# HiCuM model enhancement for reliability investigation

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# Purpose

- Presenting the measurement result and modeling of the storage accelerated aging tests performed on InP/InGaAs/InP HBT
- From the Gummel characteristics, we observe that the principle mode of device degradation results from the increase of base current and reduction in the current gain which comes from the base-emitter junction periphery.
- Implementation in compact electrical model allows to simulate the impact of device failure mechanisms on the circuit in operating conditions.

# Outline

- The InP HBT: some technological aspects
- Compact modelling of InP HBT with HiCuM
- Results of storage accelerated aging test
  - Modeling through HiCuM
  - Modeling through TCAD
- Physical investigation of aging mechanisms
- Extension of the HiCuM model
- Some results (Common emitter amplifier)
- Discussion

# The InP HBT: some technological aspects

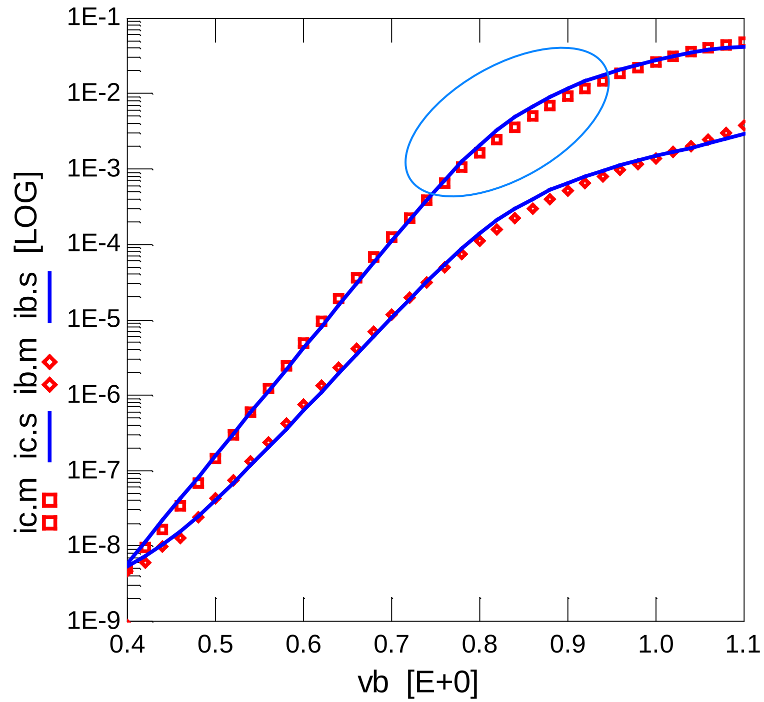
- The HBT devices were grown at III-V Lab on InP substrates by MBE.
- The devices were fabricated using self-aligned triple-mesa process.
- Ti/Au metallization has been used.
- This device has benzocyclobutene (BCB) planarization.

| Name | Material | Level ($cm^{-3}$) | Thickness (nm) |
|---|---|---|---|
| Cont Em | $In_{0.53}Ga_{0.47}As$ | $>10^{19}$ | 100 |
| Emitter 2 | InP | $>10^{19}$ | 195 |
| Emitter 1 | InP | $2x10^{17}$ | 25 |
| Base | $In_{X-1}Ga_XAs$ | $>8\ x10^{19}$ | ≈30 |
| Buffer | $In_{0.53}Ga_{0.47}As$ | $1x10^{16}$ | 30 |
| Collector 2 | InP | $5x10^{17}$ | 20 |
| Collector 1 | InP | $5x10^{16}$ | 80 |
| Cont Co 3 | InP | $>10^{19}$ | 150 |
| Cont Co 2 | $In_{0.53}Ga_{0.47}As$ | $>10^{19}$ | 150 |
| Cont Co 1 | InP | $>10^{19}$ | 350 |
| Etch-Stop | $In_{0.53}Ga_{0.47}As$ | | 10 |

# Compact modelling of InP HBT with HiCuM

- Forward Gummel Plot @ VBC=0V, T=300K

- Measured collector current is lower than the predicted by the model (here the model tradeoff washes the difference slightly)



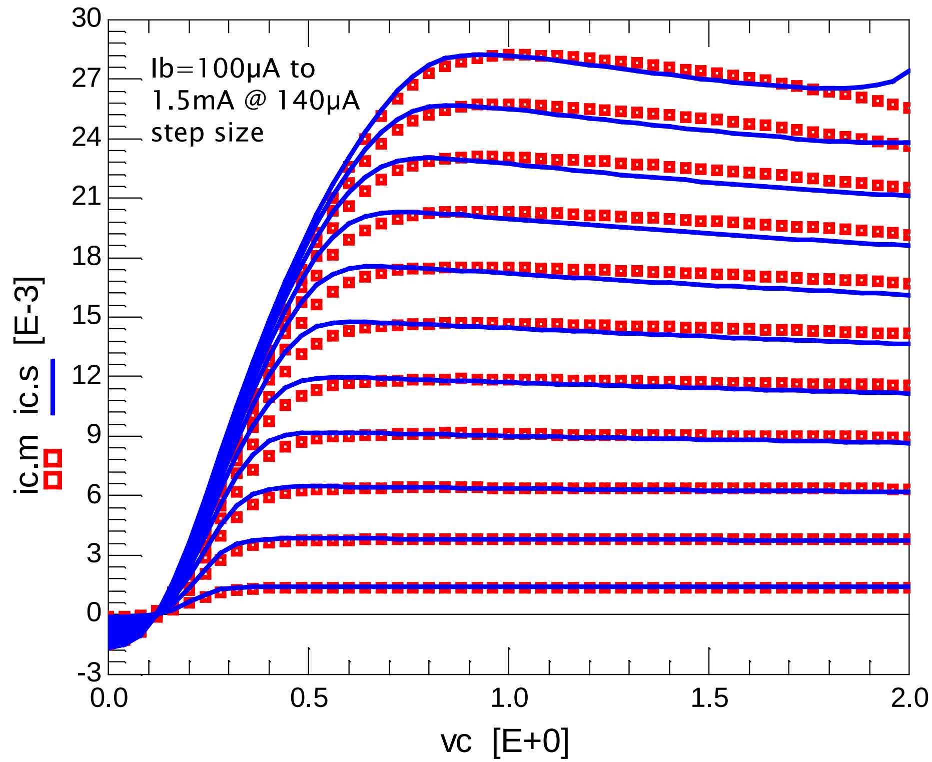
# MCDCR

- **M**edium **C**urrent **D**ensities **C**urrent **R**eduction (MCDCR) is an unexpected collector current reduction at medium current range
- There is no complete theoretical description of the phenomenon
- The origin is not completely understood for InP HBT
- Perspective: Using HiCuM L2 to solve MCDCR:
  - New formulation proposed for SiGe HBTs (HiCuM WS2009*)

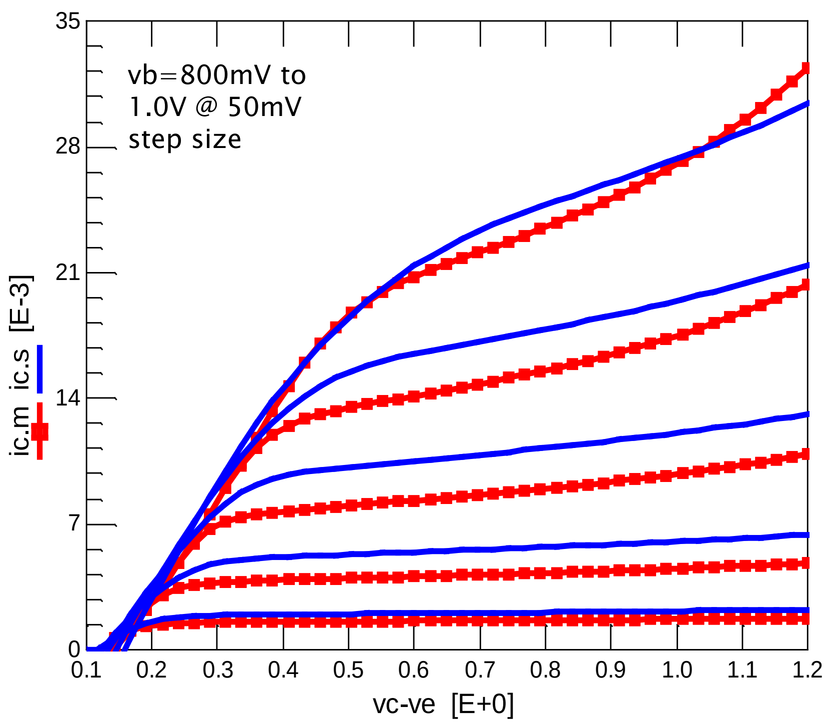
*''A HICUM extension for medium current Densities'' A. Pawlak, M. Schröter, J. Krause.

# Forward Output Characteristics

- Very good physical description for the quasi-saturation in HiCUM

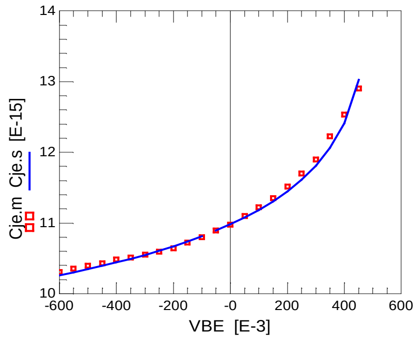


# Forward Output Characteristics

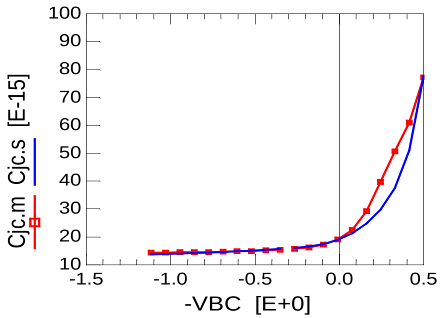



- VBE driven output characteristics has a significant discrepancy at medium bias, while IB driven output characteristics is good enough
- This is the effect of MCDCR

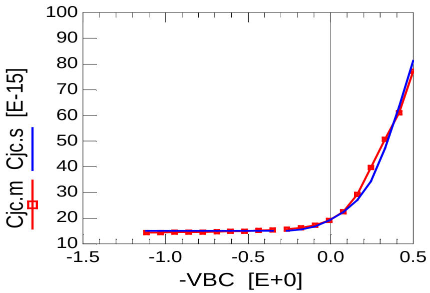
# Total Base Emitter & Base Collector Junction Capacitance




B-E junction capacitance




B-C junction capacitance

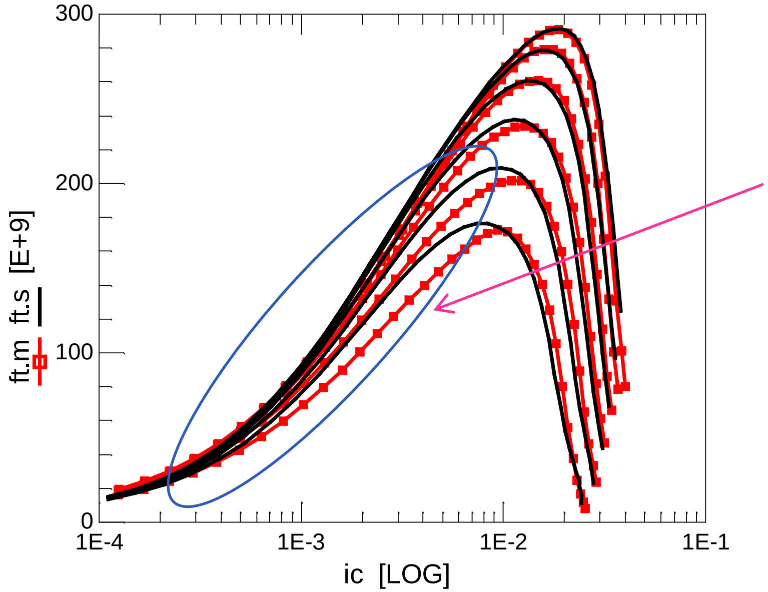



B-C junction capacitance after parameter optimization (device physics is lost !)

# Base Collector Junction Capacitance

- B-C junction capacitance formulation is not accurate enough for this geometry due to the multilayer collector structure
- Well fitted curve can be obtained with tricky optimization of other parameters
- But this represents a workaround and the capacitance loses its physical meaning

# Transit Frequency

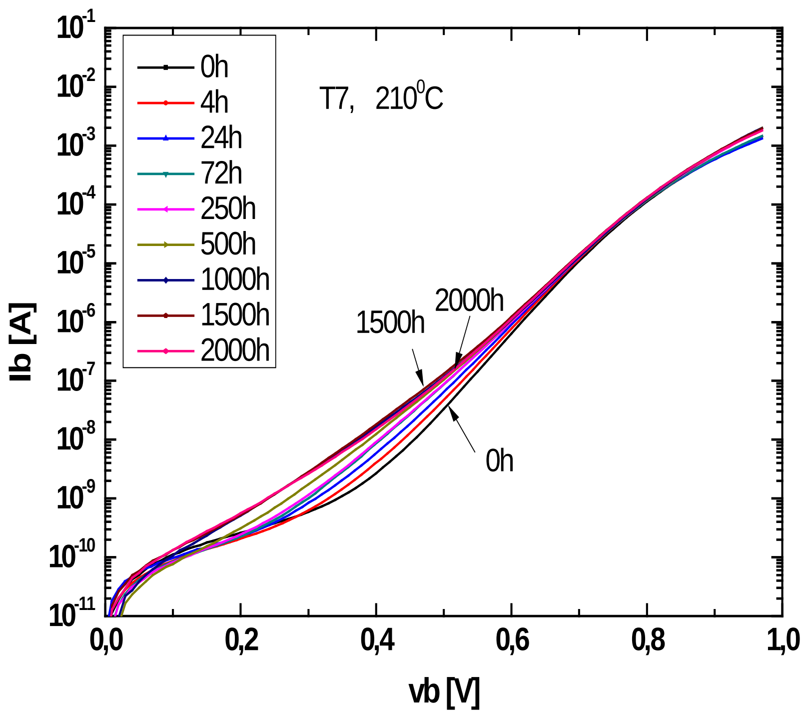


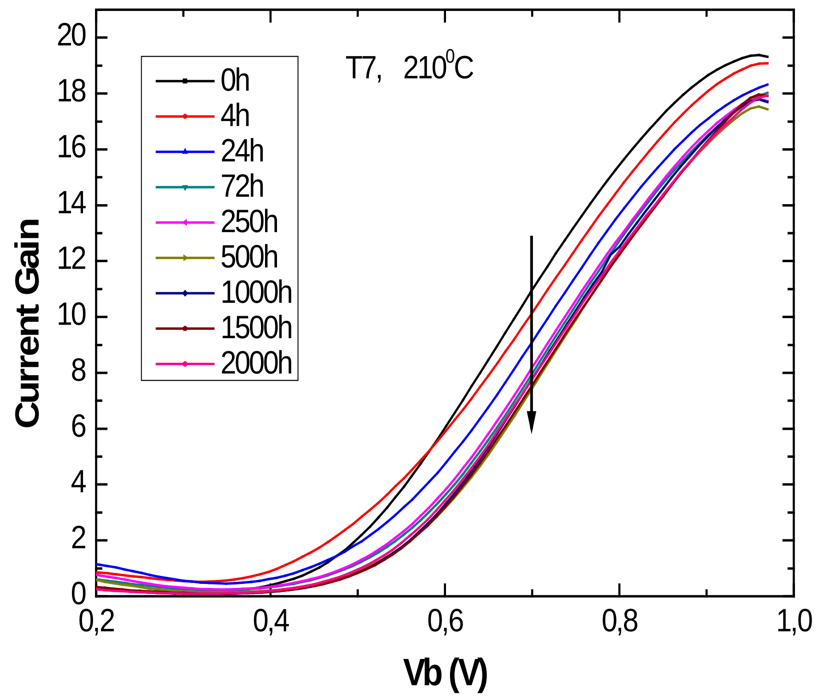

Not very good fitted due to the limitation of B-C junction capacitance formulation

Transit frequency as a function of collector current, VCE from 600mV to 1.1V @ 100mV step size, and VBE from 700mV to 1.05V @ 10mV step size

# Results of storage accelerated aging test

- Focus on base current $I_B$ degradation due to the thermal stress



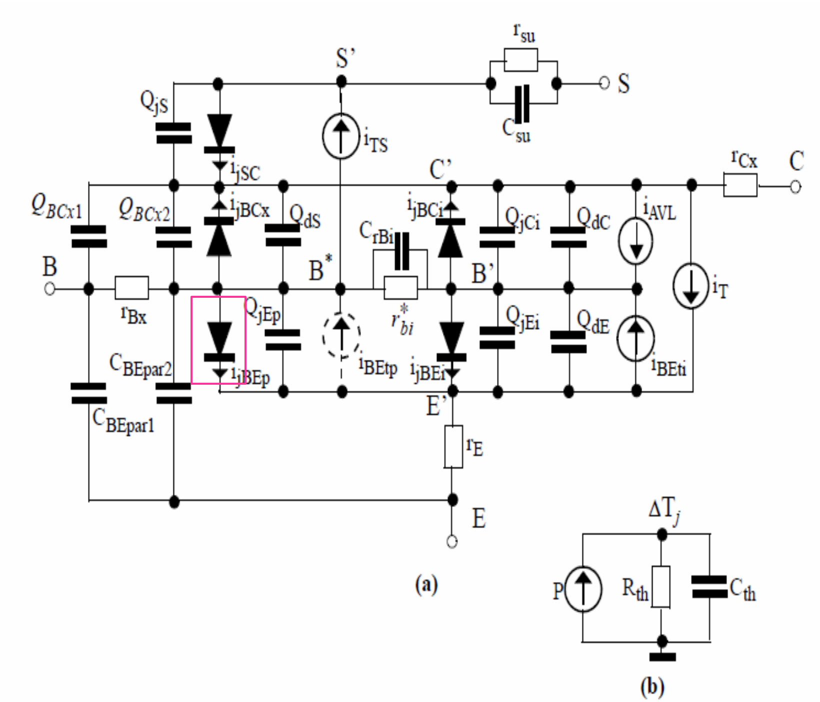



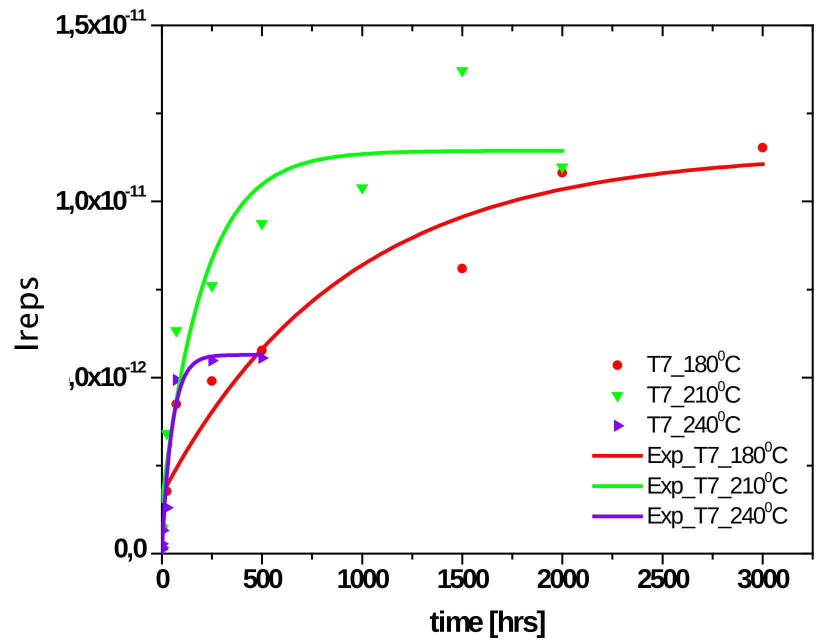
# Modeling through HiCuM

- The base current injected across the emitter periphery is given by:

$$i_{jBEp} = I_{BEpS}\left[\exp\left(\frac{v_{B*E}}{m_{BEp}V_T}\right)-1\right]+I_{REpS}\left[\exp\left(\frac{v_{B*E}}{m_{REp}V_T}\right)-1\right]$$

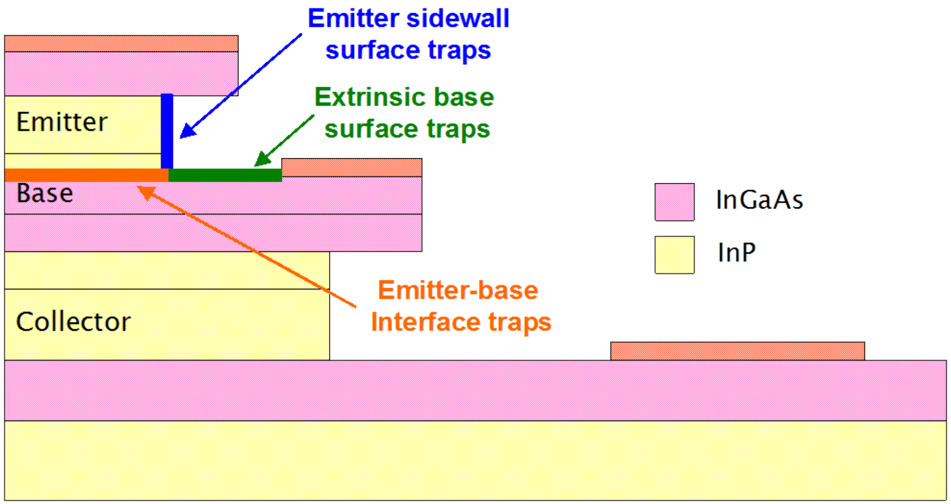
- Diffusion component: Ibeps, Recombination component: Ireps

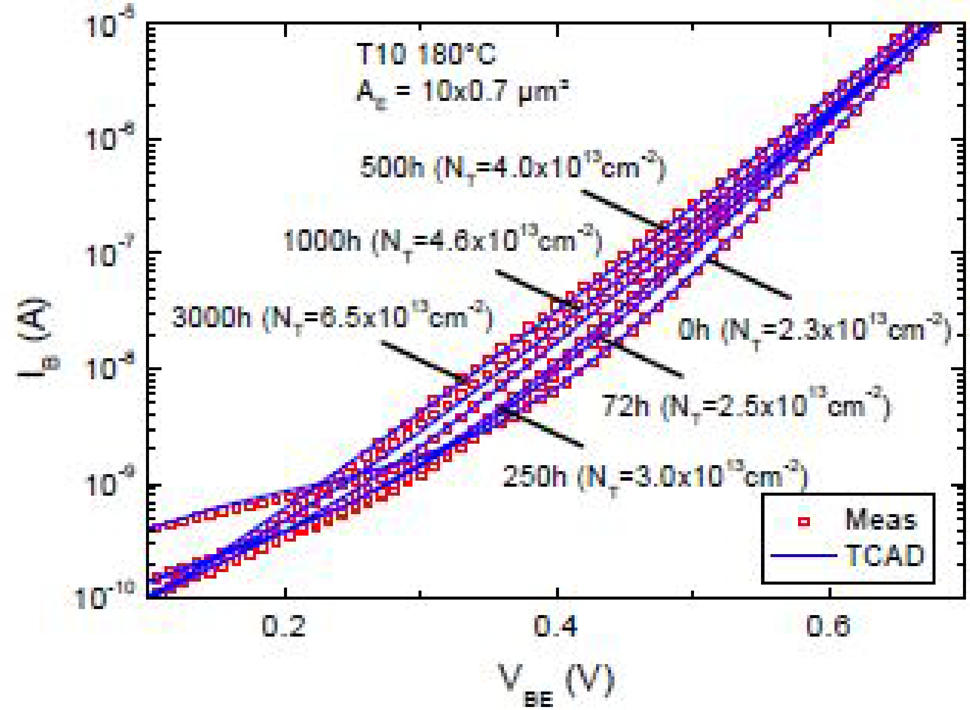


# Modeling through TCAD

- **TCAD simulations have allowed to link the base current gradually rise to an increase of the trap density on emitter sidewalls**



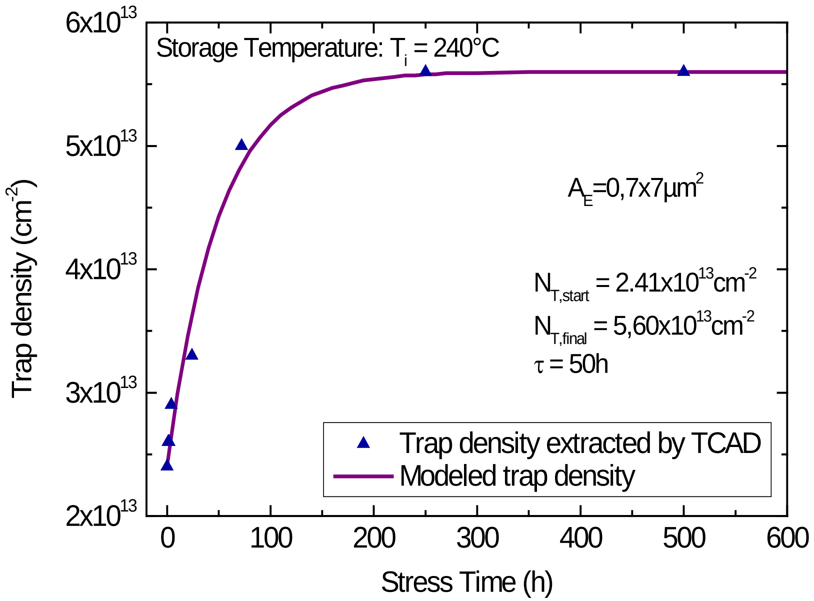



# Electrical aging model

- The evolution of trap density vs stress time can be explained by the equation

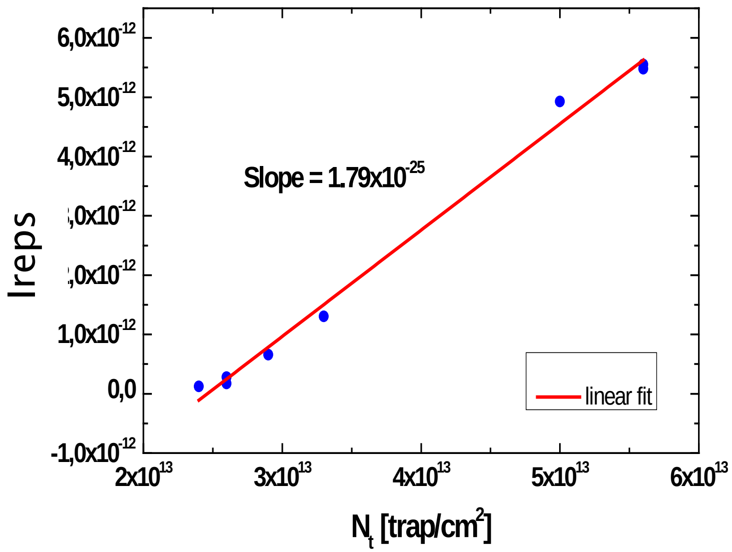
$$\frac{dN_t(t)}{dt} = g(T) - r(T)N_t(t)$$

- Where g(T) is the generation rate of trap, r(T) is the probability of annihilation of traps by unit of time and T is the stress temperature during aging.



# Link: aging model <–> compact model

- Correlation between trap density $N_T$ and saturation current $I_{REPS}$




$$\frac{dI_{REpS}(t)}{dt} = G(T) - r(T) I_{REpS}(t)$$

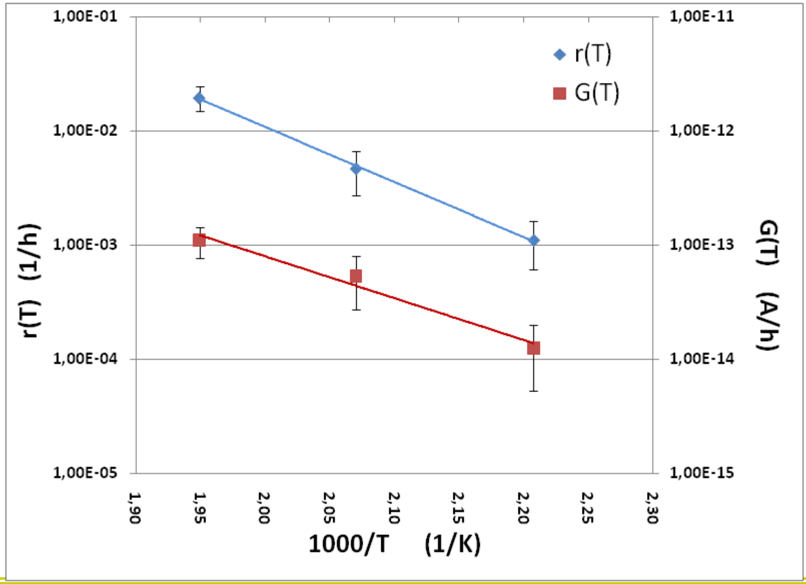
- Where G(T) is proportional to g(T).

# Temperature dependence

- We assume that g(T) and r(T) follow the Arrhenius Law

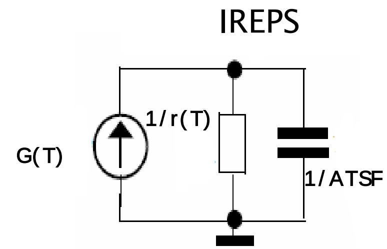
$$x(T) = B_x[\exp(-\frac{E_{a,x}}{k_B T})]$$

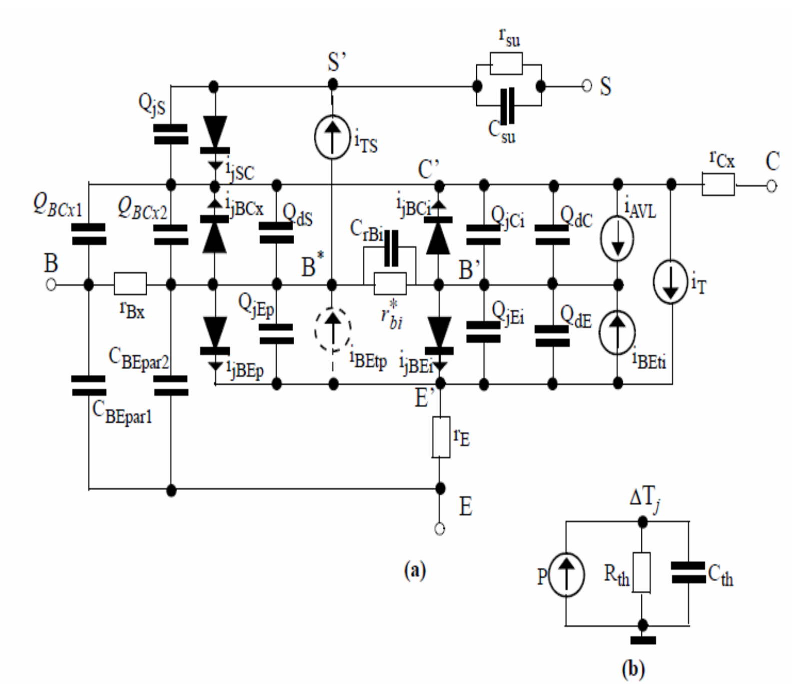
- Where x(T) is the reaction rate (here, g(T) or r(T)), $B_x$ and $E_{a,x}$ are the pre exponential factor and activation energy associated to x(T) and $k_B$ is the Boltzmann constant.
- Due to proportionality of *IREpS* and $N_t$, G(T) must follow the Arrhenius law too



# Implementation into HiCuM

- **Adding a new node that gives $I_{REPS}(t, T)$**

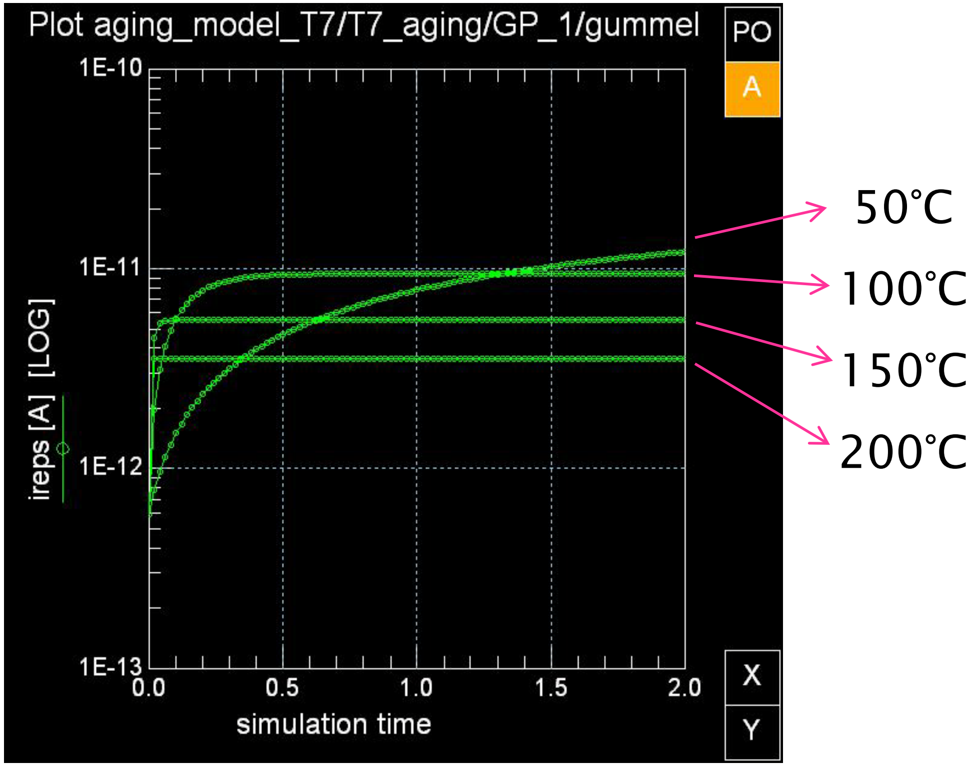



- **G(T): represent generation rate**
- **r(T): recombination rate**
- **ATSF: Aging Time Scale Factor**

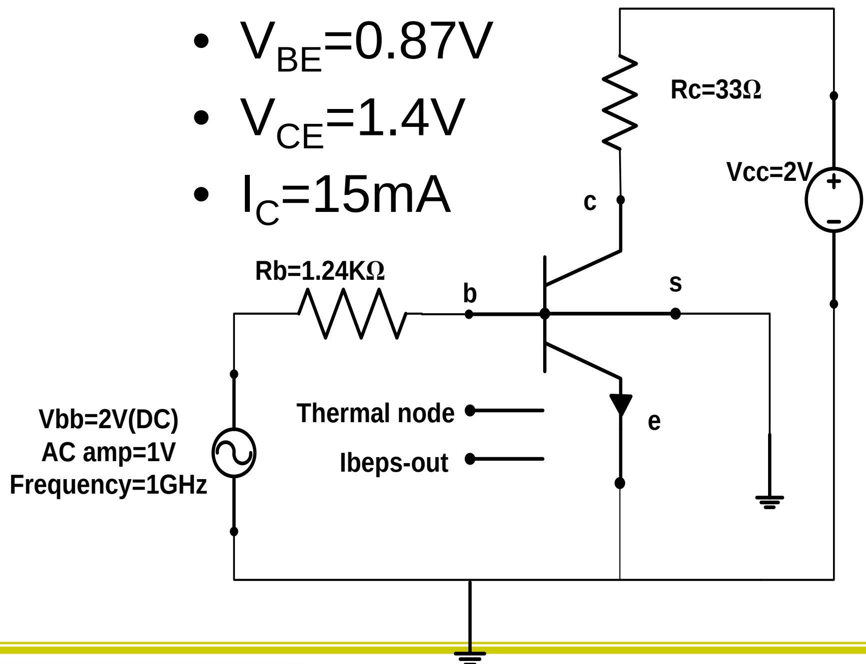
# Simulation results: device level

- Verification of new HiCuM version
  - DC simulation (Gummel Plot etc)
  - AC simulation
  - Tran simulation
- New node: gives variation of model parameter IREPS as a function of time and junction temperature

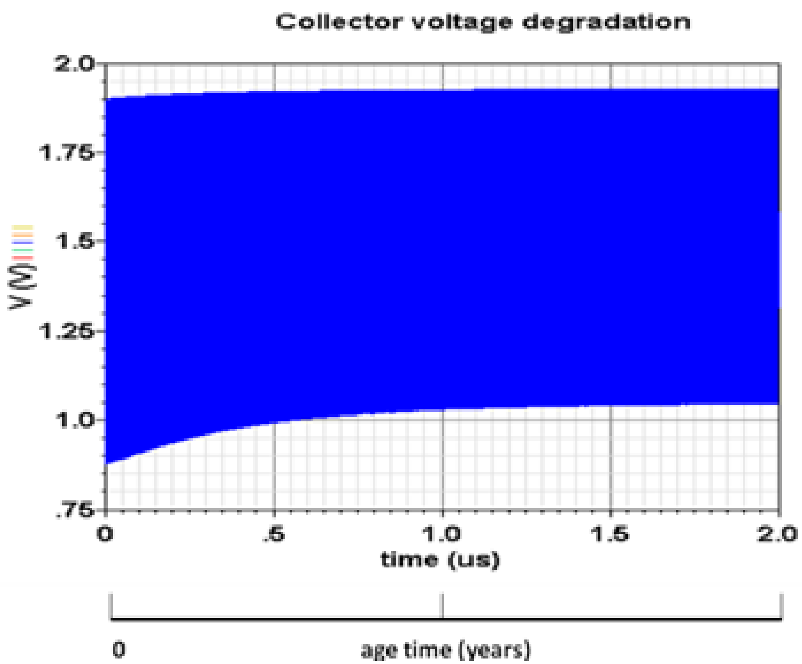


# Simulation results: circuit level

- **Common emitter amplifier**
  - Operating point (near peak $f_T$):
    - $V_{BE}$=0.87V
    - $V_{CE}$=1.4V
    - $I_C$=15mA




- **Transient simulation results**



# Time scales

## ❑ Three different time scales:

- ➢ Electrical operating conditions (e.g.: frequency f=1GHz or higher, period $\tau$=1ns or less)
- ➢ Thermal effect (CTH*RTH thermal time constant: 10ns to 10µs)
- ➢ Aging effect has to be simulated with respect to life time of the system (several years)
  - Introduction of ATSF: Aging Time Scale Factor
  - Gives a parallel time scale: actual time scale * ATSF

# Discussion

- Implementation of “aging” into HiCuM
  - Adapt time scales: ATSF and CTH
- Convergence
  - No particular problems detected so far
  - Allowed parameter ranges have to be checked
- Simulation time
  - An additional node: “trans” simulation time is increased by a factor of about 1.5 (tested on RO results: 26 transistors, about 50 components)

# Conclusion

- Investigation of reliability on InP HBTs
- Measurements and compact modeling at t=0
- Aging of devices at different temperature (up to 3000h) + intermediate characterization + parameter extraction
- TCAD modeling
  - calibration of TCAD parameters
  - Investigation of reliability issues for each intermediate characterization result
- Link of compact model and aging law and TCAD
- Development of new compact model including aging
- Application to circuit design

# Perspectives

- **Application of this procedure to SiGe HBT**
  - Access to aging results
- **Test with different designs**

# Acknowledgement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**THANKS**

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