21th AKB (Bipolar ArbeitsKreis)
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HICUM L0 1.2 experience on various ST BiCMOS technologies

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OUTLINE

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- About the parameters translation
- HICUM L0 1.2 results for the ST 0.25µm SiGe-C technology
- HICUM L0 1.2 results for the ST 0.13µm SiGe-C “low-cost” technology
- HICUM L0 1.2 results for the ST 0.13µm SiGe-C MMW technology
- Conclusion
- References

MOTIVATION (1/3)

- Last HICUM WS 2008 Böblingen :

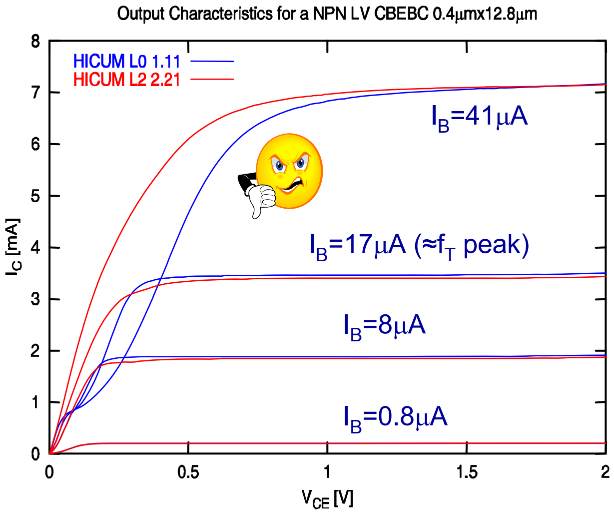
  "From HICUM level 2 to HICUM level 0", N. Derrier, STMicroelectronics [3]

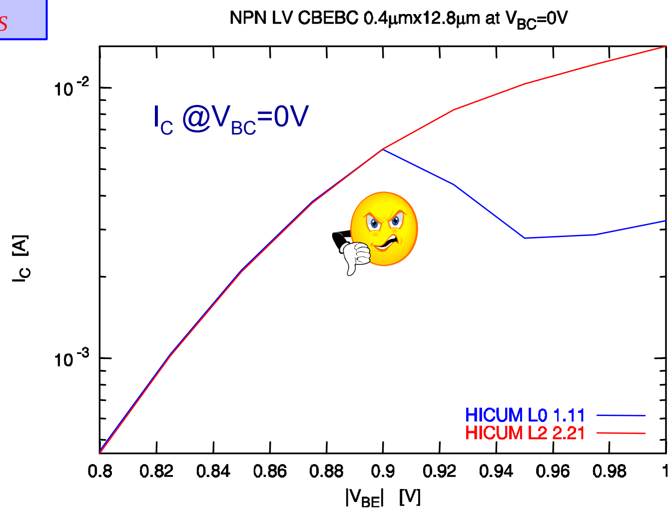
  Presentation of a complete set of equations to translate directly HICUM L2 parameters into HICUM L0 ones.

- Yes, but some HICUM L0 known issues, especially the collector current @high current density, f_T instability, unaccuracy of temperature behavior (m_{CF}) ([2],[3],[4],[6],[7])
- The direct translation of some parameters does not work, like I_{QFH}, T_{FH} etc… :

$$I_{QFH} = \frac{Q_{P0}^{*}}{\tau_{HCS}}$$

$$T_{FH} = \frac{\tau_{EF0}}{2\tau_{HCS}}$$





MOTIVATION (2/3)

- So, new HICUM L0 formulation from C. Thiele, Infineon ([2]) :

$$q_{pT} = \frac{q_j}{2} + \sqrt{\left(\frac{q_j}{2}\right)^2 + q_m}$$

$$\text{with } q_m = \frac{I_{TF}}{I_{QF}} + \frac{I_{TR}}{I_{QR}} + \frac{I_{TF}.w(I_{TF})^2}{I_{QFH}} + \left(\frac{I_{TF}{}^2}{I_{CK}}\frac{T_{FH}}{I_{QFH}}\right)^{2/3}$$

$$w = \frac{a + \sqrt{a^2 + 0.01}}{1 + \sqrt{1 + 0.01}}, \qquad a = \frac{1 - \dfrac{I_{ck}}{I_{TFi}\left(1 + AHQ\right)} q_{pT,l}}{1 + \left(q_{pT,h} - q_{pT,l}\right)\dfrac{I_{ck}}{I_{TFi}\left(1 + AHQ\right)}}$$

$$\text{with } q_j = \frac{q_{jci}}{V_{EF}} + \frac{q_{je}}{V_{ER}} + 1, \qquad V_{ER} = \frac{Q_{p0}}{h_{jei} C_{je}}$$

$$I_T = I_{TF} - I_{TR}$$

$$I_{TF} = \frac{I_{TFi}}{q_{pT}} \text{ and } I_{TR} = \frac{I_{TRi}}{q_{pT}}$$

$$\text{With the ideal forward transfer current } I_{TFi} = I_S.\exp\left(\frac{V_{B'E'}}{m_{CF} \cdot V_T}\right)$$

$$\text{With the ideal reverse transfer current } I_{TRi} = I_S.\exp\left(\frac{V_{B'C'}}{m_{CR} \cdot V_T}\right)$$

$$\text{New temperature dependence of } \mathrm{I_{QF}} : I_{QF}(T) = I_{QF}(T_0)\left(\frac{T}{T_0}\right)^{ZETAIQF}$$

VerilogA code HICUM L0 1.2

(delivered by Infineon and TU Dresden in 09/2008)

MOTIVATION (3/3)

- Previous theoretical set of equations ≈ almost **Chinese** language

- So, real simulation benchmarks on several ST technologies and devices are welcome to qualify the HL0 1.2 model…

ST techno & device	fT/fmax peak @V_{CE}=1.5V	BVCEO	β @V_{BE}=0.75V, V_{CB}=0V	Comments
NPN HS 0.25µm SiGe-C	70Ghz / 90Ghz	2.5V	255	Buried layer, DTI
NPN 0.13µm SiGe-C "low-cost"	50Ghz / 120Ghz	3.8V	300	No buried layer, no DTI
NPN HS 0.13µm SiGeC MMW	230Ghz / 250Ghz	1.5V	1000	Buried layer, DTI

About the parameters translation (1/2)

From HICUM L2

to HICUM L0 1.11/1.12

$$I_S = \frac{C_{10}}{Q_{P0}}$$

$$m_{CF} = m_{CR} = \frac{V_{BE,OP}}{V_T \ln\left(\frac{I_C\left(V_{BE,OP}\right)}{I_S}\right)}$$

$$I_{QF} = \frac{Q_{P0}{}^*}{\tau_0} \quad \text{and} \quad I_{QR} = \frac{Q_{P0}{}^*}{\tau_R}$$

$$I_{QFH} = \frac{Q_{P0}{}^*}{\tau_{HCS}}$$

$$T_{FH} = \frac{\tau_{EF0}}{2\tau_{HCS}}$$

— HL0 parameters

— HL2 parameters

— HL0 1.2 new parameters

From HICUM L2

to HICUM L0 1.2

$$I_S = \frac{C_{10}}{Q_{P0}}$$

$$\left\{ \begin{array}{l} \boldsymbol{m_{CF} = m_{CR} = 1.0} \\ V_{ER} = \dfrac{V_T}{\left(\dfrac{V_{BE,OP}}{V_T \ln\left(\frac{I_C\left(V_{BE,OP}\right)}{I_S}\right)} - 1\right)} \end{array} \right.$$

$$I_{QF} = \frac{Q_{P0}{}^*}{\tau_0} \quad \text{and} \quad I_{QR} = \frac{Q_{P0}{}^*}{\tau_R}$$

$$I_{QFH} = \frac{Q_{P0}{}^*}{\tau_{HCS}}$$

$$T_{FH} = \frac{\tau_{EF0}}{2\tau_{HCS}}$$

$ZETA_{IQF}$ = extracted with temperature measurements

AHQ = extracted at high current

About the parameters translation (2/2)

$$q_m = \frac{I_{TF}}{I_{QF}} + \frac{I_{TR}}{I_{QR}} + \frac{I_{TF}.w(I_{TF})^2}{I_{QFH}} + \left(\frac{I_{TF}{}^2}{I_{CK}} \frac{T_{FH}}{I_{QFH}} \right)^{2/3}$$

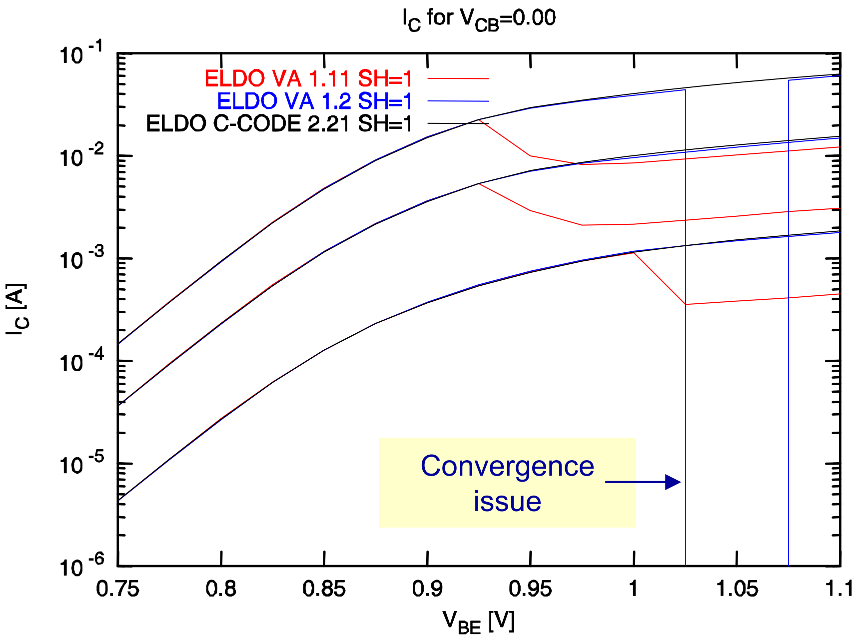
In the verilogA code :

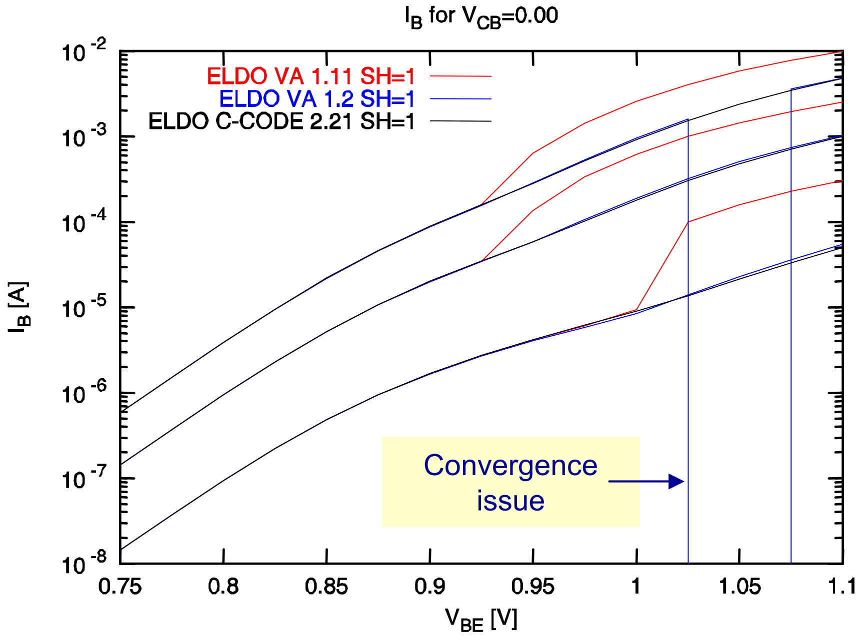
$$\left(\frac{I_{TF}{}^2}{I_{CK}} \frac{T_{FH}}{I_{QFH}} \right)^{2/3} = e^{\frac{2}{3}\ln\left(\frac{I_{TF}{}^2}{I_{CK}} \frac{T_{FH}}{I_{QFH}} \right)}$$

- Since HL0 v1.12 : T_{FH}=[0;INF)
- If T_{FH}=0 : BUG (Ln(0))
- To be corrected…

1st technology : NPN HS 0.25µm SiGe-C
Gummel plot (1/4)

- Mentor ELDO 2008.1 simulations for 3 geometries : CBEBC 0.4x0.8µm², 0.4x6.4µm², 0.4x25.6µm² (drawn dimensions)
- VerilogA codes compiled with VLAC
- Self-heating activated

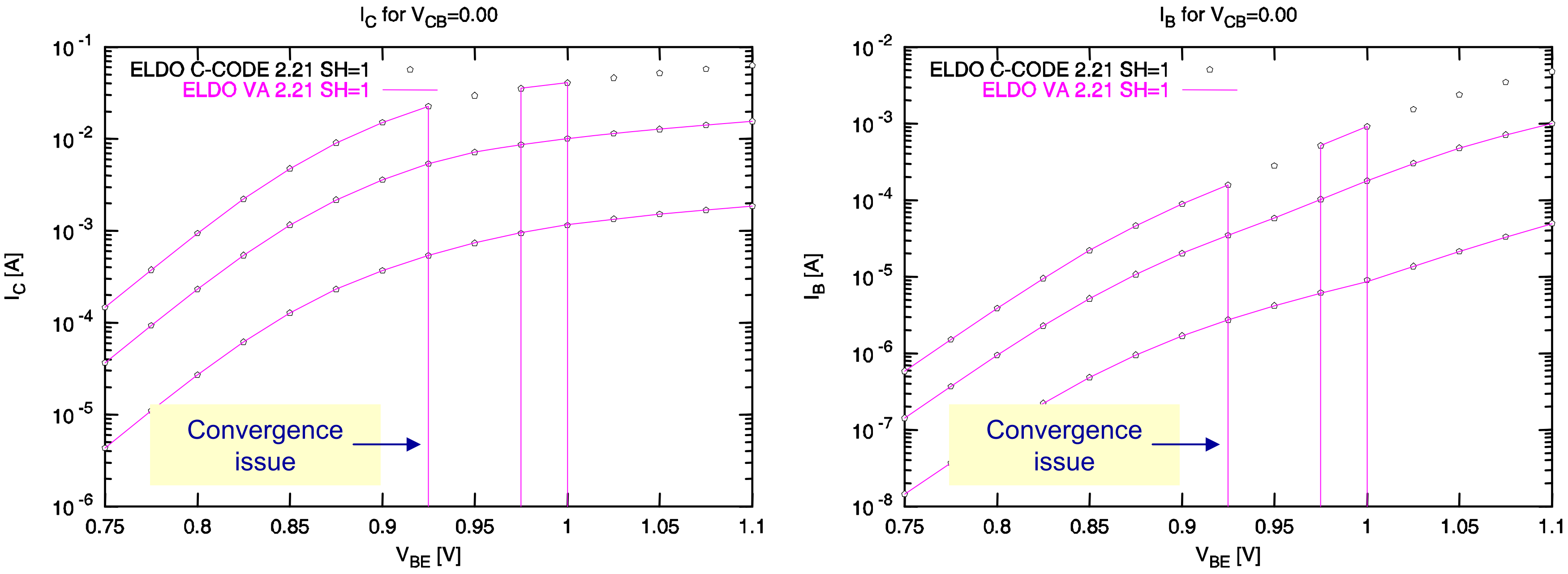




- No convergence for VerilogA simulation HL0 1.2 @ very high current…
- Problem of HL0 1.2 VerilogA code or simulator compiler ?

1^{st} technology : NPN HS 0.25µm SiGe-C
Gummel plot (2/4)

- Same simulated characteristic but : HL2 2.21 VA versus ELDO C-CODE

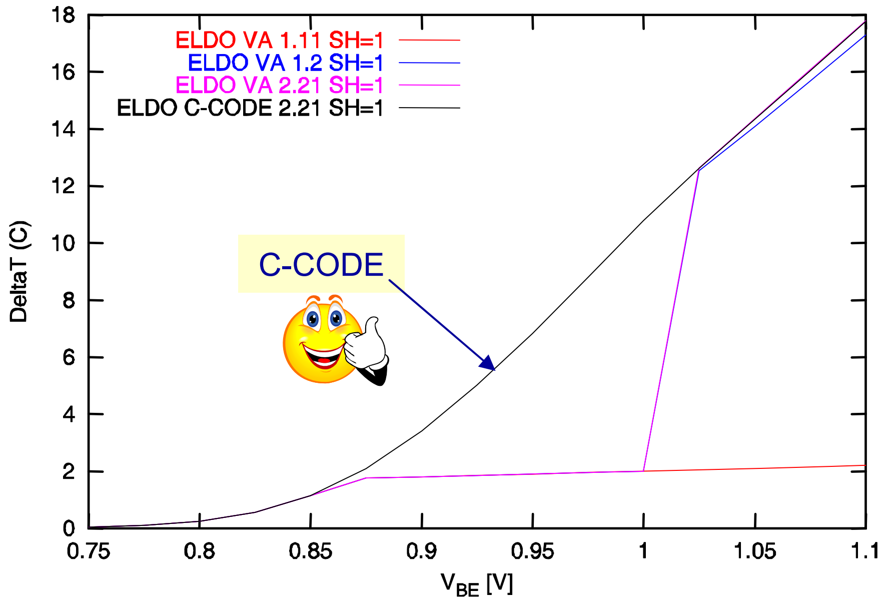


- No convergence neither for HL2 VA simulation @ very high current
- OK with C-CODE implementation
- So, not a problem specific to HL0 1.2 VA equations…

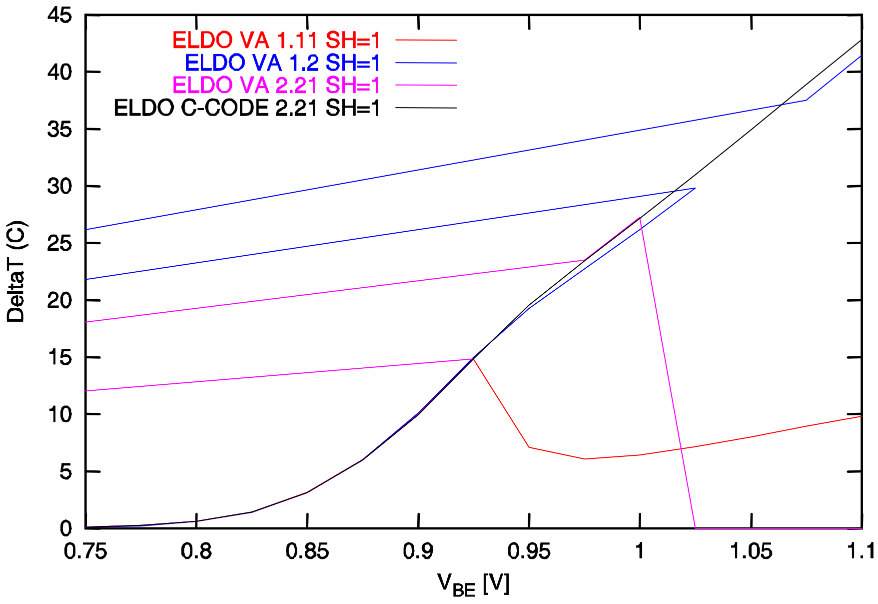
- Problem @ high current = coming from SH/temperature computation ?

1st technology : NPN HS 0.25µm SiGe-C
Gummel plot (3/4)

- Now, looking at the temperature computation, using the thermal node, for 2 devices geometries (the smallest one and the largest one).
- Comparing all HICUM releases VA codes versus the HL2 2.21 ELDO C-CODE.



Temperature increase with self-heating activated for a NPN CBEBC 0.4x0.8um



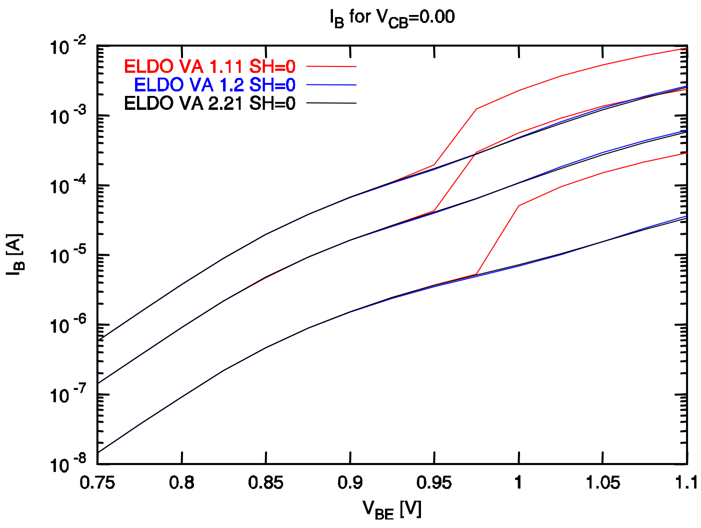
Temperature increase with self-heating activated for a NPN CBEBC 0.4x25.6um

- instability of all VA simulations : confirmation the problem is coming from SH/temperature computation.
- Cause : VA SH equations instability ? Mentor ELDO compiler and VA interpretation?

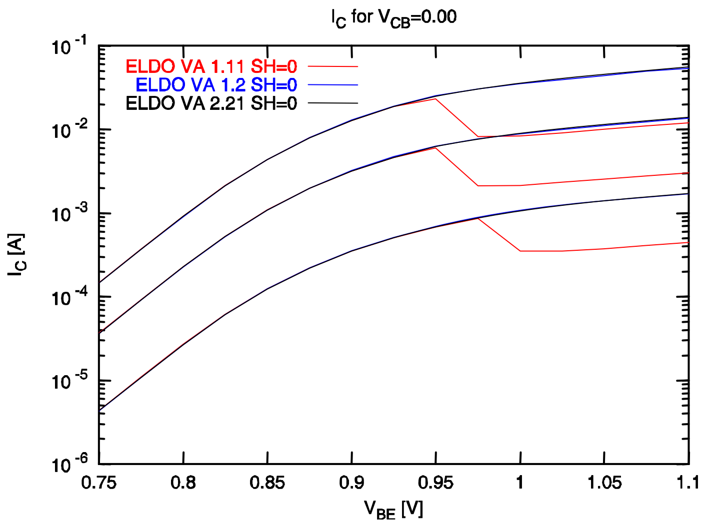
- For all following tests & simulations : NO SH.

1st technology : NPN HS 0.25µm SiGe-C
Gummel plot (4/4)

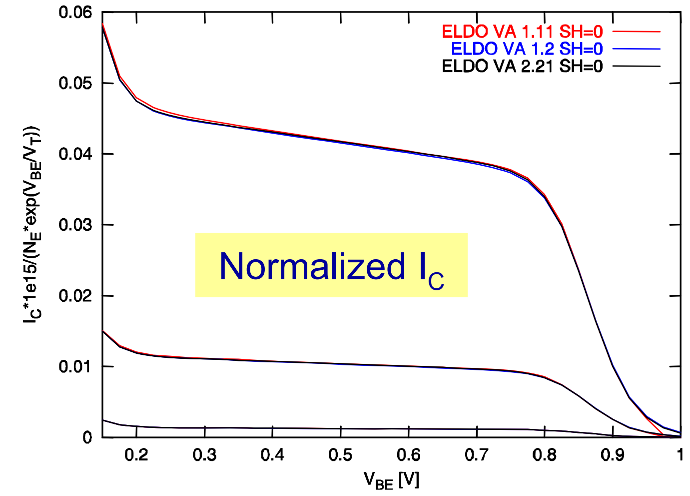
- Same simulations as slide #8 without SH.
- HL0 1.2 OK (I_C negative slope corrected at high current densities)



I_B for V_{CB}=0.00



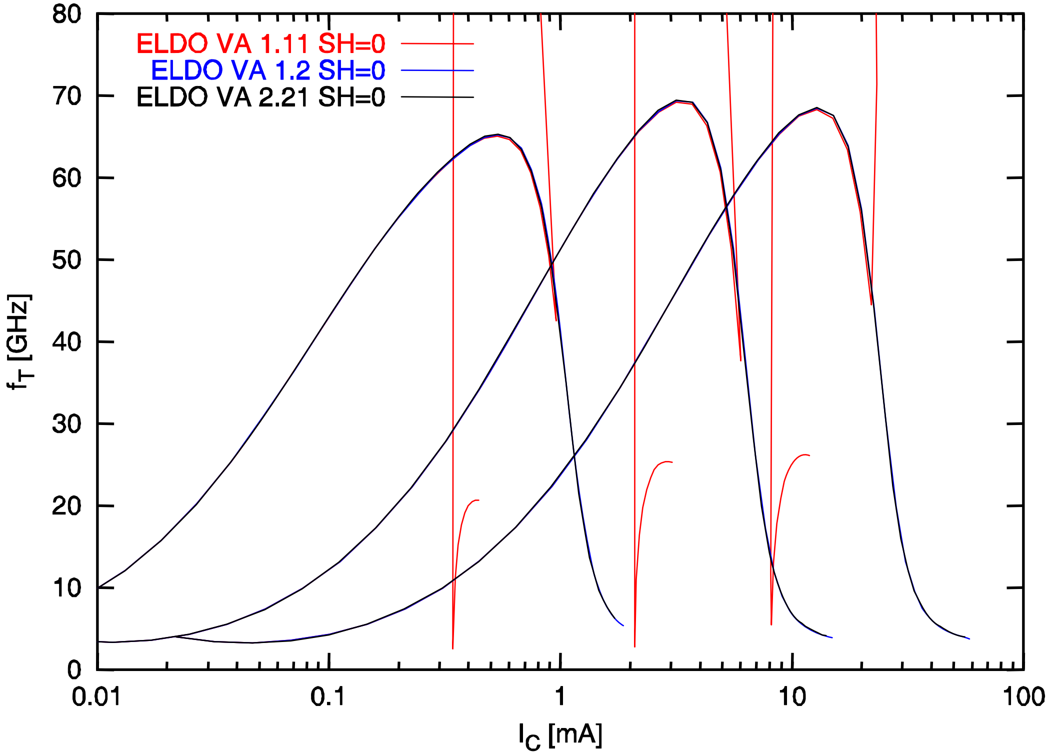
I_C for V_{CB}=0.00



Normalized I_C

1^{st} technology : NPN HS 0.25µm SiGe-C
f_T vs I_C characteristic @V_{BC}=0V (1/1)

- Mentor ELDO 2008.1 simulations for 3 geometries : CBEBC 0.4x0.8µm², 0.4x6.4µm², 0.4x25.6µm² (drawn dimensions)
- HL0 1.2 OK (no more f_T instability at high current densities)



1st technology : NPN HS 0.25µm SiGe-C
Temperature behavior (1/1)

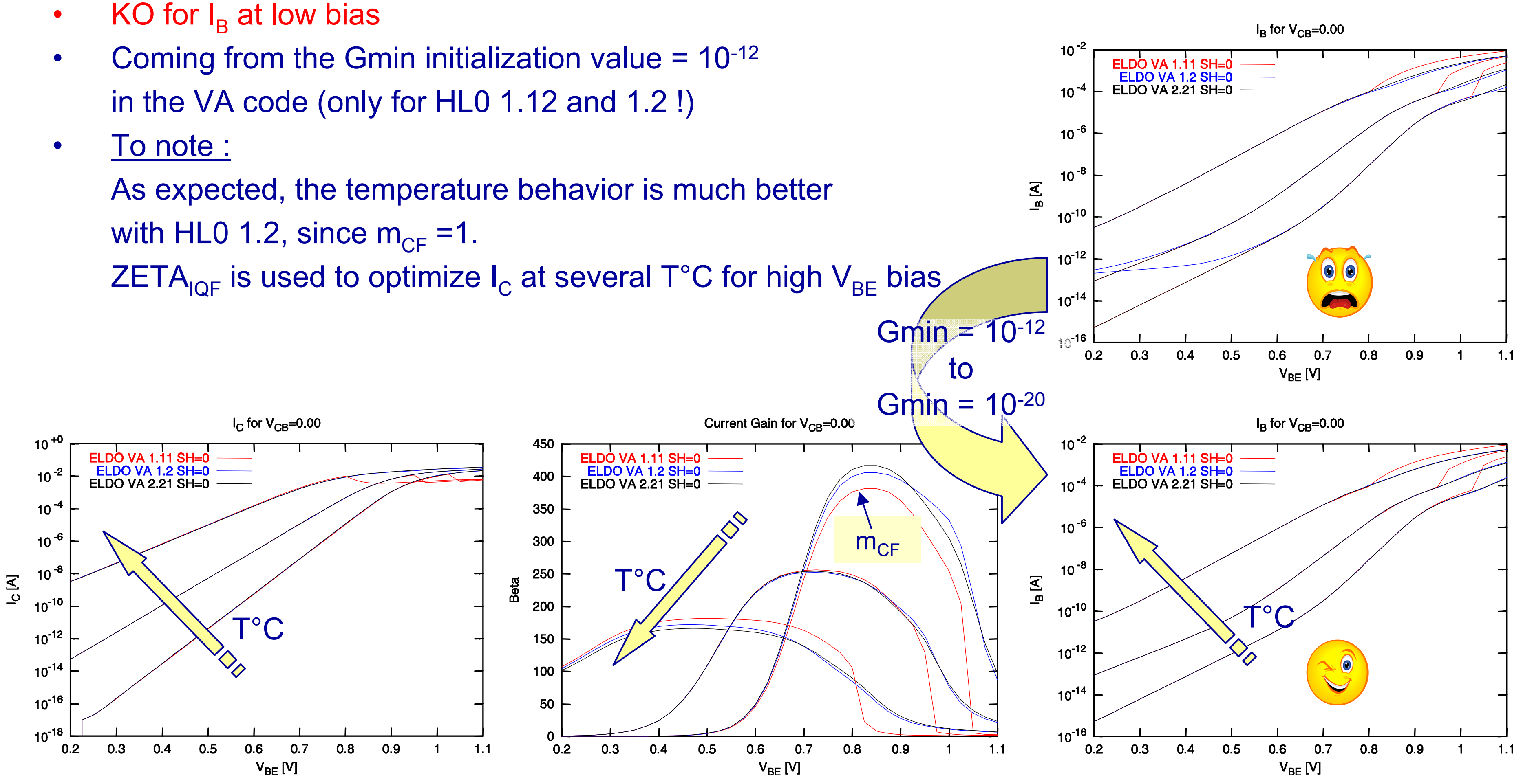
- Mentor ELDO 2008.1 simulations for 1 geometry CBEBC 0.4x12.8µm^2 (drawn dimensions) @ 3 temperatures -40°C, +27°C, +150°C
- OK for I_C, β
- KO for I_B at low bias
- Coming from the Gmin initialization value = 10^{-12}

  in the VA code (only for HL0 1.12 and 1.2 !)
- To note :

  As expected, the temperature behavior is much better

  with HL0 1.2, since m_{CF} =1.

  $ZETA_{IQF}$ is used to optimize I_C at several T°C for high V_{BE} bias



1^{st} technology : NPN HS 0.25µm SiGe-C
Output characteristic I_C vs V_{CE} (1/1)

- Mentor ELDO 2008.1 simulations for 1 geometry CBEBC 0.4x12.8µm², I_C vs V_{CE} @ several constant I_B
- HL0 1.2 OK (I_C negative slope corrected)
- To note : no convergence for HL2 VA simulation at high I_B (after the f_T peak)

Numerical application

for a NPN CBEBC 0.4µmx12.8µm :

I_S = 2.47.10^{-17} A

m_{CF} = 1.0 for HL0 1.2 (= 1.00936 for HL0 1.11)

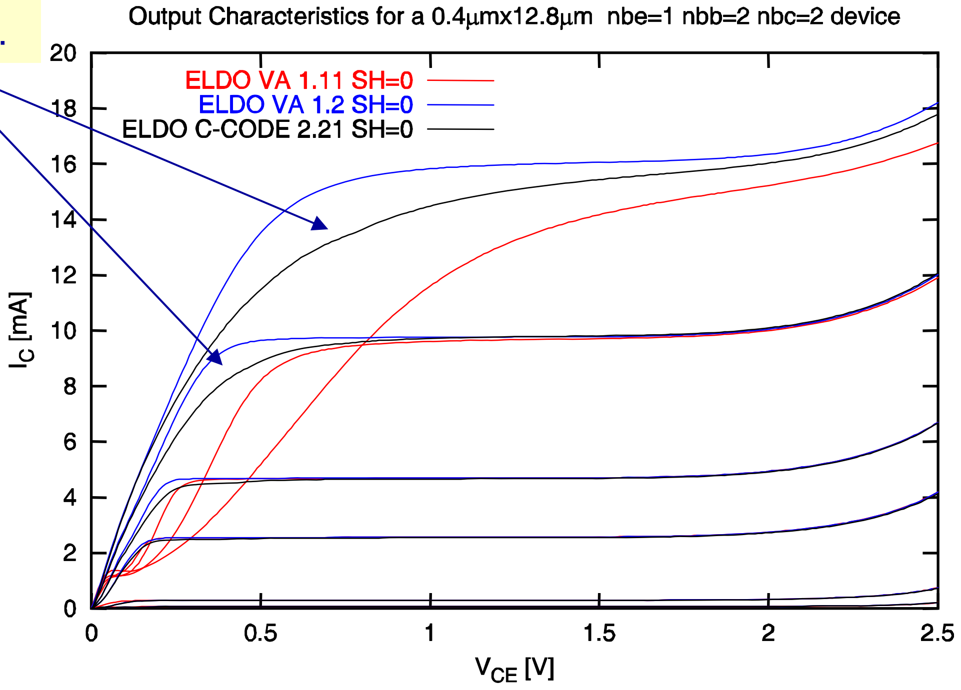
V_{ER} = 2.99V

$ZETA_{IQF}$ = -3 (optimized with T°C meas.)

AHQ = 0.5 (optimized with I_C at high current)

I_{QFH} = 6.577.10^{-4} A (not optimized)

T_{FH} = 10^{-6} (not optimized)

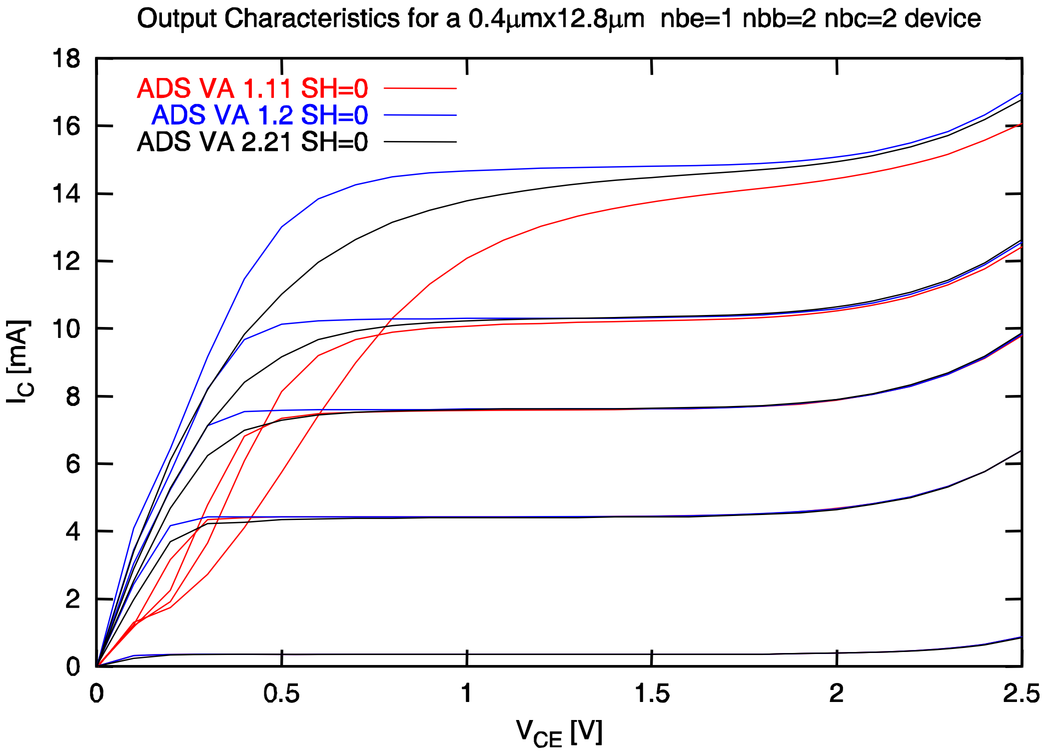


I_{QFH},T_{FH} to be optimized here…

1^{st} technology : NPN HS 0.25μm SiGe-C
And with another EDA simulator ?

- Agilent ADS 2008.U1 simulations for 1 geometry CBEBC 0.4x12.8μm² @ several constant I_B
- VA codes compiled on the fly with Tiburon
- HL0 1.2 OK (I_C negative slope corrected)
- <u>To note :</u>

  Contrary to Eldo, with ADS, the HL2 VA simulation of I_C vs V_{CE} converges at high I_B (after the f_T peak)
- Hypothesis of Eldo no convergence : problem of VA compilation (Tiburon better ?)



2^{nd} technology : NPN low-cost 0.13µm SiGe-C
Gummel plot (1/2)

- Mentor ELDO 2008.1 simulations for 3 geometries : CBEBC 0.3x2µm², 0.3x10µm², 0.3x25µm²
- VerilogA codes compiled with VLAC
- Self-heating activated
- All VA simulations converge !
- HL0 1.2 OK

Numerical application for a NPN CBEBC 0.3µmx10µm :

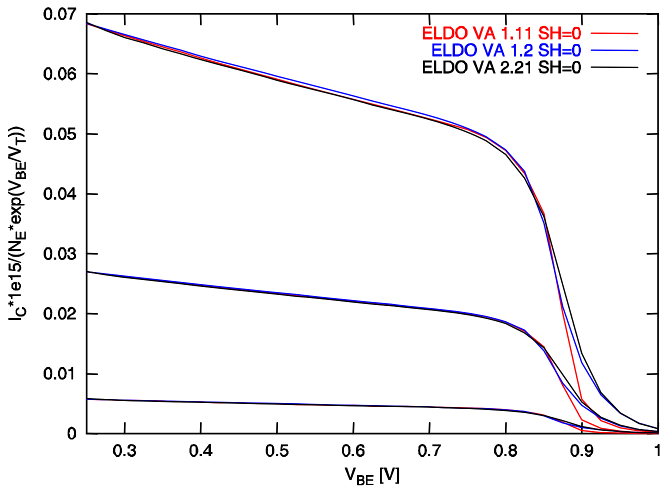
I_S = 3.11.10^{-17} A V_{ER} = 1.66V

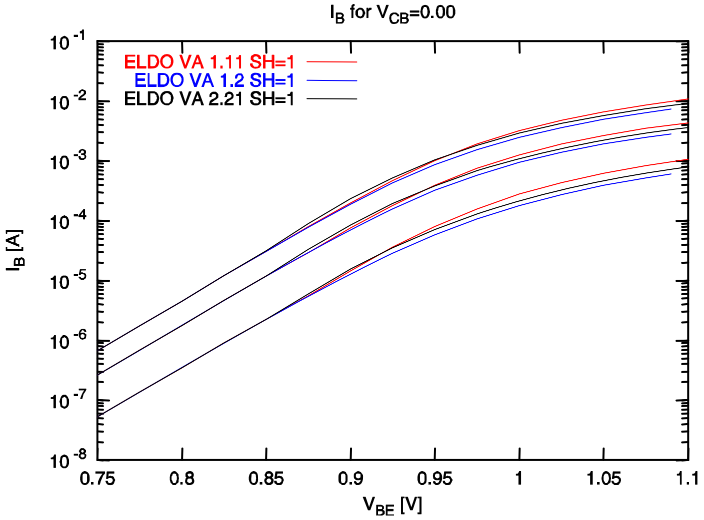
m_{CF} = 1.0 for HL0 1.2 (= 1.016 for HL0 1.11)

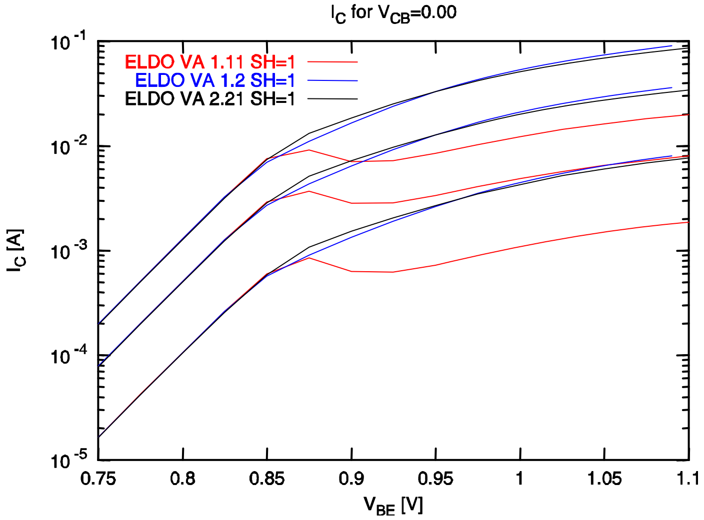
$ZETA_{IQF}$ = -1 (optimized with T°C meas.)

AHQ = 1.5 (optimized with I_C at high current)

I_{QFH} = 1.15.10^{-3} A / T_{FH} = 10^{-6} (not optimized)



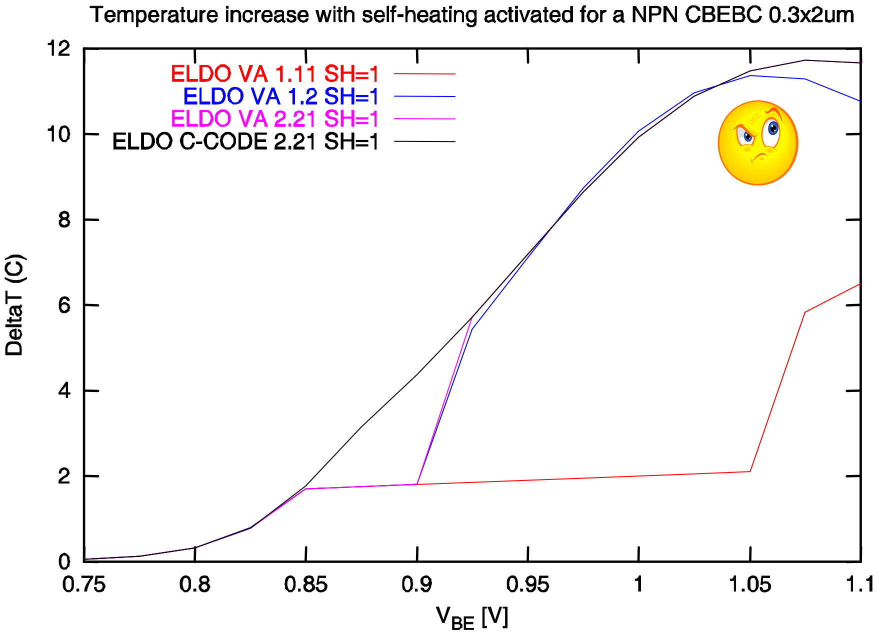

I_B for V_{CB}=0.00

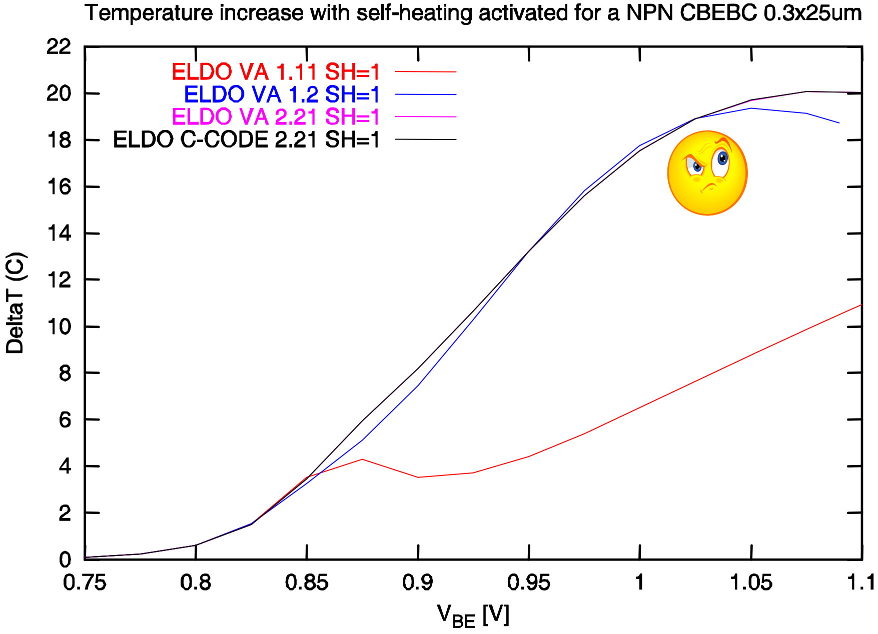

I_C for V_{CB}=0.00

2nd technology : NPN low-cost 0.13µm SiGe-C
Gummel plot (2/2)

- Now, looking at the temperature computation, using the thermal node, for 2 devices geometries (the smallest one and the largest one).
- Comparing all HICUM VA codes with the HL2 2.21 ELDO C-CODE.

- As a link with the good convergence in the previous slide, there's almost no instability here in the thermal node plots.
- <u>To note :</u> the temperature discontinuity of the small device simulation, not visible on the Gummel plot in log scale…

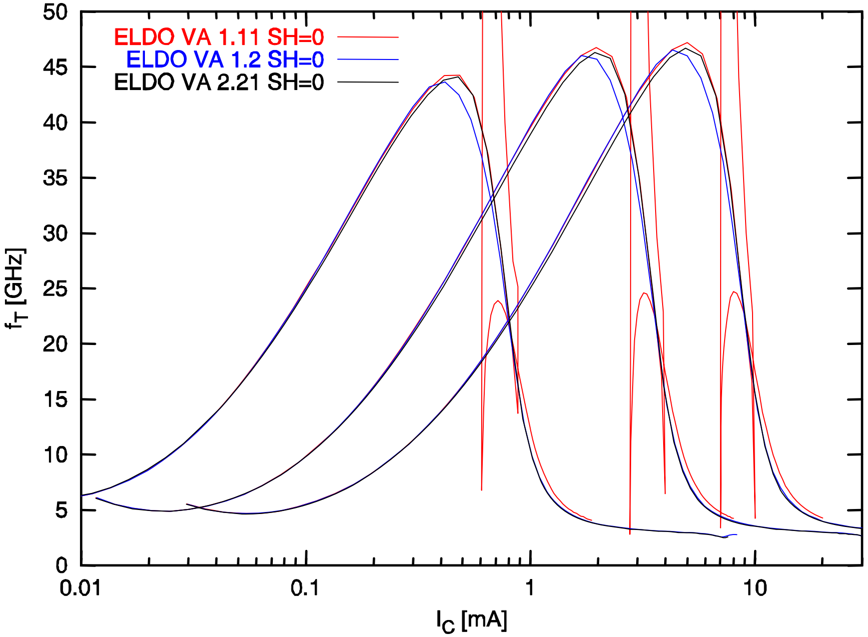


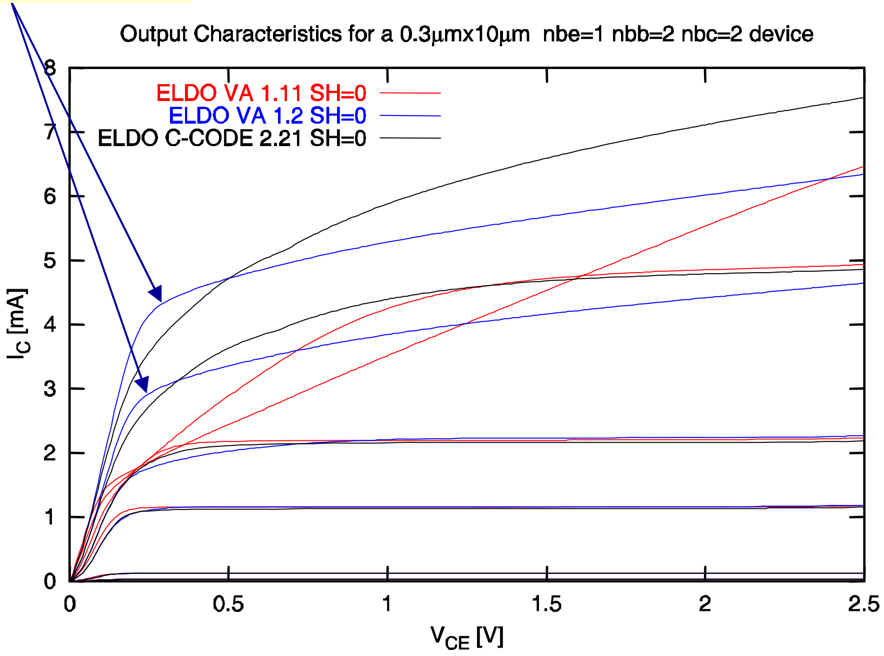


2^{nd} technology : NPN low-cost 0.13µm SiGe-C (f_T vs I_C) and (I_C vs V_{CE}) characteristics (1/1)

- Mentor ELDO 2008.1 simulations
- f_T vs I_C : 3 geometries CBEBC 0.3x2µm², 0.3x10µm², 0.3x25µm²
- I_C vs V_{CE} : 1 geometry CBEBC 0.3x10µm²
- To note : no convergence for HL2 VA simulation at high I_B (after the f_T peak)
- HL0 1.2 OK (no more f_T instability at high current densities and I_C negative slope)

I_{QFH},T_{FH} to be optimized here…



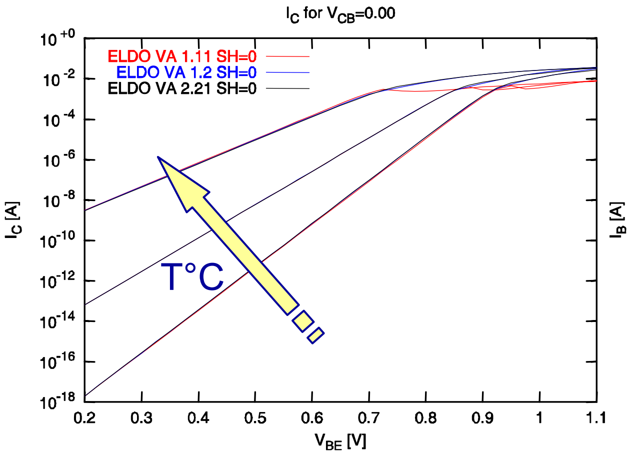


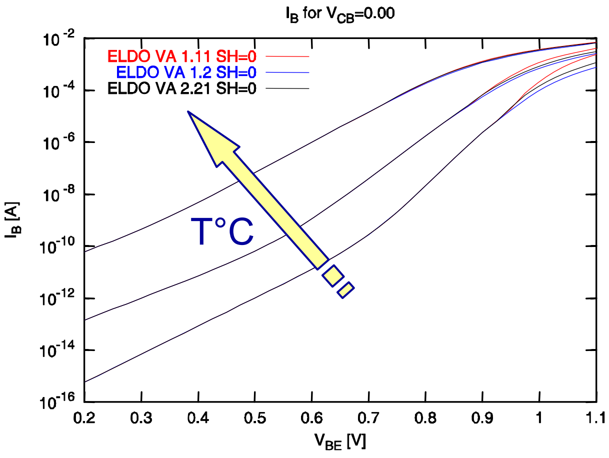
2nd technology : NPN low-cost 0.13µm SiGe-C
Temperature behavior (1/1)

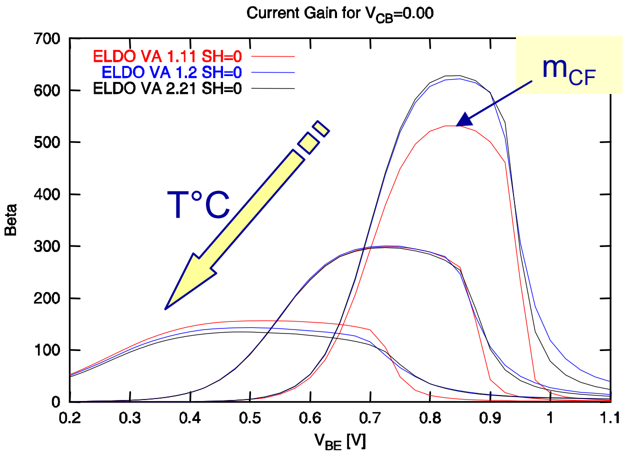
- Mentor ELDO 2008.1 simulations for 1 geometry CBEBC 0.3x10µm^2 @ 3 temperatures -40°C, +27°C, +150°C
- OK for I_C, β, I_B
- To note :

  As expected, the temperature behavior is much better with HL0 1.2, since m_{CF} =1.

  $ZETA_{IQF}$ is used to optimize I_C at several T°C for high V_{BE} bias

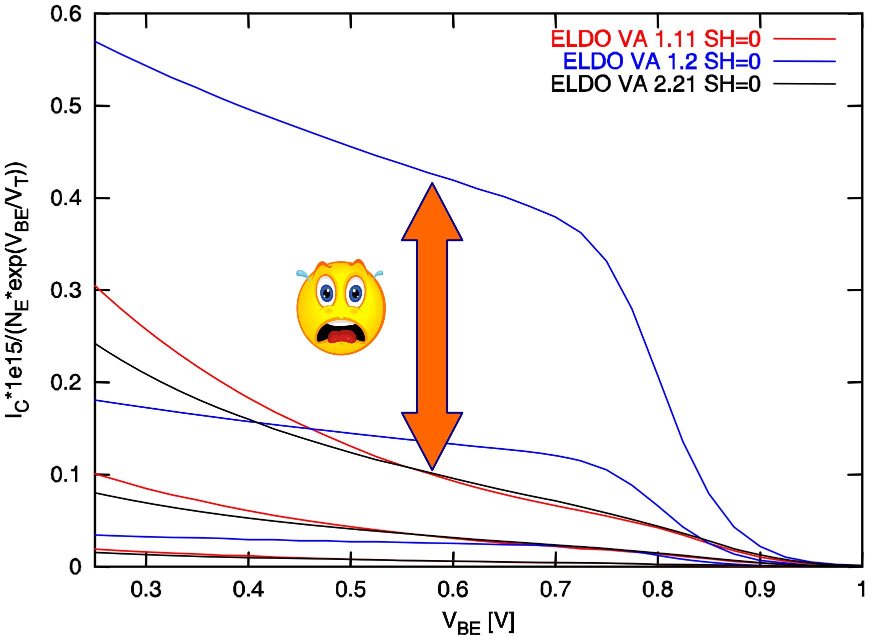

I_C for V_{CB}=0.00


I_B for V_{CB}=0.00


Current Gain for V_{CB}=0.00

3rd technology : NPN HS 0.13µm SiGe-C MMW
Gummel plot (1/3)

- Mentor ELDO 2008.1 simulations for 3 geometries : CBEBC 0.27x1µm², 0.27x5µm², 0.27x15µm²
- For the ST MMW technology, the Ge profile induces a non negligible bias dependence of the BE weight factor h_{jEi}
- To model this technology behavior with HL2, we adjusted the partition of the BE depletion charge (internal vs external)
- With HL0 1.11, there's no problem since reverse Early Effect does not use the BE charge
- With HL0 1.2, reverse Early Effect uses the BE charge without any possible partitioning
- Therefore, the HL0 1.2 direct translation does not work anymore



Numerical application

for a NPN CBEBC 0.27µmx5µm :

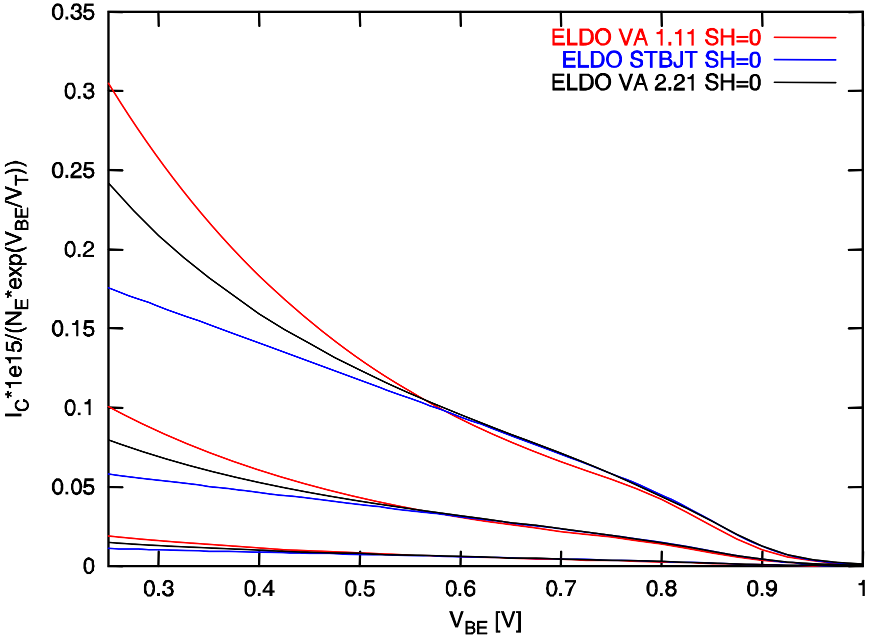
C_{10} = 5.82 10^{-32} A.C
Q_{P0} = 2.47 10^{-16} C
m_{CF} = 1.0
HL2 2.21

I_S = 2.35 10^{-16} A (=C_{10}/Q_{P0})
m_{CF} = 1.0967
HL0 1.11

I_S = 2.35 10^{-16} A (=C_{10}/Q_{P0})
V_{ER} = 0.84V
m_{CF} = 1.0
HL0 1.2

3^{rd} technology : NPN HS 0.13μm SiGe-C MMW
Gummel plot (2/3)

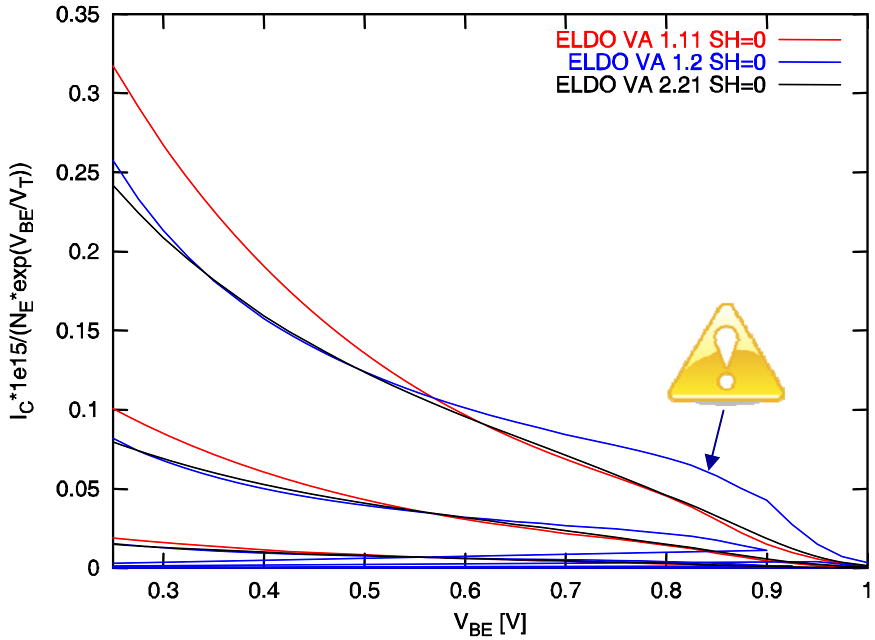
- For such a technology model, even the SGP formulation is more suitable than HL0 1.2 (see STBJT simulation below – with I_S=2.35 10^{-16} A and V_{ER}=0.84V)
- Same observations as in BIPAK 2008 D. Celi's presentation [1]



3rd technology : NPN HS 0.13μm SiGe-C MMW
Gummel plot (3/3)

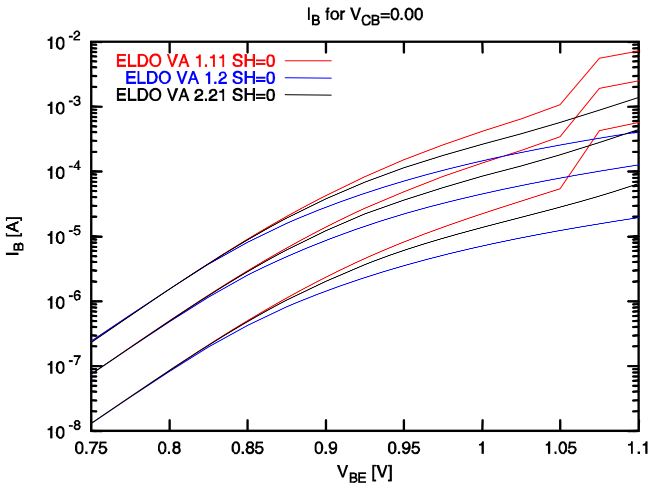
- Of course, some HL0 1.2 “tuning” parameters could be found to better fit the characteristic, but NOT physical

  I_S=1.2 10^{-13} A V_{ER}=1.74 10^{-4} V
- However, we keep these unphysical parameters to finish the benchmark of the HL0 1.2 on this technology…

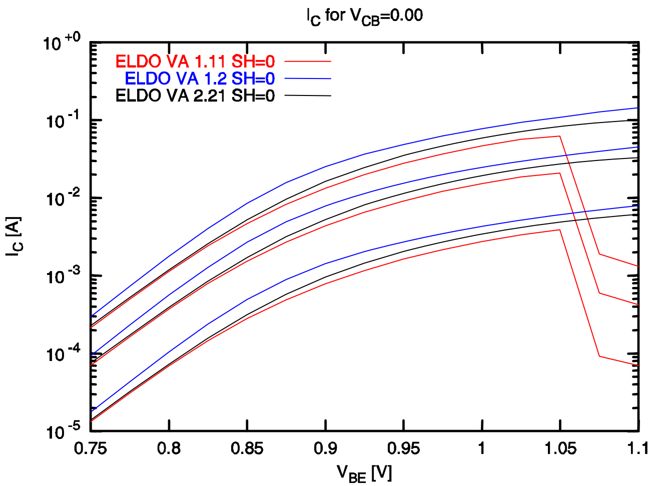


3^{rd} technology : NPN HS 0.13µm SiGe-C MMW
Gummel plot (3/3)

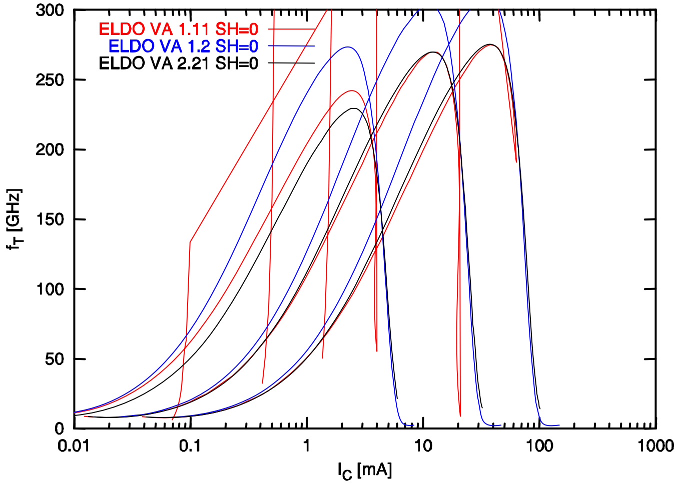
- In any case, even on this technology, the negative slope of the collector current at high current densities is corrected
- The f_T instability at high current densities is corrected too



I_B for V_{CB}=0.00

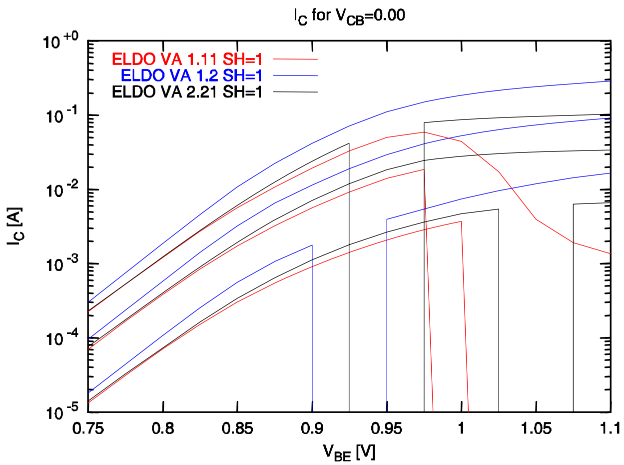


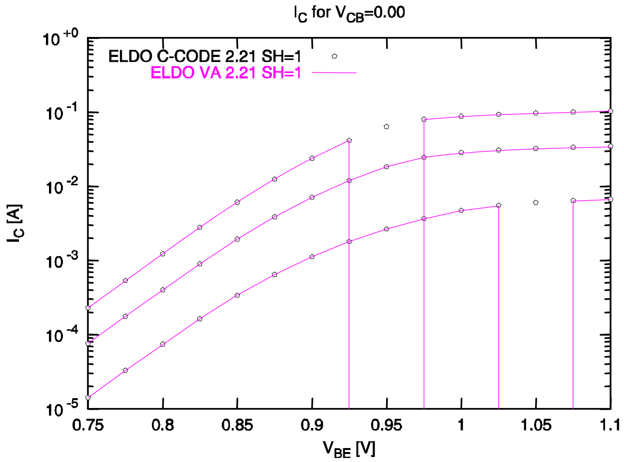
I_C for V_{CB}=0.00

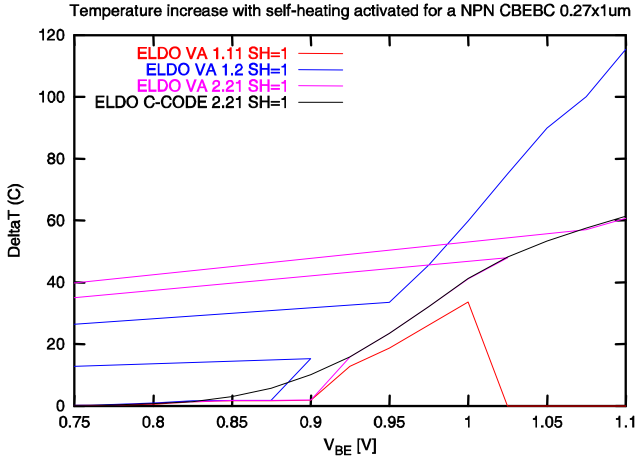


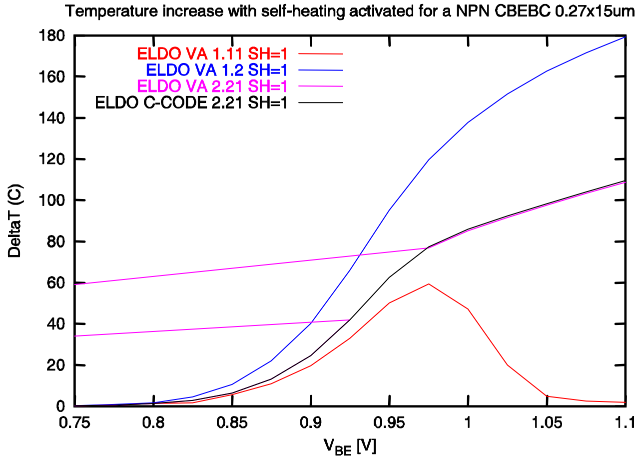
3^{rd} technology : NPN HS 0.13µm SiGe-C MMW
Self-heating activated (1/1)

- With SH=1, instability of all VA simulations once again
- Now, looking at the temperature computation, using the thermal node, for 2 devices geometries (the smallest one and the largest one).
- Comparing all HICUM VA codes with the HL2 2.21 ELDO C-CODE.


I_C for V_{CB}=0.00

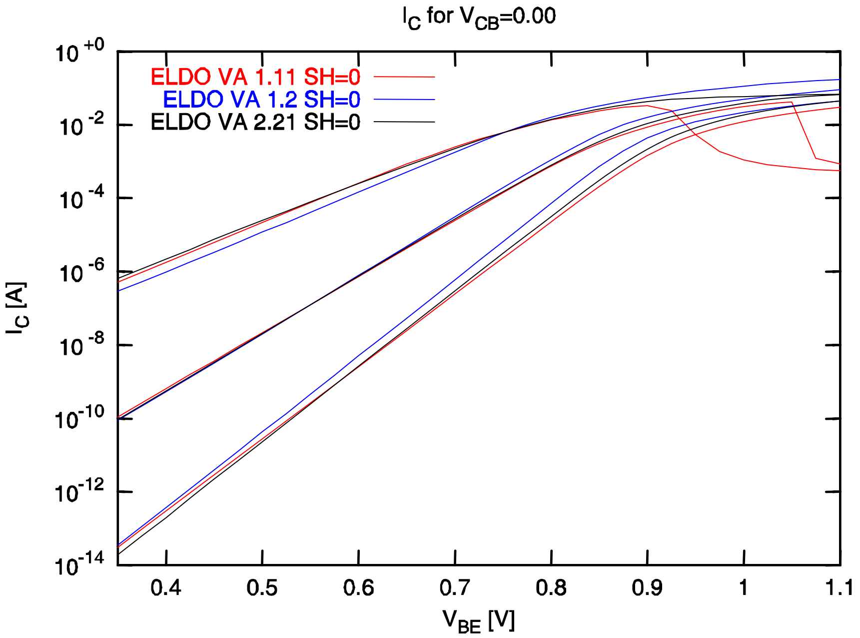

I_C for V_{CB}=0.00

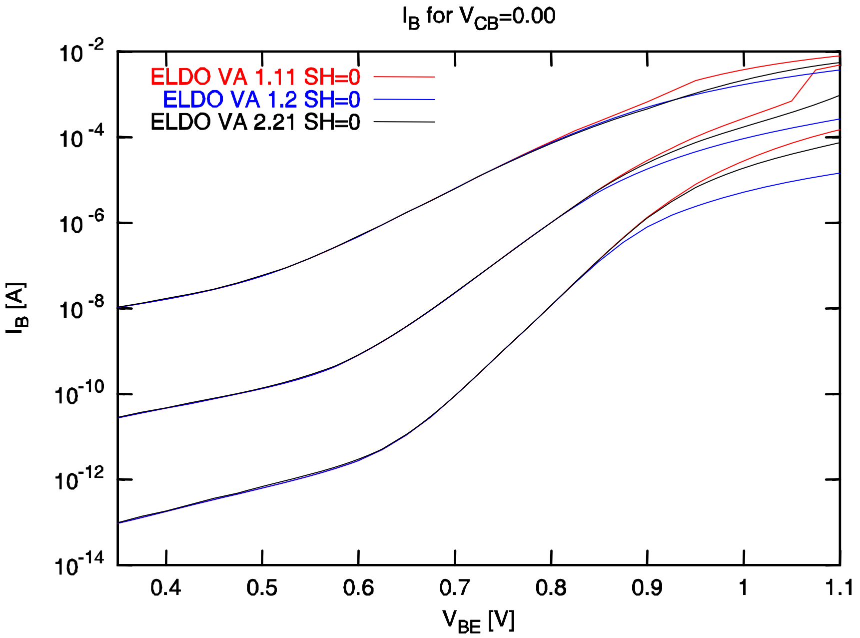

Temperature increase with self-heating activated for a NPN CBEBC 0.27x1um


Temperature increase with self-heating activated for a NPN CBEBC 0.27x15um

3rd technology : NPN HS 0.13µm SiGe-C MMW
Temperature behavior (1/1)

- Mentor ELDO 2008.1 simulations for 1 geometry CBEBC 0.27x10µm² @ 3 temperatures -40°C, +27°C, +150°C
- No negative slope or simulation instability when varying the temperature





CONCLUSION

- A practical validation of the new release v1.2 of HICUM L0 has been done using 3 representative ST BiCMOS technologies.
- We compared different HICUM releases (L0 1.2, L0 1.11, L2 2.21), using VA codes and internal C-codes, mainly with Mentor ELDO (with Agilent ADS too for some characteristics).
- We extracted/optimized the HL0 v1.2 parameters (T_{FH}, I_{QFH}, A_{HQ}, $ZETA_{IQF}$) with success.

- HICUM L0 1.2 shows very good results, whatever the technology and the device geometry, and it eliminates the known issues of releases 1.11/1.12 :
  - No more negative slope of the collector current in

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