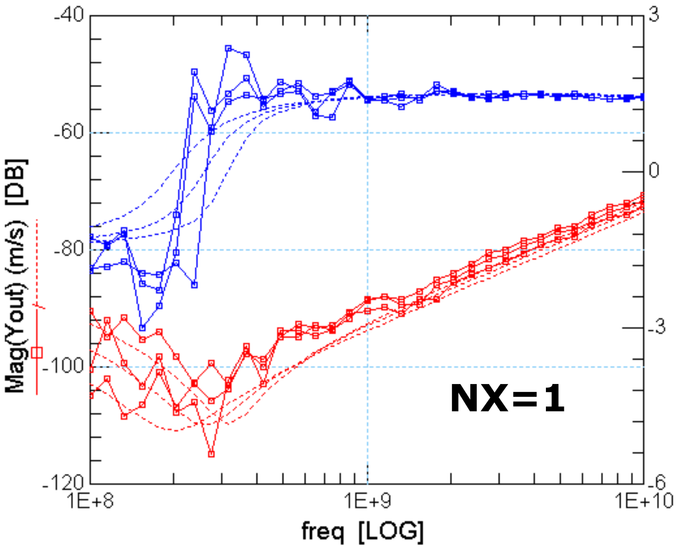
Phase shift of Ph(Y_{out}) and minimum of Mag(Y_{out}) slightly above 100 MHz → estimation of τ_{TH} ~ 26ns possible !

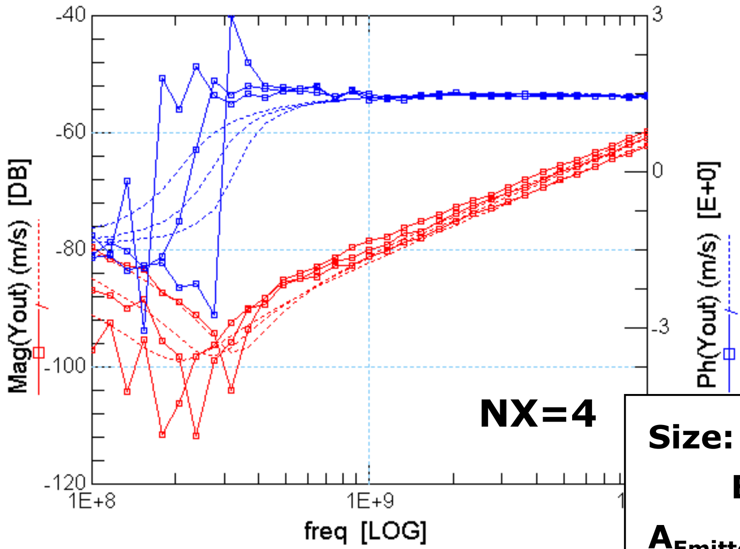
SG25H3 – HS-HBT (f_T=110GHz)

V_{CE} = 1.5V,

V_{BE} =0.88(0.02)0.92V

peak-f_T @V_{BE} = 0.90V





Size: emitter number scaling – BEC layout

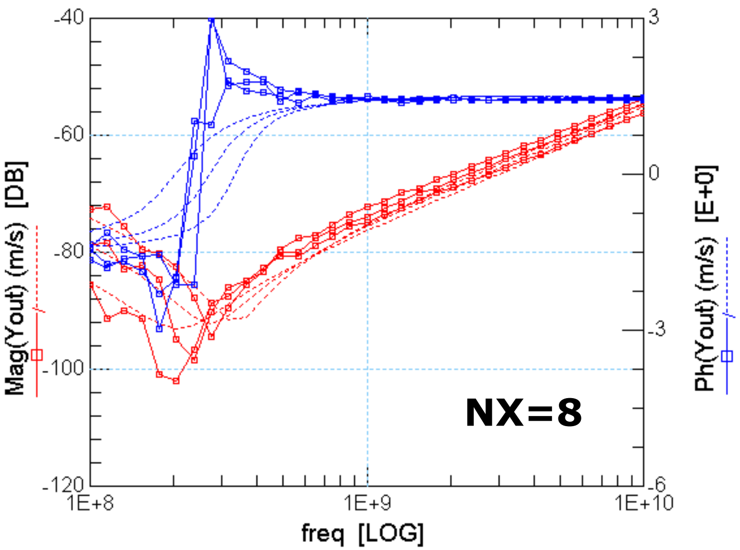
$A_{Emitter}$ = NXx0. 3x0.92µm²

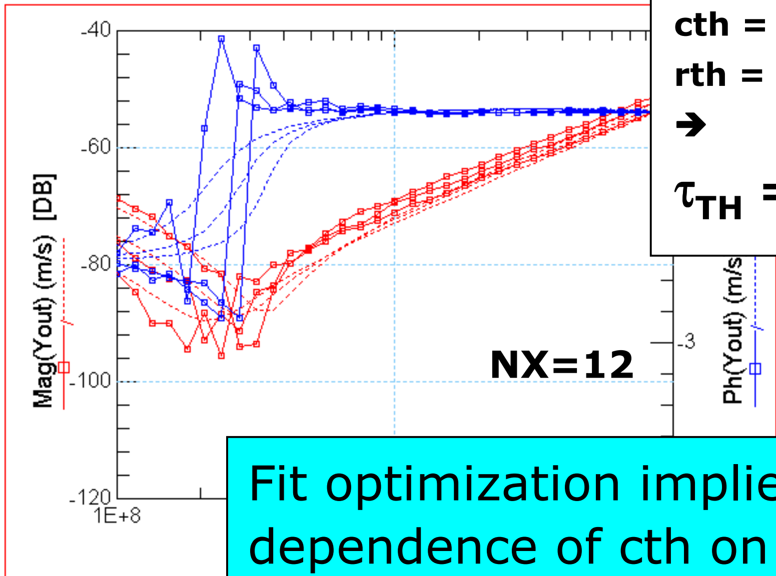
cth = $2.25\cdot10^{-12}\cdot$NX J/K

rth = $6498\cdot NX^{-0.85}$ K/W

➔

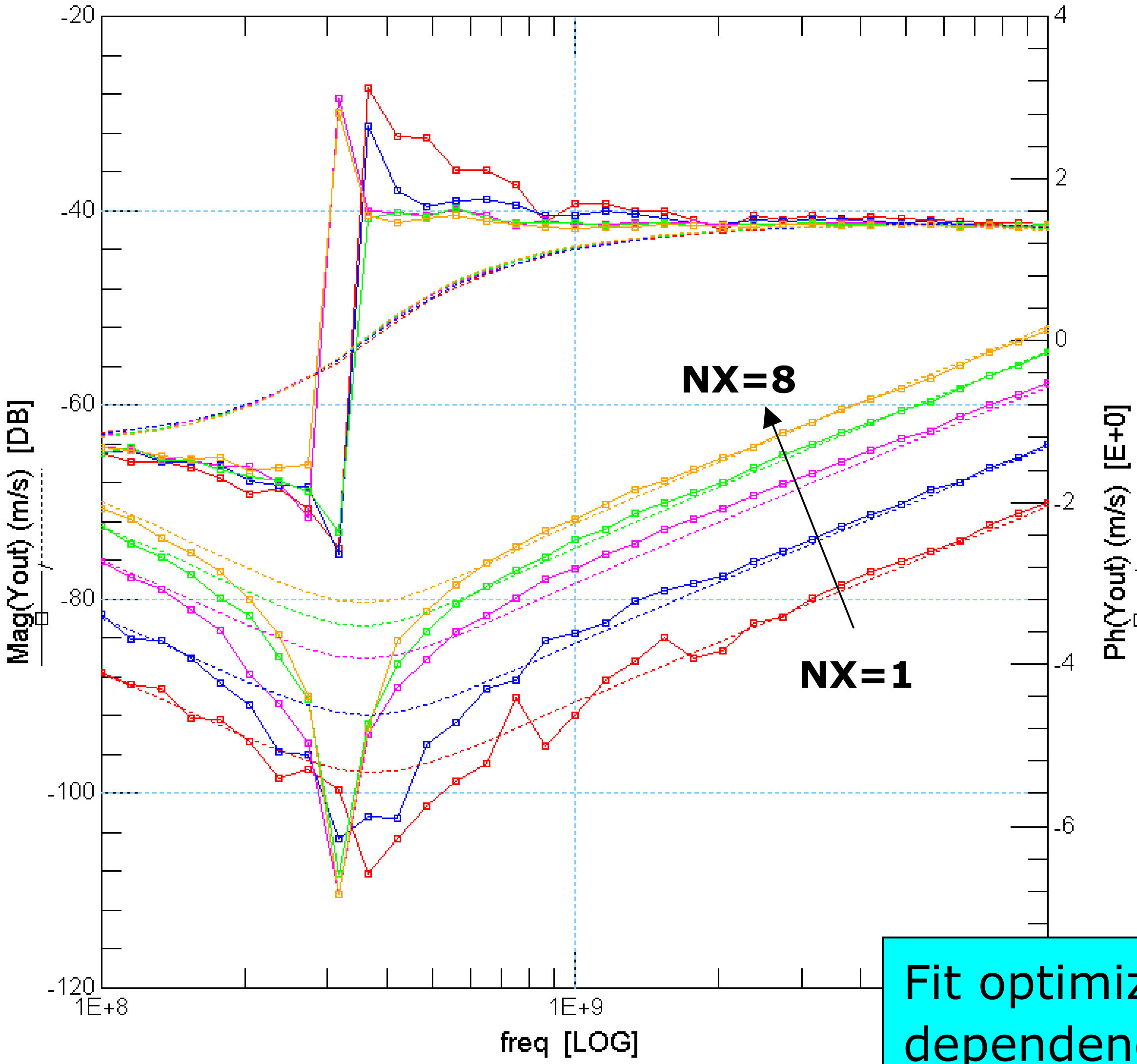
τ_{TH} = $14.6\cdot NX^{0.15}$ ns





Fit optimization implies a linear dependence of cth on emitter number and $\tau_{TH} \sim NX^{0.15}$.

SG25H1 – HS-B (f_T=180GHz)



V_{CE} = 1.5V,
V_{BE} =0.91V
peak-f_T @V_{BE} = 0.91V

Size: emitter number scaling – BEC layout

$A_{Emitter}$ = NXx0. 26x0.92µm²

cth = $1.4 \cdot 10^{-12} \cdot$NX J/K

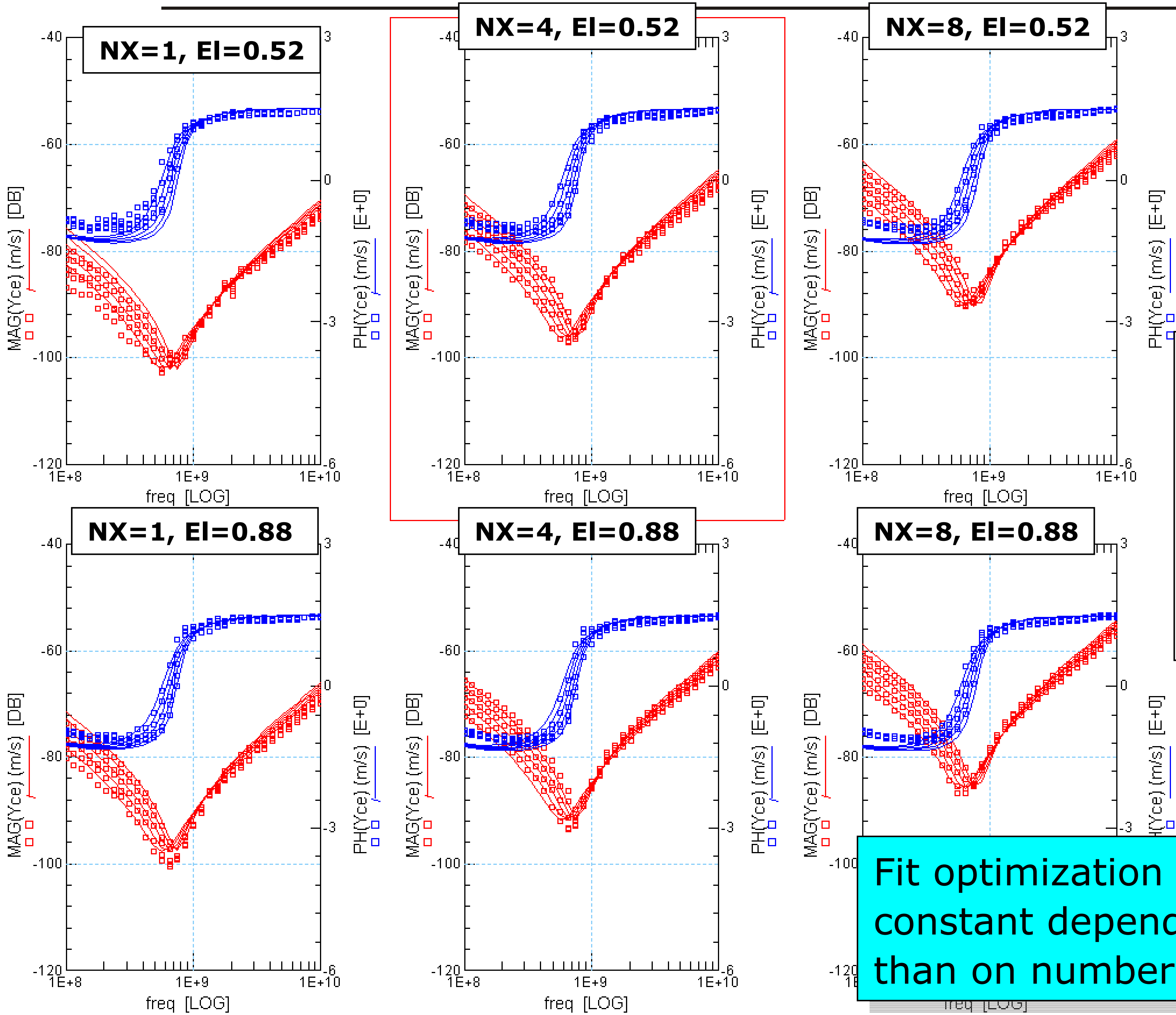
rth = $7430 \cdot NX^{-0.8}$ K/W

➔

τ_{TH} = $10 \cdot NX^{0.2}$ ns

Fit optimization implies a linear dependence of cth on emitter number and $\tau_{TH} \sim NX^{0.2}$.

SG13 – HS-BEC (f_T=250GHz)



V_{CE} = 1.2V,

V_{BE} = 0.90(0.01)0.94V

peak-f_T @V_{BE} = 0.94V

Size: emitter number + length scaling – BEC layout

$A_{Emitter}$ = NXx0. 16xEl µm²

cth = $0.50 \cdot 10^{-12} \cdot NX^{1.0} \cdot El^{1.1}$ J/K

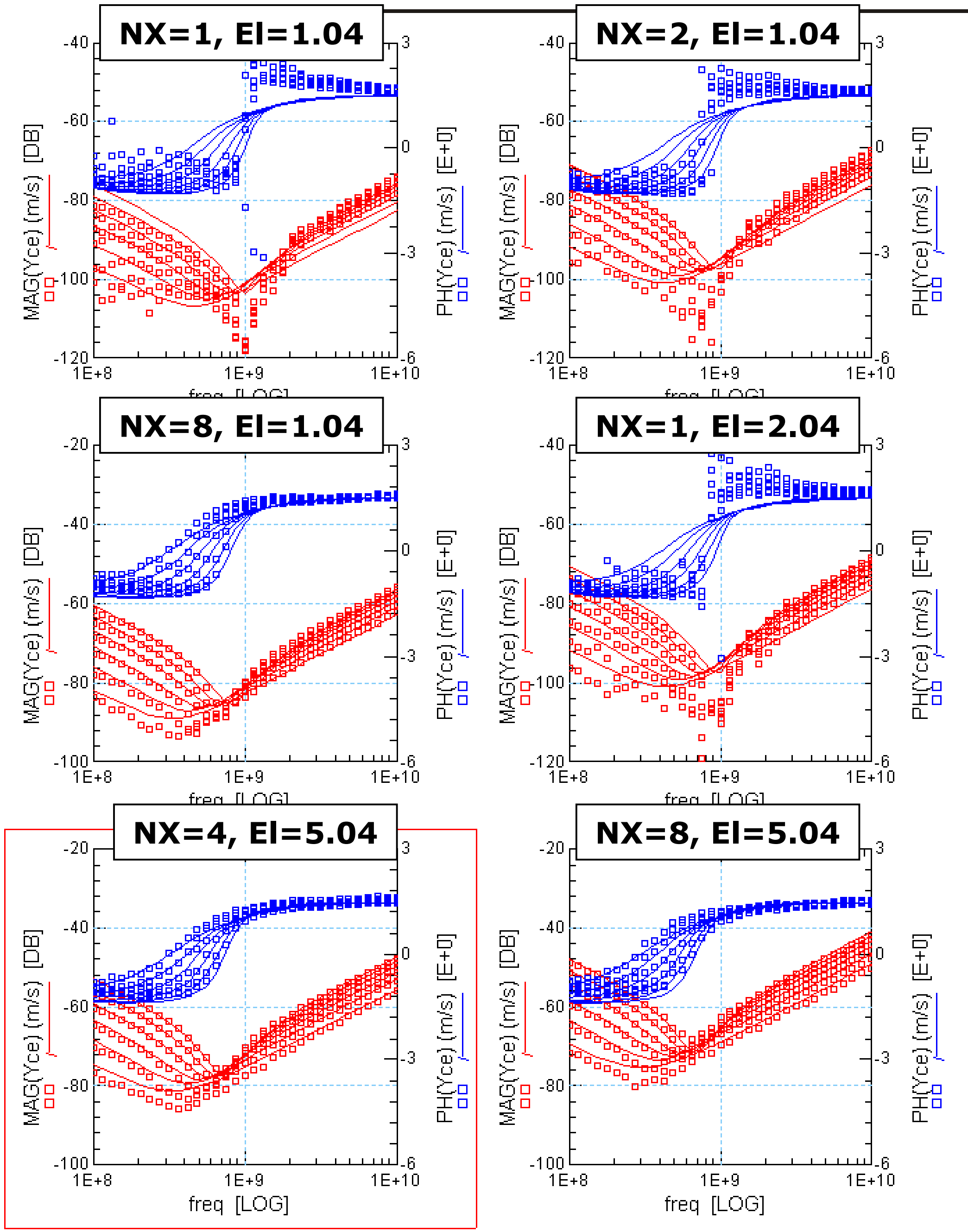
rth = $8602 \cdot NX^{-0.9} \cdot El^{-0.9}$ K/W

➔

$\tau_{TH} = 4.3 \cdot NX^{0.1} \cdot El^{0.2}$ ns

Fit optimization shows that thermal time constant depends more on emitter length than on number scaling.

SG13 – HS-CBEBC (f_T=250GHz)



V_{CE} = 1.2V,

V_{BE} = 0.84(0.02)0.94V

peak-f_T @V_{BE} = 0.94V

Size: emitter number + length scaling – CBEBC layout

$A_{Emitter}$ = NXx0. 16xEl μm²

cth = $0.34 \cdot 10^{-12} \cdot NX^{1.15} \cdot El^{1.1}$ J/K

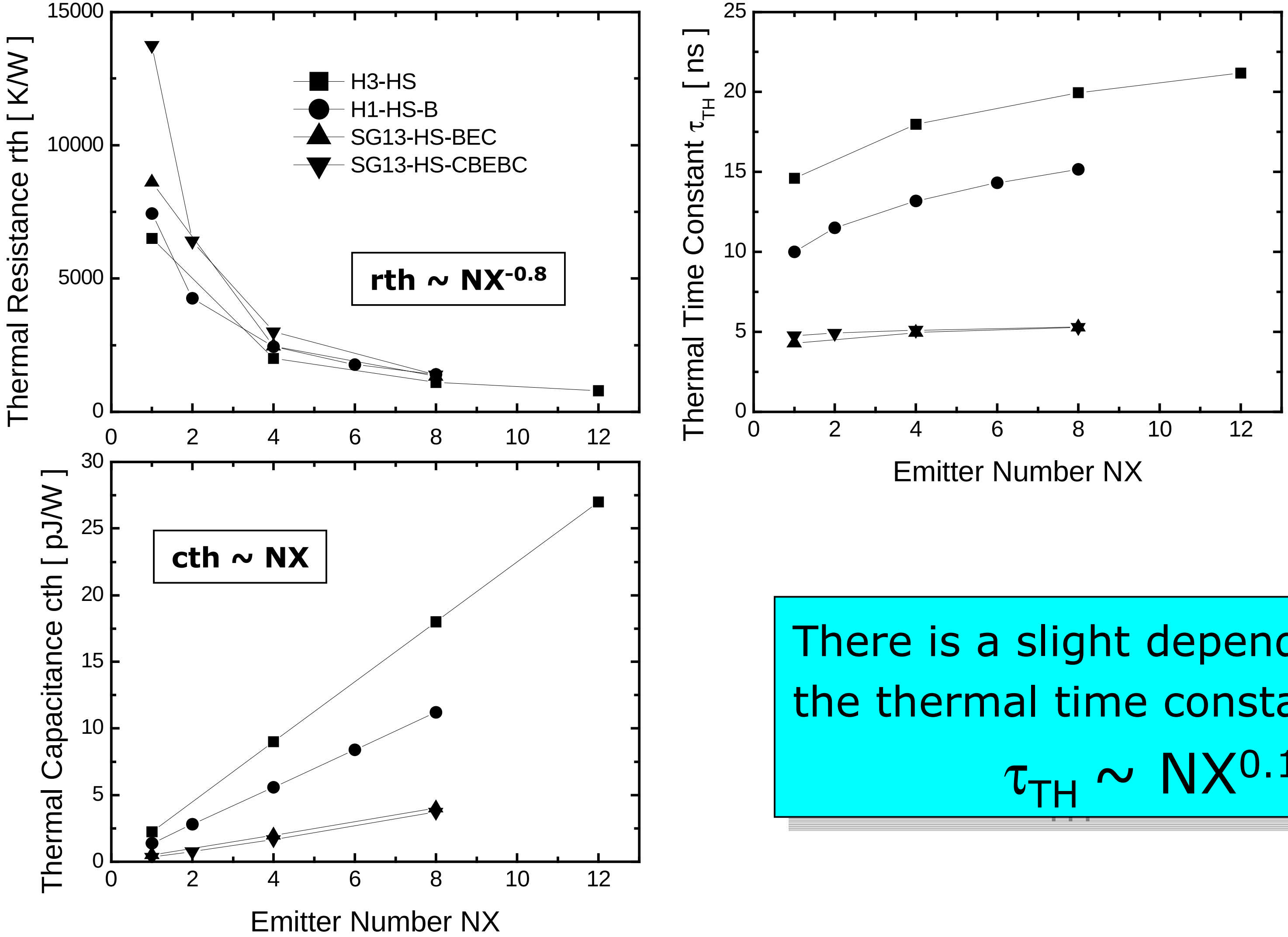
rth = $13750 \cdot NX^{-1.1} \cdot El^{-0.8}$ K/W

➔

τ_{TH} = $4.76 \cdot NX^{0.05} \cdot El^{0.3}$ ns

Fit optimization shows that thermal time constant depends weakly on NX and is mainly a function of emitter length.

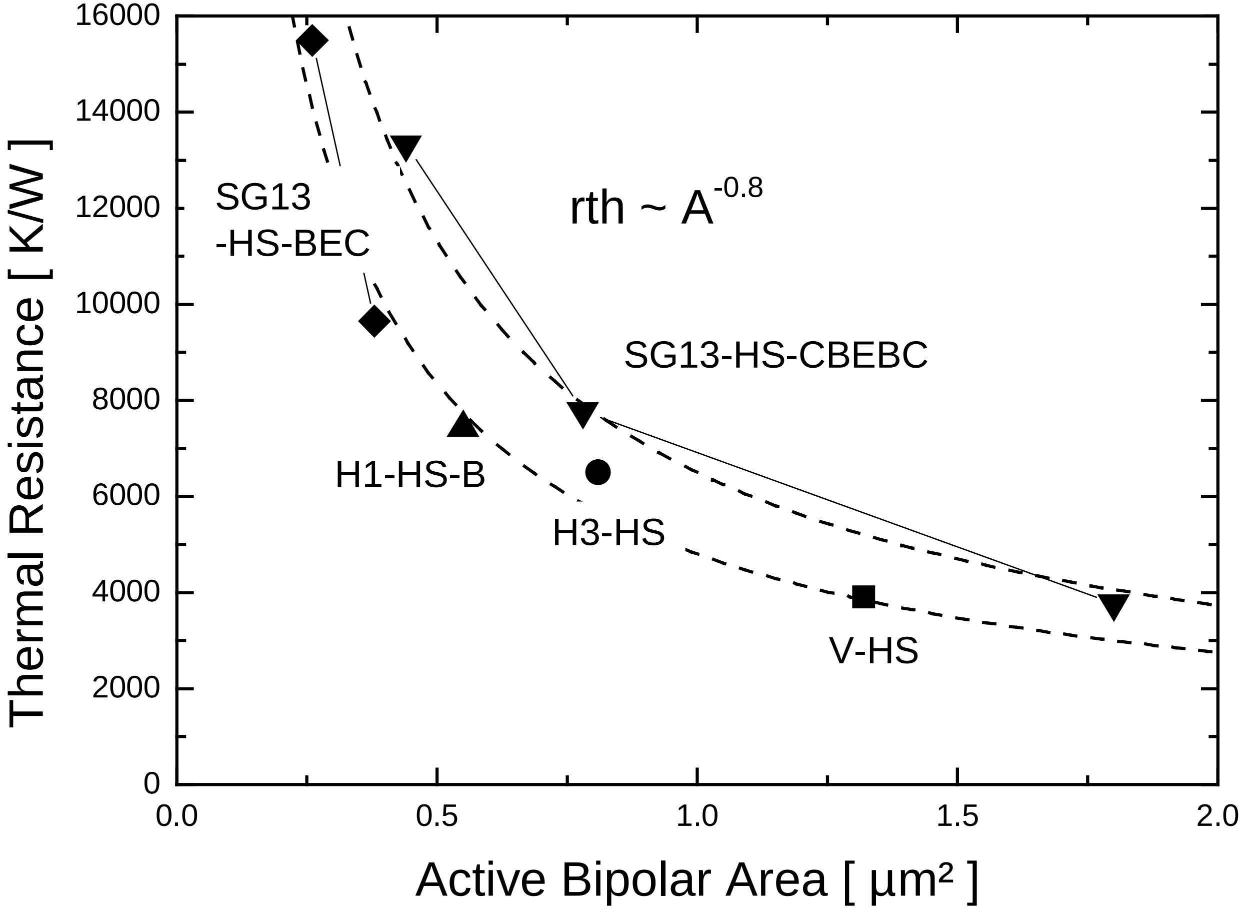
τ_{TH} as Function of Emitter Number NX



There is a slight dependence of the thermal time constant on NX:

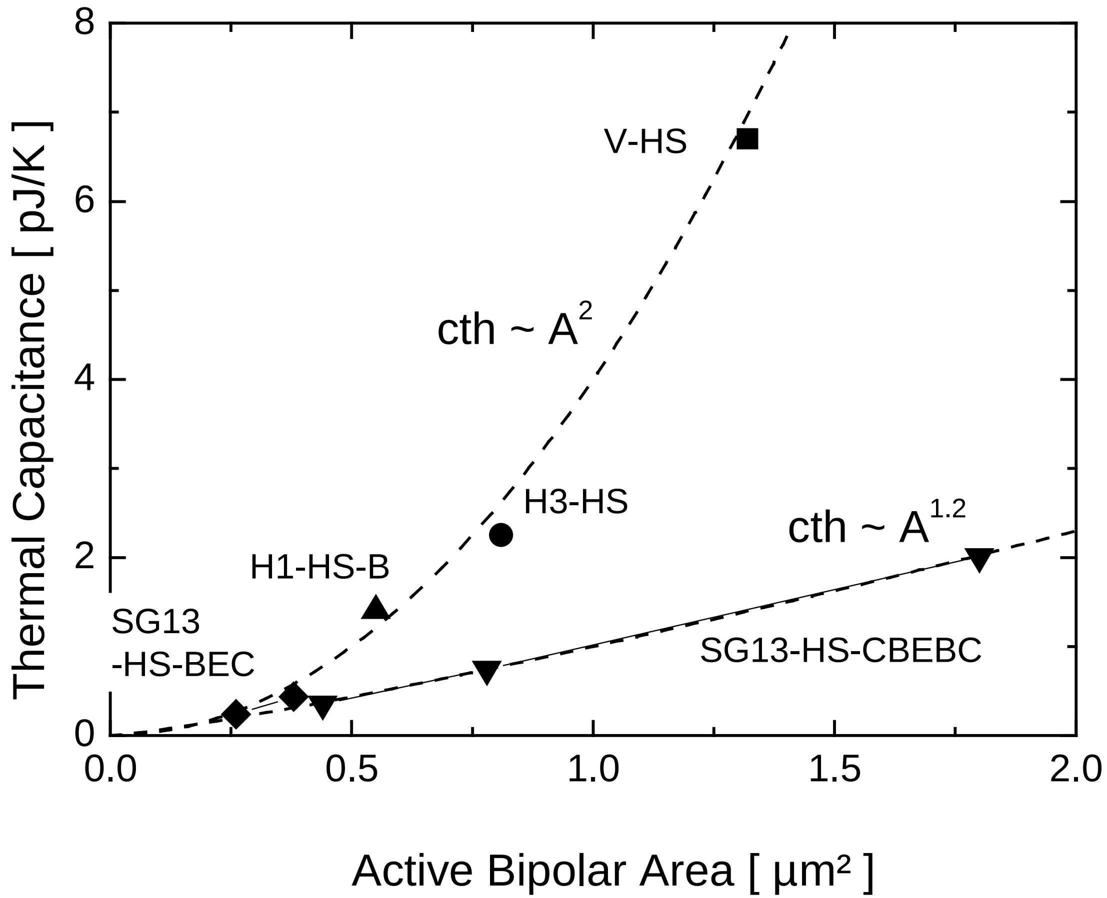
$$\tau_{TH} \sim NX^{0.1}$$

rth as Function of Active Bipolar Area



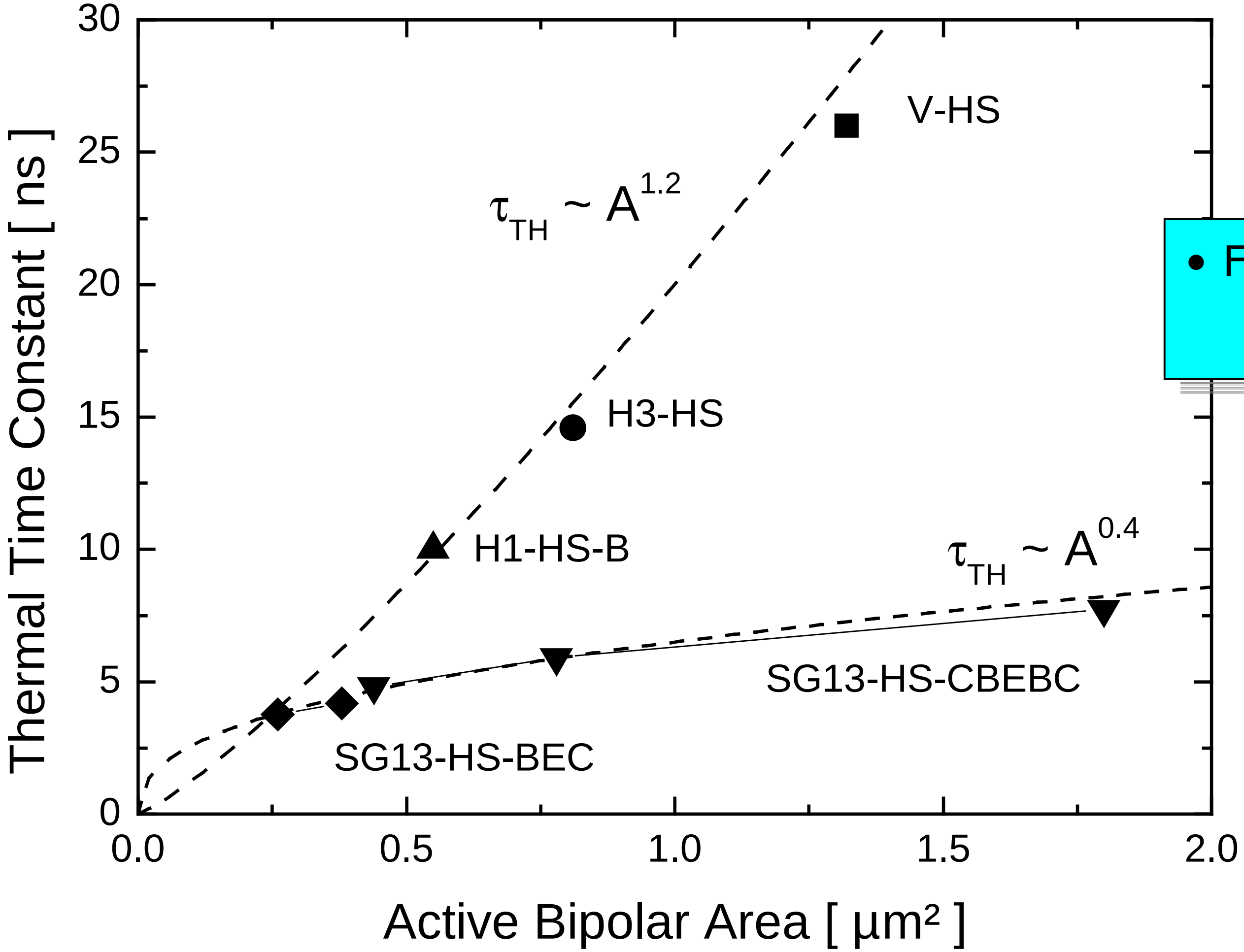
- A rth~$A^{-0.8}$ was usually assumed for IHP scaled models (like for SG13-HS-CBEBC).
- The comparison here shows that it is also valid “inter”-technology.
- The pre-factor depends on the layout type.

cth as Function of Active Bipolar Area



- Simulations of cth by a customer predicted: cth~A².
- For BEC this fits well to the current "inter"-technology results.

τ_{TH} as Function of Active Bipolar Area



- Finally, one gets for BEC

$$\tau_{TH} \sim A^{1.2}$$

Summary

- Presented a simple extraction of cth for HS-HBTs by modeling Y_{out} in the low frequency range of a standard 50 MHz - 50 GHz NWA.

- Thermal time constant is a function of active bipolar area size and scales ~ $A^{1.2}$ for BEC configuration. For CBEBC a lower rise ~ $A^{0.4}$ has been observed.