HICUM Level 0 temperature modeling: towards improvement

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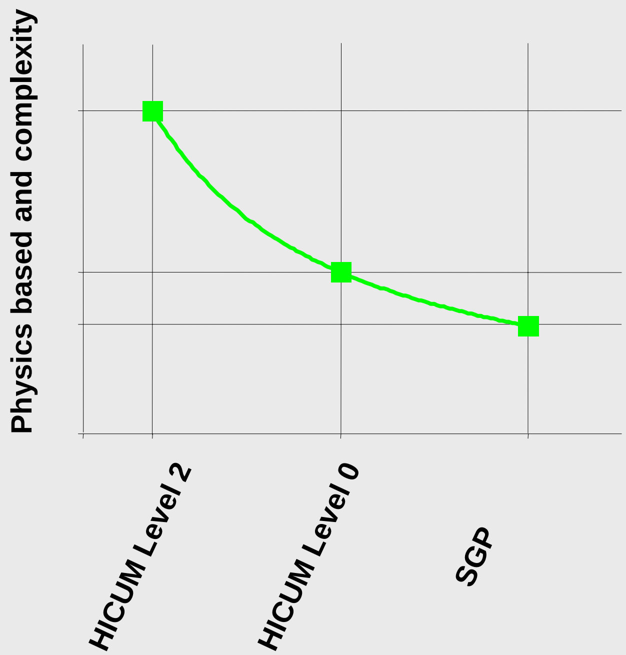
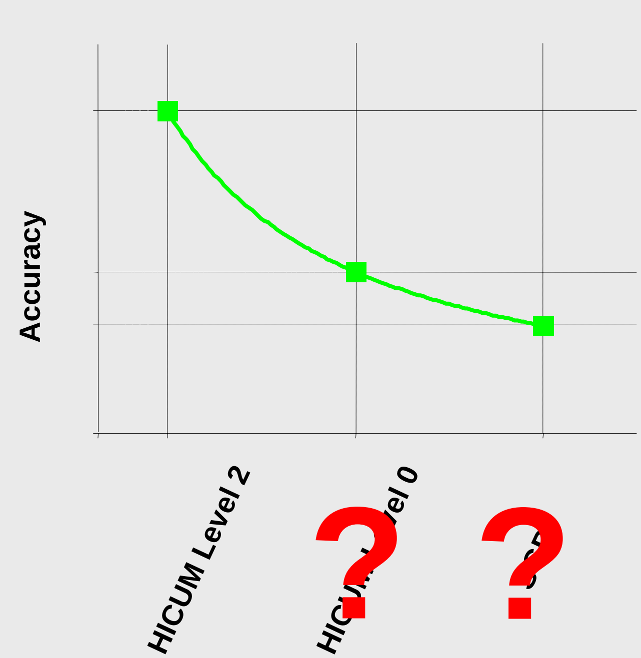
Motivation





[1] D. Céli, “About Modeling the Reverse Early Effect in HICUM Level 0”, 6th European HICUM Workshop, June 12-13, 2006, Heilbronn

Outline

- Motivation
- Early effect
    - Weak point
    - Solution
- Breakdown
    - Weak point
    - Solution
- Conclusion

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Early effect modeling in HICUM Level 0

HICUM Level 2

$$I_C(T) \approx \frac{I_S(T)}{1 + h_{jEi} \cdot \frac{Q_{jEi}(T)}{Q_{P0}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

@ low injection, V_{BC} = 0 V

Simplification to HICUM Level 0, main idea [2]:

Internal BE depletion charge not available ⇨ Introduction of a new reference charge Q_{P0}^*

$$Q_{P0}^*(T) = Q_{P0}(T) + h_{jEi} \cdot Q_{jEi,OP}(T)$$

And

$$\Delta Q_{jEi}(T) = Q_{jEi}(T) - Q_{jEi,OP}(T)$$

[2] M. Schröter et al., “A Computationally Efficient Physics-Based Compact Bipolar Transistor Model for Circuit Design – Part I: Model Formulation”, IEEE Trans. on Elec. Dev., Vol. 53, nº 2, February 2006

Early effect modeling in HICUM Level 0

HICUM Level 2

$$I_C(T) \approx \frac{I_S(T)}{1 + h_{jEi} \cdot \frac{Q_{jEi}(T)}{Q_{P0}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

@ low injection, $V_{BC} = 0$ V

Considering $Q_{P0}^{*}(T) = Q_{P0}(T) + h_{jEi} \cdot Q_{jEi,OP}(T)$

And $\Delta Q_{jEi}(T) = Q_{jEi}(T) - Q_{jEi,OP}(T)$

$$I_C(T) \approx \frac{C_{10}(T) / Q_{P0}^{*}(T)}{1 + h_{jEi} \cdot \frac{\Delta Q_{jEi}(T)}{Q_{P0}^{*}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

Considering $\Delta Q_{jEi}(T) << Q_{P0}^{*}(T)$ $\Longrightarrow$ $1 + h_{jEi} \cdot \frac{\Delta Q_{jEi}(T)}{Q_{P0}^{*}(T)} \approx \exp\left(h_{jEi} \cdot \frac{\Delta Q_{jEi}(T)}{Q_{P0}^{*}(T)}\right)$

$$I_C(T) \approx \frac{C_{10}(T)}{Q_{P0}^{*}(T)} \cdot \exp\left(-h_{jEi} \cdot \frac{\Delta Q_{jEi}(T)}{Q_{P0}^{*}(T)}\right) \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

Early effect modeling in HICUM Level 0

As $\Delta Q_{jEi}(T) = Q_{jEi}(T) - Q_{jEi,OP}(T)$ $\Longrightarrow$ $\Delta Q_{jEi}(T) = \int_0^{V_{B'E'}} C_{jEi}(V,T)dV - \int_0^{V_{B'E',OP}} C_{jEi}(V,T)dV$

$$\Delta Q_{jEi}(T) \approx (V_{B'E'} - V_{B'E',OP}) \cdot C_{jEi,OP}(T)$$

Thus $I_C(T) \approx \frac{C_{10}(T)}{Q_{P0}^*(T)} \cdot \exp\left(-h_{jEi} \cdot \frac{(V_{B'E'} - V_{B'E',OP}) \cdot C_{jEi,OP}(T)}{Q_{P0}^*(T)}\right) \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$

Temperature dependence of the Early effect

$$I_C(T) \approx \frac{C_{10}(T) \cdot \exp\left(h_{jEi} \cdot \frac{V_{B'E',OP} \cdot C_{jEi,OP}(T)}{Q_{P0}^*(T)}\right)}{Q_{P0}^*(T)} \cdot \exp\left(\left(1 - h_{jEi} \cdot \boxed{\frac{V_T \cdot C_{jEi,OP}(T)}{Q_{P0}^*(T)}}\right)\frac{V_{B'E'}}{V_T}\right)$$

No temperature dependence of the Early effect

HICUM Level 0 $I_C(T) \approx I_S^*(T) \cdot \exp\left(\frac{V_{B'E'}}{\boxed{m_{CF}} \cdot V_T}\right)$ @ low injection, $V_{BC} = 0$ V

Early effect modeling: comparison HICUM L2 / L0

HICUM Level 2

Low injection, $V_{BC} = 0$ V

$$I_C(T) \approx \frac{I_S(T)}{1 + \boxed{h_{jEi}} \cdot \boxed{\frac{Q_{jEi}(T)}{Q_{P0}(T)}}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

$$I_C(T) = \frac{\boxed{I_S(T)}}{1 + \boxed{h_{jEi}} \cdot \boxed{q_{jEi}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

h_{jEi} = weighting factor in HBTs.
q_{jEi} = normalized BE depletion charge.

Temperature dependence of the Early effect

HICUM Level 0

Low injection, $V_{BC} = 0$ V

$$I_C(T) \approx \boxed{I_S^*(T)} \cdot \exp\left(\frac{V_{B'E'}}{\boxed{m_{CF}} \cdot V_T}\right)$$

Which difference between I_S and I_S^* ?

m_{CF} = Non-ideality coefficient of forward collector current.

No temperature dependence of the Early effect

Comparison HICUM L2 / L0: difference between I_S and I_S^*

HICUM Level 2 | HICUM Level 0

$$I_S(T) \neq I_S(T)^*$$

HICUM Level 0 saturation current has not the same expression as HICUM Level 2. “However, since the parameters are determined generally by measurements and not from HICUM/L2 their values will in practice not be different, although their definition is different.” [3]

C_{10} temperature dependence

$$I_S(T_0) = I_S(T_0)^*$$

$$I_S(T) = I_S(T_0) \cdot \frac{\boxed{\left(\frac{T}{T_0}\right)^{Z_{ETACT}} \cdot \exp\left(\frac{V_{GB}}{V_T} \cdot \left(\frac{T}{T_0} - 1\right)\right)}}{\boxed{2 - \left(\frac{V_{DEI}(T)}{V_{DEI}(T_0)}\right)^{Z_{EI}}}}$$

$$I_S(T) = I_S(T_0) \cdot \boxed{\left(\frac{T}{T_0}\right)^{Z_{ETACT}} \cdot \exp\left(\frac{V_{GB}}{V_T} \cdot \left(\frac{T}{T_0} - 1\right)\right)}$$

Q_{P0} temperature dependence

[3] M. Schröter, Private communication

Early effect modeling: statement of the comparison HICUM L2 / L0

HICUM Level 2

Low injection, V_{BC} = 0 V

$$I_C(T) = \frac{\boxed{I_S(T)}}{1 + h_{jEi} \cdot \boxed{q_{jEi}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

Temperature dependence of the Early effect

HICUM Level 0

Low injection, V_{BC} = 0 V

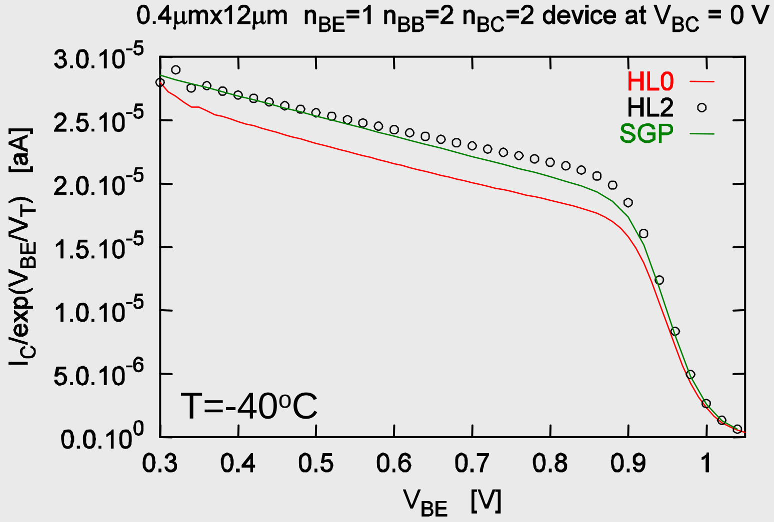
$$I_C(T) \approx \boxed{I_S^*(T)} \cdot \exp\left(\frac{V_{B'E'}}{\boxed{m_{CF}} \cdot V_T}\right)$$

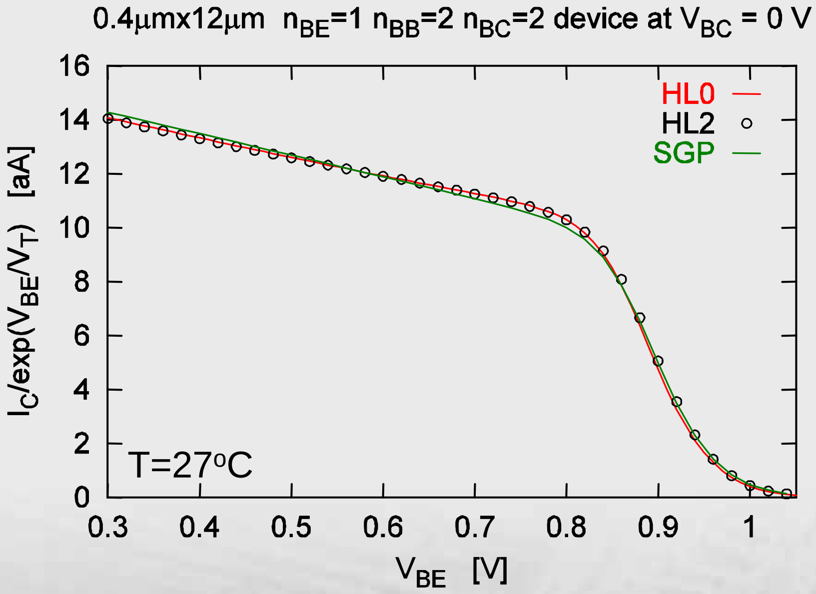
No temperature dependence of the Early effect

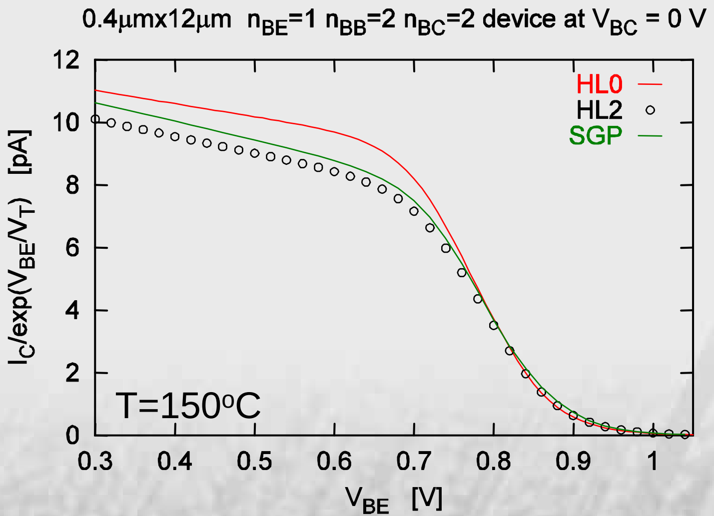
I_S and I_S^* temperature variation is slightly different

Impact of the approximation

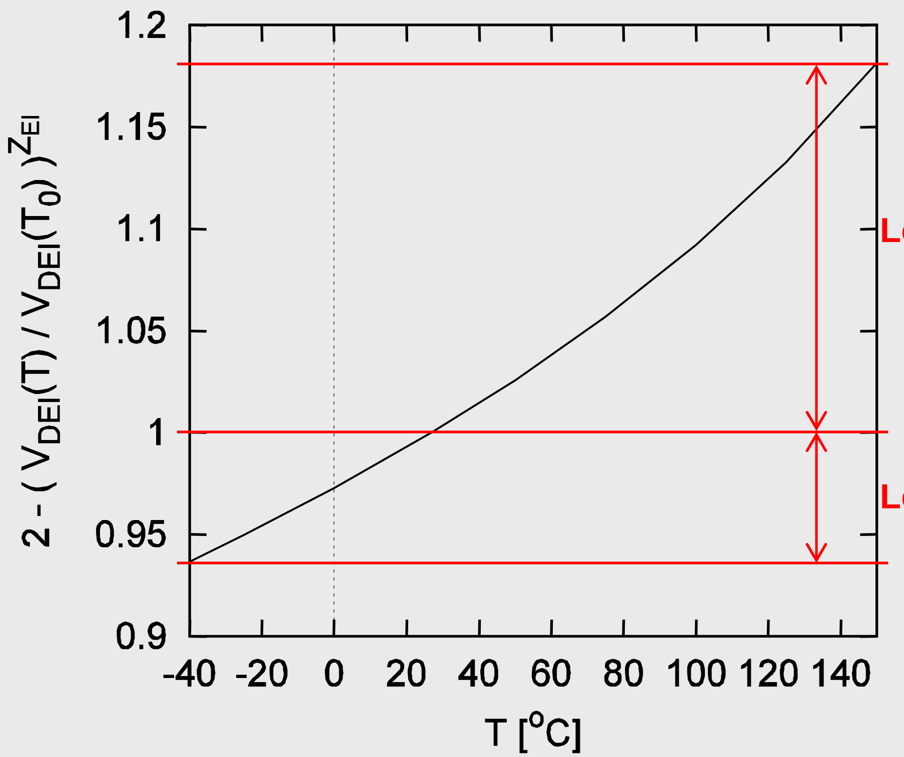
HL2 / HL0 = Eldo version 6.8_3.1 ams 2006.2b







Evaluation of Q_{P0} variation with temperature



What is the impact of this variation ???

Early effect V_{ER} based approach: a solution ?

HICUM Level 2

$$I_C(T) \approx \frac{I_S(T)}{1 + h_{jEi} \cdot \frac{Q_{jEi}(T)}{Q_{P0}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

@ low injection, V_{BC} = 0 V

Considering $Q_{P0}^{*}(T) = Q_{P0}(T) + h_{jEi} \cdot Q_{jEi,OP}(T)$ and $\Delta Q_{jEi}(T) = Q_{jEi}(T) - Q_{jEi,OP}(T)$

$$I_C(T) \approx \frac{C_{10}(T)}{Q_{P0}^{*}(T)} \cdot \exp\left(-h_{jEi} \cdot \frac{\left(V_{B'E'} - V_{B'E',OP}\right) \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)}\right) \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

$$I_C(T) \approx \boxed{\frac{C_{10}(T)}{Q_{P0}^{*}(T)} \cdot \exp\left(h_{jEi} \cdot \frac{V_{B'E',OP} \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)}\right)} \cdot \boxed{\exp\left(-h_{jEi} \cdot \frac{V_{B'E'} \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)}\right)} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

Considering $\text{hjei} \cdot \frac{V_{B'E'} \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)} << 1 \Rightarrow 1 + h_{jEi} \cdot \frac{V_{B'E'} \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)} \approx \exp\left(h_{jEi} \cdot \frac{V_{B'E'} \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)}\right)$

$$I_C(T) \approx \frac{\boxed{I_S^{*}(T)}}{\boxed{1 + \frac{h_{jEi} \cdot C_{jEi,OP}(T)}{Q_{P0}^{*}(T)} \cdot V_{B'E'}}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

Early effect V_{ER} based approach: a solution ?

HICUM Level 2

$$I_C(T) \approx \frac{I_S(T)}{1 + h_{jEi} \cdot \frac{Q_{jEi}(T)}{Q_{P0}(T)}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

@ low injection, V_{BC} = 0 V

$$I_C(T) \approx \frac{I_S^*(T)}{1 + \boxed{\frac{h_{jEi} \cdot C_{jEi,OP}(T)}{Q_{P0}^*(T)}} \cdot V_{B'E'}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

HICUM Level 0: a solution

$$I_C(T) \approx \frac{I_S^*(T)}{1 + \frac{V_{B'E'}}{\boxed{V_{ER}}}} \cdot \exp\left(\frac{V_{B'E'}}{V_T}\right)$$

@ low injection, V_{BC} = 0 V

HICUM Level 0

$$m_{CF} = \frac{1}{1 - h_{jEi} \cdot \frac{V_T \cdot C_{jEi,OP}(T)}{Q_{P0}^*(T)}} = cte$$

Proposed solution

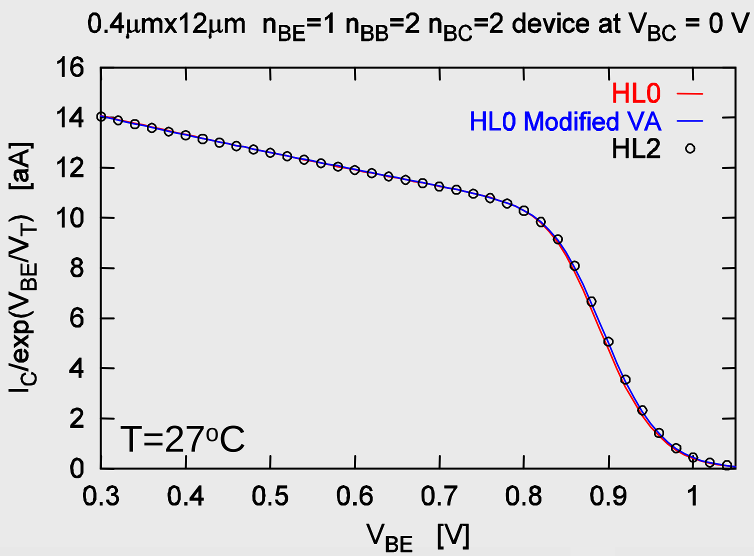
$$V_{ER} = \frac{1}{\frac{h_{jEi} \cdot C_{jEi,OP}(T)}{Q_{P0}^*(T)}} = cte$$

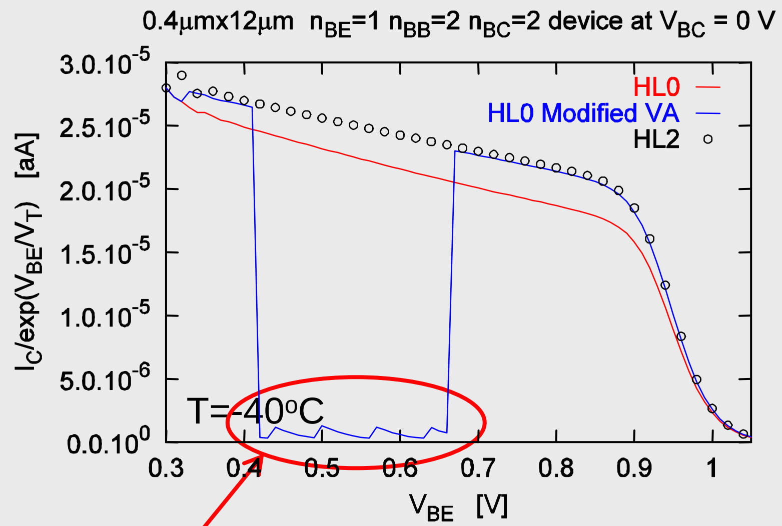
$C_{jEi,OP}$ and Q_{P0}^* temperature dependence still neglected!

Comparison proposed solution / HICUM L2

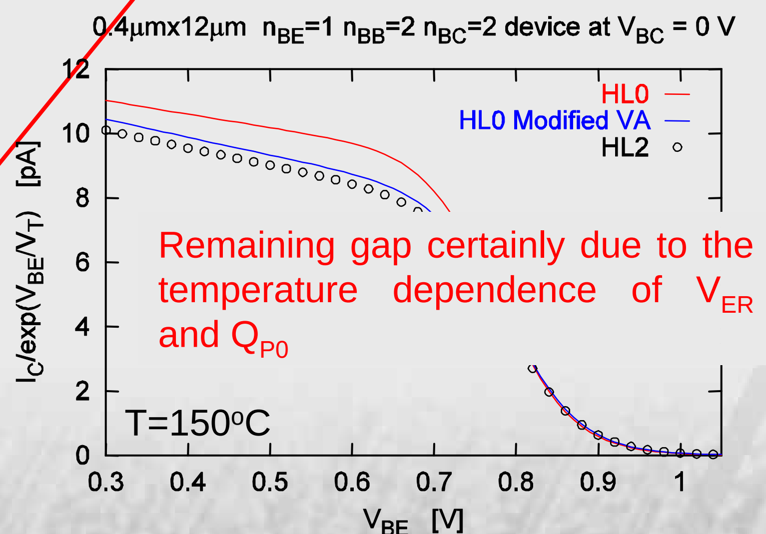
HL2 / HL0 = Eldo version 6.8_3.1 ams 2006.2b

HL0 Modified VA = HL0 with “new” Early effect





Bug using Eldo and Verilog A
No link with model modification



Remaining gap certainly due to the temperature dependence of V_{ER} and Q_{P0}

Other advantage of the proposed solution

Conclusion of D. Céli presentation in the 6th European HICUM workshop [1] about the modeling of the reverse Early effect in HICUM Level 0:

- It has been demonstrated that in some bias conditions (satured region), the modeling of the reverse Early effect in HICUM Level 0 can be not enough accurate.
- To overcome this model issue, 2 possibilities:
  - ➢ To use the same non-ideality factor in forward and reverse (m_{CR} = m_{CF}). Inconsistent with a correct description of the reverse Gummel characteristics.
  - ➢ To come back to the SGP model formulation by using a reverse Early voltage V_{AR} instead of a non-ideality factor m_{CF}.

The V_{ER} based solution is consistent with this proposal and allow to solve this issue

[1] D. Céli, "About Modeling the Reverse Early Effect in HICUM Level 0", 6th European HICUM Workshop, June 12-13, 2006, Heilbronn

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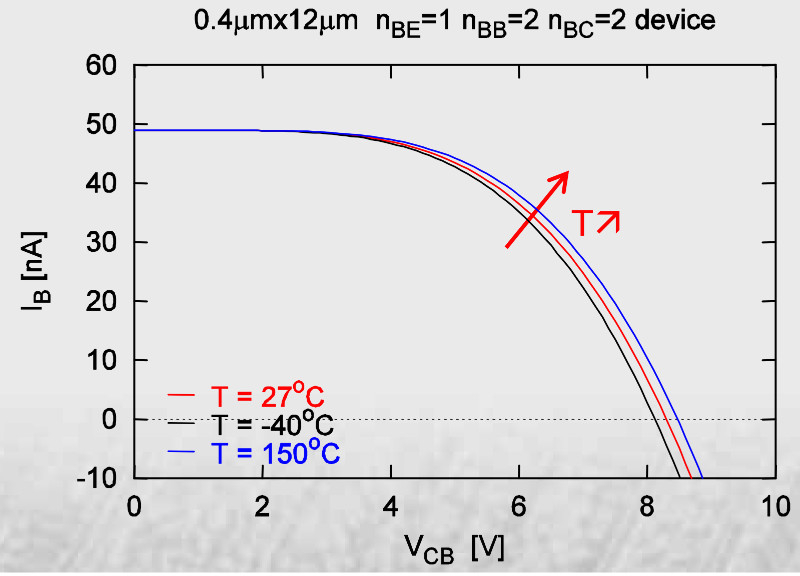
Breakdown modeling in HICUM Level 2

$$I_{AVL} = I_{TF}(T)\cdot \boxed{F_{AVL}}(T)\cdot (V_{DCi}(T)-V_{B'C'})\cdot \exp\left(-\boxed{Q_{AVL}}(T)\cdot \frac{(V_{DCi}(T)-V_{B'C'})^{Z_{CI}-1}}{C_{jCi0}(T)\cdot V_{DCi}(T)^{Z_{CI}}}\right)$$

Breakdown parameter temperature variation

$$F_{AVL}(T) = F_{AVL}(T_0)\cdot \exp(A_{LFAV}\cdot \Delta T)$$
$$Q_{AVL}(T) = Q_{AVL}(T_0)\cdot \exp(A_{LQAV}\cdot \Delta T)$$

Keeping A_{LFAV} = 0 and A_{LQAV} = 0 ⇨



Breakdown modeling in HICUM Level 0

$$I_{AVL} = \frac{I_{TF}(T)}{c_c^{\,1/Z_{CI}}} \cdot K_{AVL}(T) \cdot \exp\left(-E_{AVL}(T) \cdot c_c^{\,1/Z_{CI}-1}\right)$$

with $$c_c = \frac{C_{jCi}(V_{B'C'},T)}{C_{jCi0}(T)} = \frac{V_{DCi}(T)^{Z_{CI}}}{(V_{DCi}(T) - V_{B'C'})^{Z_{CI}}}$$

thus $$I_{AVL} = I_{TF}(T) \cdot \frac{\boxed{K_{AVL}}(T)}{V_{DCi}(T)} \cdot (V_{DCi}(T) - V_{B'C'}) \cdot \exp\left(-\boxed{E_{AVL}}(T) \cdot V_{DCi}(T) \cdot \frac{(V_{DCi}(T) - V_{B'C'})^{Z_{CI}-1}}{V_{DCi}(T)^{Z_{CI}}}\right)$$

Breakdown parameter temperature variation

$$K_{AVL}(T) = K_{AVL}(T_0) \cdot \exp(A_{LKAV} \cdot \Delta T)$$
$$E_{AVL}(T) = E_{AVL}(T_0) \cdot \exp(A_{LEAV} \cdot \Delta T)$$

Both level use identical equations

Comparison HICUM L2 / L0

HICUM Level 2	HICUM Level 0
$I_{AVL} = I_{TF}(T) \cdot \boxed{F_{AVL}(T)} \cdot (V_{DCi}(T) - V_{B'C'}) \cdot \exp\left(-\boxed{Q_{AVL}(T)} \cdot \frac{(V_{DCi}(T) - V_{B'C'})^{Z_{CI}-1}}{\boxed{C_{jCi0}(T)} \cdot V_{DCi}(T)^{Z_{CI}}} \right)$	$I_{AVL} = I_{TF}(T) \cdot \boxed{\frac{K_{AVL}(T)}{V_{DCi}(T)}} \cdot (V_{DCi}(T) - V_{B'C'}) \cdot \exp\left(-\boxed{E_{AVL}(T) \cdot V_{DCi}(T)} \cdot \frac{(V_{DCi}(T) - V_{B'C'})^{Z_{CI}-1}}{V_{DCi}(T)^{Z_{CI}}} \right)$

$$F_{AVL}(T) = \frac{K_{AVL}(T)}{\boxed{V_{DCi}(T)}}$$

$$\frac{Q_{AVL}(T)}{\boxed{C_{jCi0}(T)}} = E_{AVL}(T) \cdot \boxed{V_{DCi}(T)}$$

$$K_{AVL}(T) = K_{AVL}(T_0) \cdot \exp(A_{LKAV} \cdot \Delta T)$$

$$E_{AVL}(T) = E_{AVL}(T_0) \cdot \exp(A_{LEAV} \cdot \Delta T)$$

and

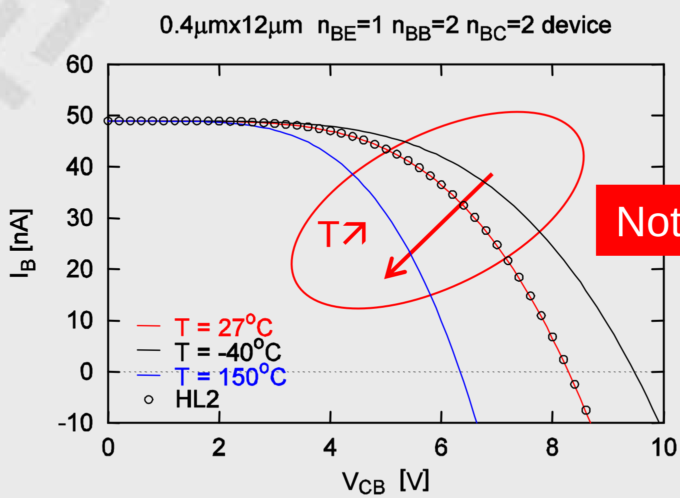
$$F_{AVL}(T) = F_{AVL}(T_0) \cdot \exp(A_{LFAV} \cdot \Delta T)$$

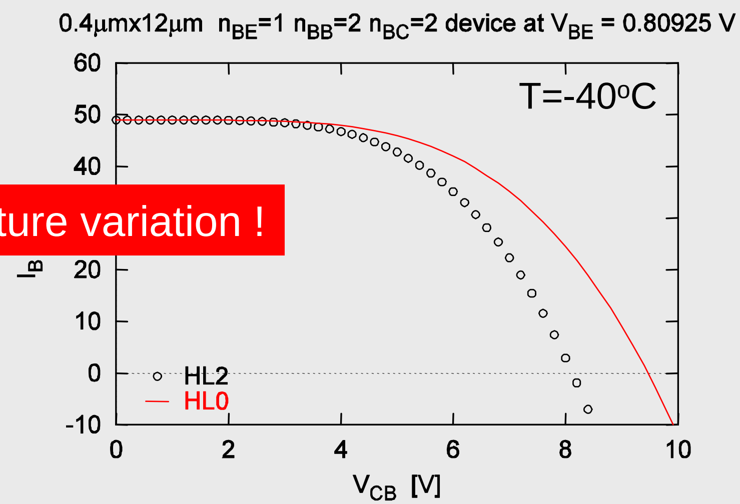
$$Q_{AVL}(T) = Q_{AVL}(T_0) \cdot \exp(A_{LQAV} \cdot \Delta T)$$

Canceling the temperature variation of F_{AVL}/Q_{AVL} and K_{AVL}/E_{AVL} does not present the same I_{AVL} temperature variation

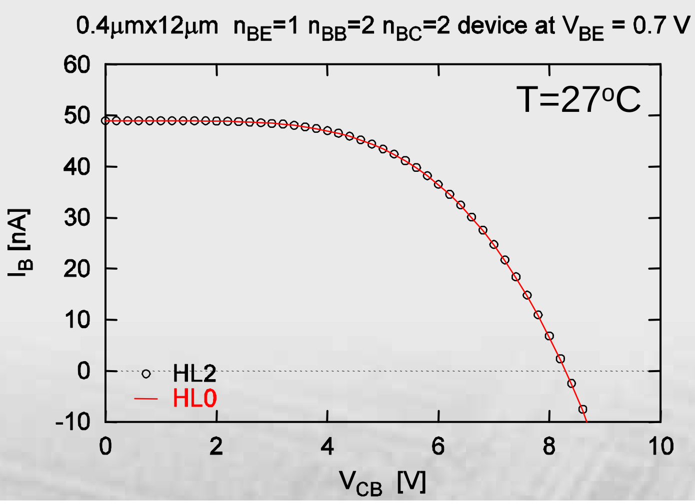
Impact of the approximation

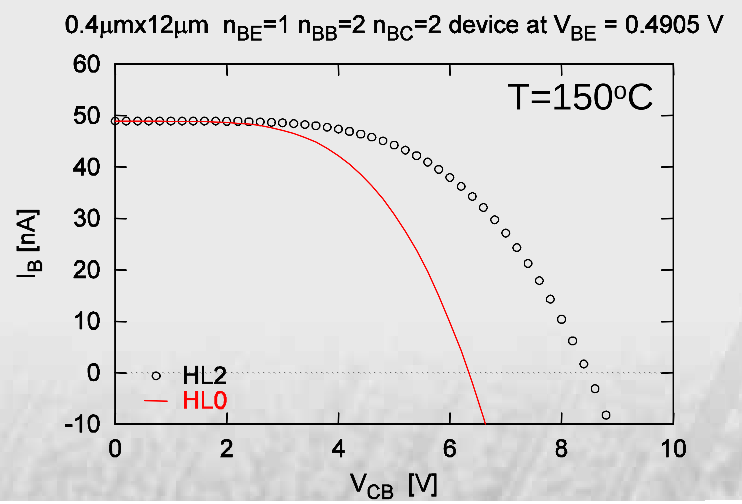
$A_{LFAV} = 0$, $A_{LQAV} = 0$, $A_{LKAV} = 0$, $A_{LEAV} = 0$





Not physical temperature variation !

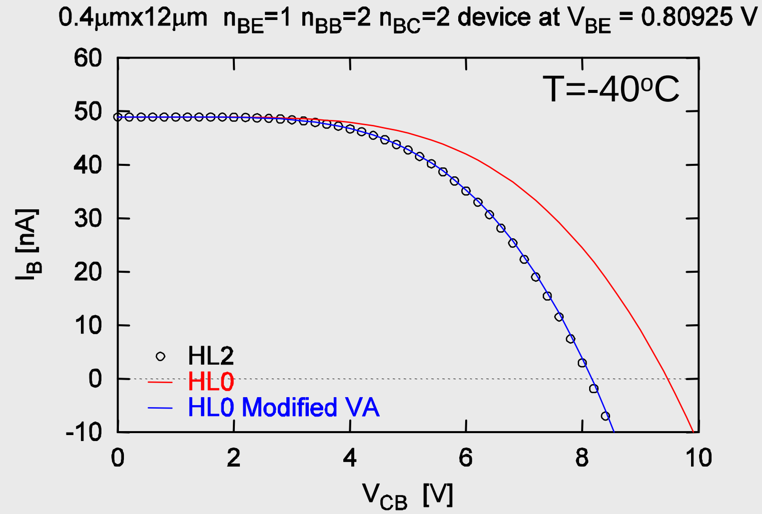


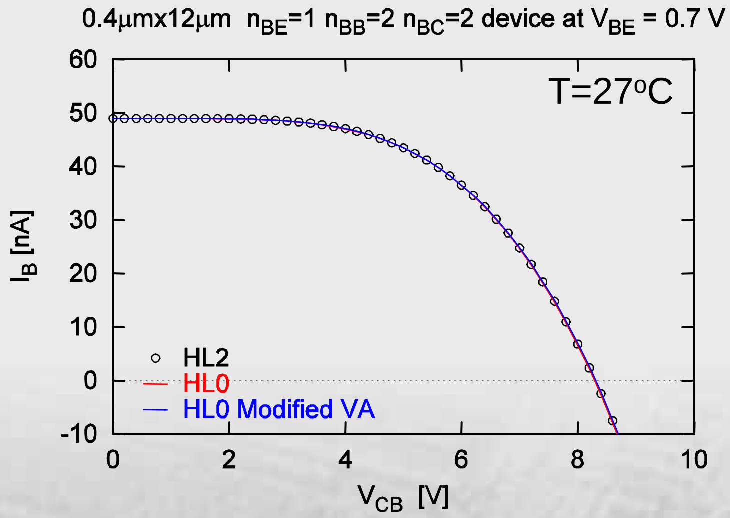


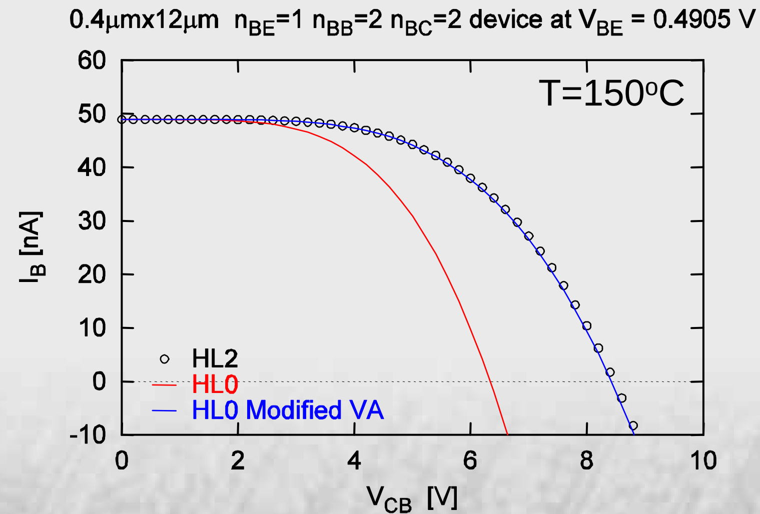
Why do not keep HICUM L2 formulation ?

HL2 / HL0 = Eldo version 6.8_3.1 ams 2006.2b

HL0 Modified VA = HL0 with HL2 breakdown







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Conclusion

- These results demonstrate that there is room for improvement in the temperature dependency of some key HICUM Level 0 model parameters.
- For Early effect modeling, a V_{ER} based approach provides better results than a m_{CF} based approach.
- Concerning the avalanche current modeling, it has been demonstrated that coming back to HICUM Level 2 model equations will be wise. It will not increase the number of parameters needed nor the model complexity.

PENDING QUESTIONS:

- Do you agree with this analysis?
- If yes, a modified HICUM Verilog A code is available for testing and for implementing a new HICUM Level 0 release (if needed)