

EUROPEAN MICROWAVE WEEK 2019

SIX DAYS · THREE CONFERENCES · ONE EXHIBITION

PORTE DE VERSAILLES PARIS, FRANCE
29TH SEPTEMBER - 4TH OCTOBER 2019

Exhibition Hours:

Tuesday, 1st October 9.30 - 18.00

Wednesday 2nd October 9.30 - 17.30

Thursday 3rd October 9.30 - 16.30

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WS-01

Recent advances in SiGe BiCMOS: technologies, modelling & circuits for 5G, radar & imaging

T A R A N T O

Advances in Aging Compact Model for Hot Carrier Degradation in SiGe HBTs under Dynamic Operating conditions for reliability-aware circuit design

C. Mukherjee¹, F. Marc¹, M. Couret¹, G. G. Fischer², M. Jaoul¹, D. Céli³, K. Aufinger⁴, T. Zimmer¹ and **C. Maneux¹**

¹University of Bordeaux; ²IHP; ³STmicroelectronics; ⁴Infineon

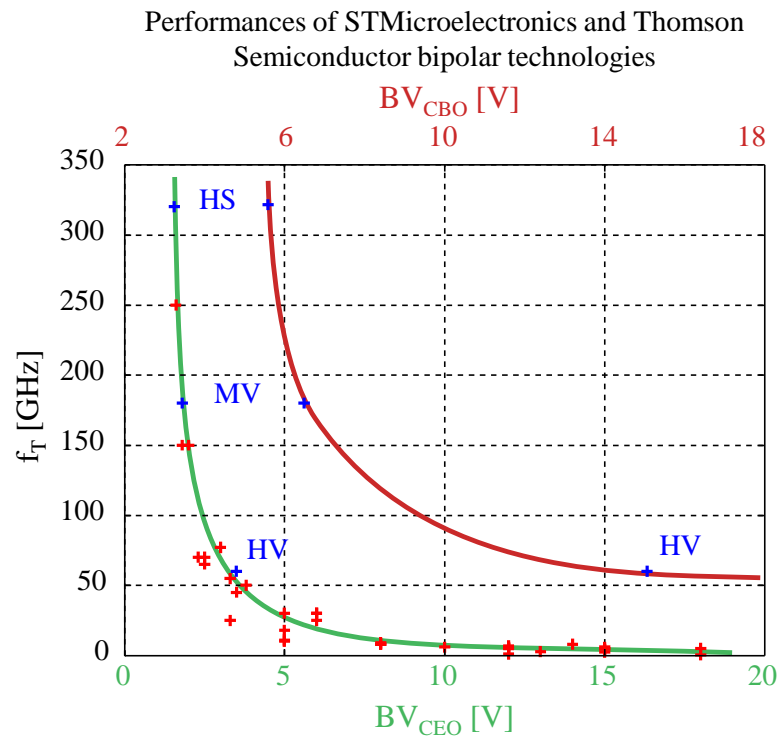
crstell.maneux@u-bordeaux.fr



- Purpose
- Aging experimental results
- TCAD investigations
- Modeling of the aging
- Results
- Conclusion



- SiGe HBTs dynamic performance enhancement has led to low breakdown voltages
- Since open base is rarely encountered for in circuit situation, BV_{CEO} can be exceeded up to the open-emitter breakdown voltage BV_{CBO}
- For power performances, designers require to use HBTs beyond BV_{CEO}

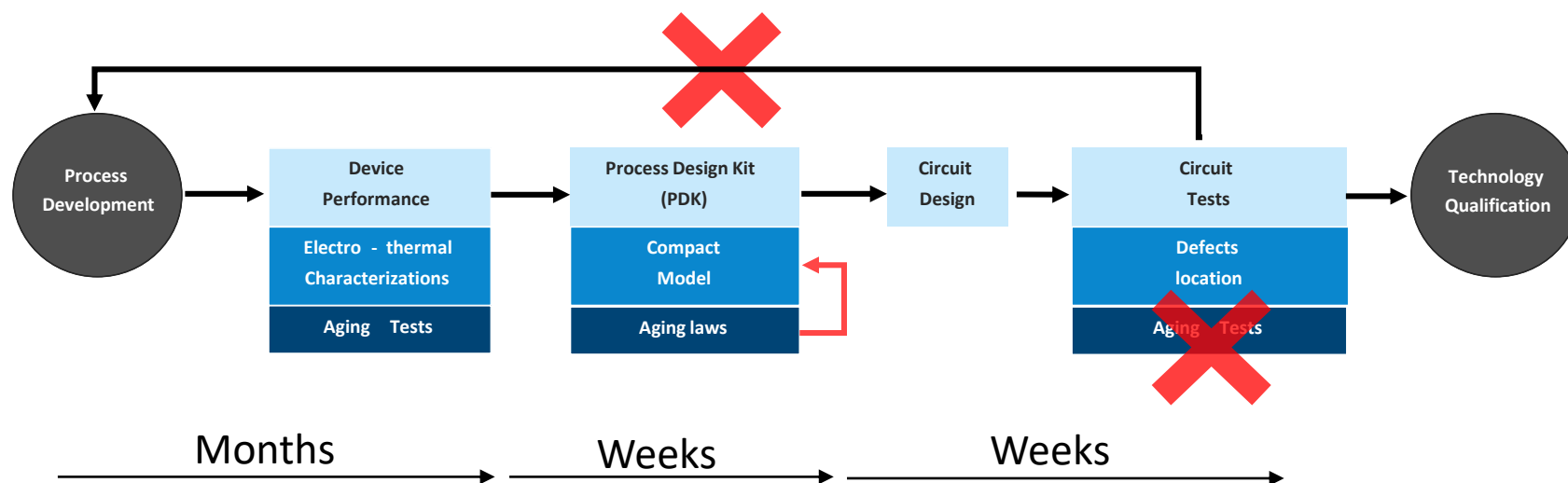


M. Jaoul, C. Maneux, D. Céli, M. Schröter and T. Zimmer, "A Compact Formulation for Avalanche Multiplication in SiGe HBTs at high injection levels," Transactions on Electron Devices, Volume: 66, Issue: 1, pp.264-270, Jan. 2019



• Circuit reliably improvement

- Reduce time and cost by limiting the aging tests at circuit level
- Use a short loop to evaluate the circuit performances
- Integrate aging laws in device compact model

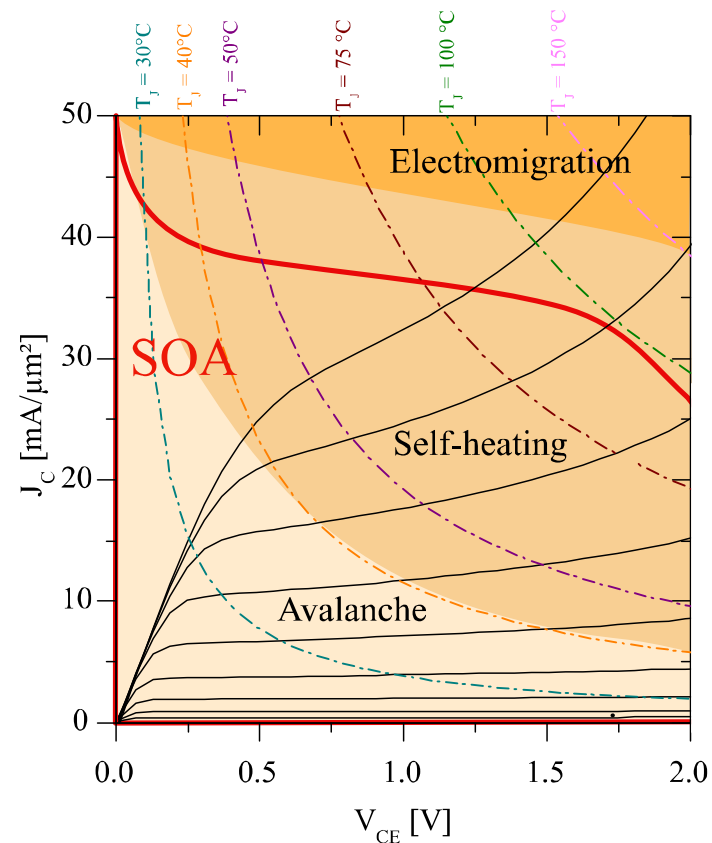


C. Mukherjee, B. Ardouin, J. Y. Dupuy, V. Nodjiadjim, M. Riet, T. Zimmer, F. Marc, and C. Maneux, "Reliability-Aware Circuit Design Methodology for Beyond-5G Communication Systems," *IEEE Trans. Device Mater. Rel.* vol. 17, no. 3, pp. 490-506, Sept. 2017, DOI: [10.1109/TDMR.2017.2710303](https://doi.org/10.1109/TDMR.2017.2710303).



Aging tests: Mixed mode at the SOA edges

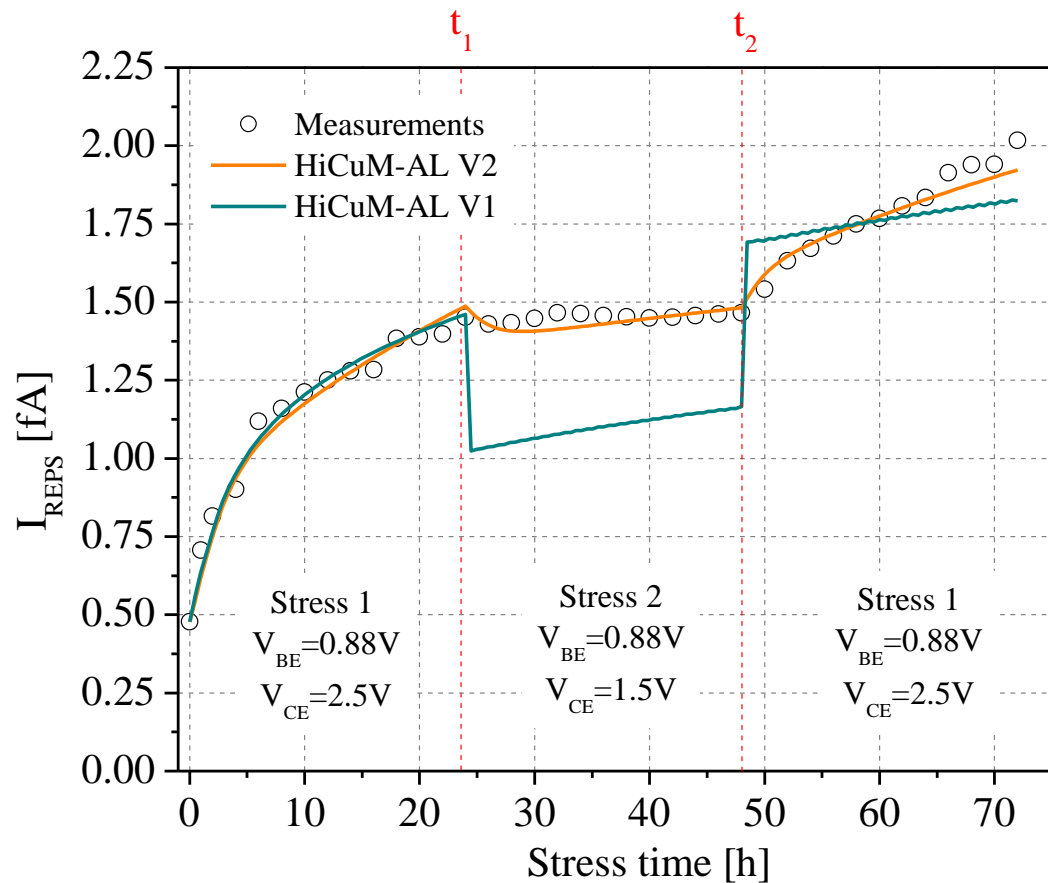
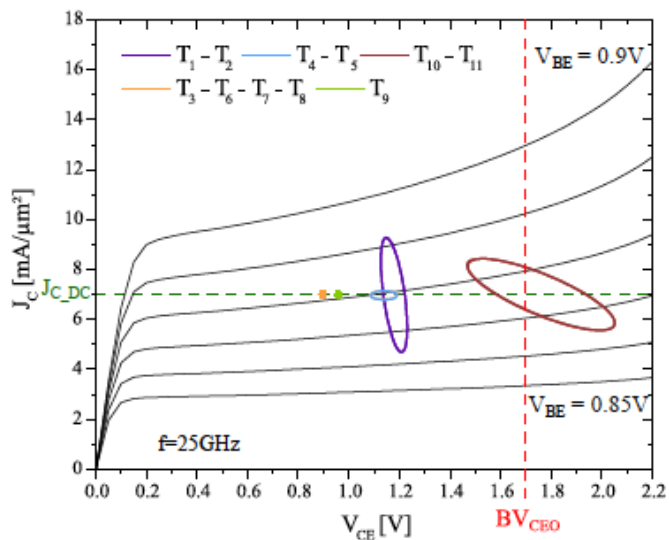
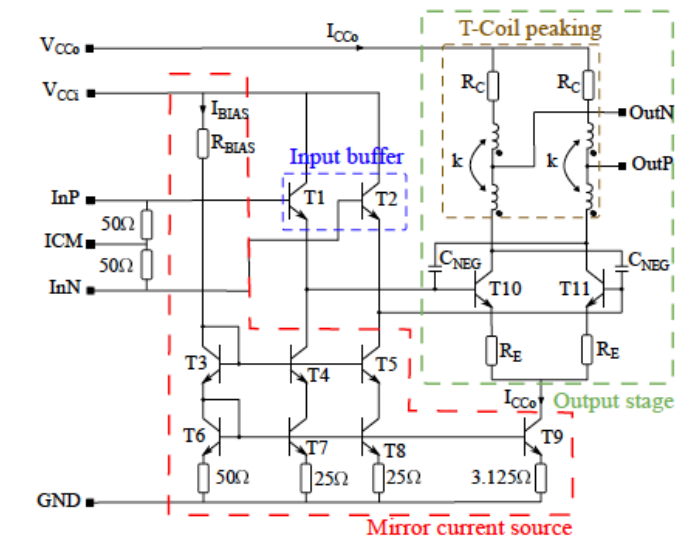
- SOA edges defined by
 - Strong avalanche regime
 - Self-heating
 - Current pinch-in effect (current crowding at the center of the emitter)
- Failure mechanism activation depends on various accelerating factors
 - Temperature
 - Electric field
 - Current density
 - Stress time



Marine Couret, Gerhard Fischer, Iria Garcia Lopez, Magali De Matos, François Marc, Cristell Maneux, "Impact of SiGe HBT Hot-Carrier Degradation on the Broadband Amplifier Output Supply Current", IEEE Proceedings of ESSDERC 2019, Cracow, Poland, 23-26 Sept 2019.



Aging tests: Dynamic mixed mode at the SOA edges

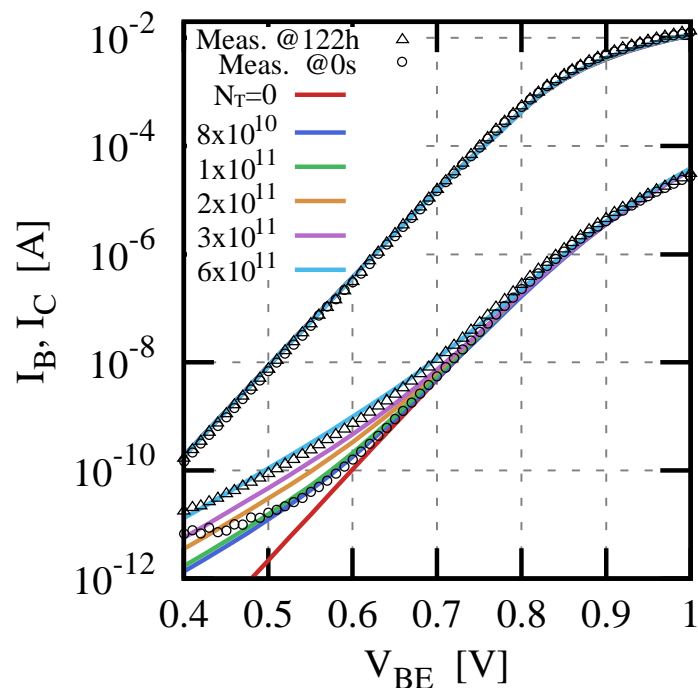
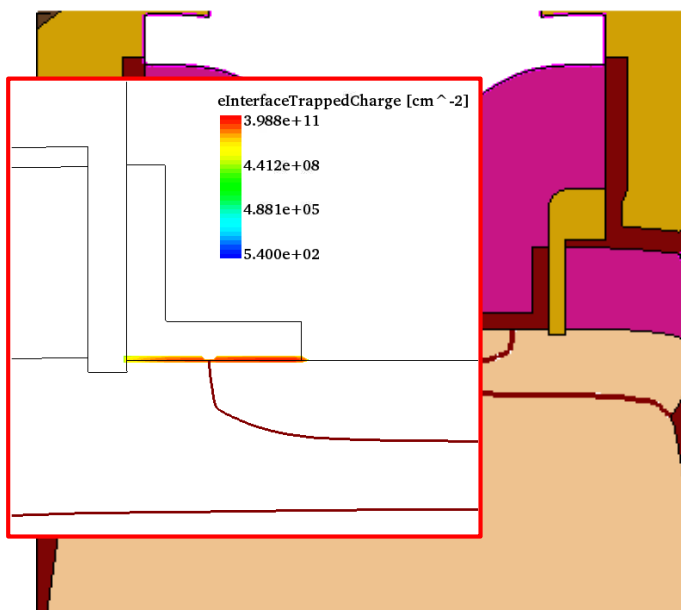


Marine Couret, Gerhard Fischer, Iria Garcia Lopez, Magali De Matos, François Marc, Cristell Maneux, "Impact of SiGe HBT Hot-Carrier Degradation on the Broadband Amplifier Output Supply Current", IEEE Proceedings of ESSDERC 2019, Cracow, Poland, 23-26 Sept 2019.



Aging tests: Failure mechanism origin investigation

- TCAD simulations
 - Trap density have been added at the EB spacer interface
 - Increasing the trap density increases the base recombination current
 - Follows the same behavior as observed on measurements at 25°C (symbols)
- I_{REPS} : HICUM parameter associated with peripheral base recombination current



M. Jaoul, D. Ney, D. Céli, Cristell Maneux and T. Zimmer, "Analysis of a failure mechanism occurring in SiGe HBTs under mixed-mode stress conditions", *IEEE ICMTS*, 18-21 Mar. 2019, Fukuoka, Japan.



Aging tests: Failure mechanism equations

- The rate of bond dissociation is governed by a chemical interaction between the carriers and the passivated Si-H bond through generation and annihilation of traps.

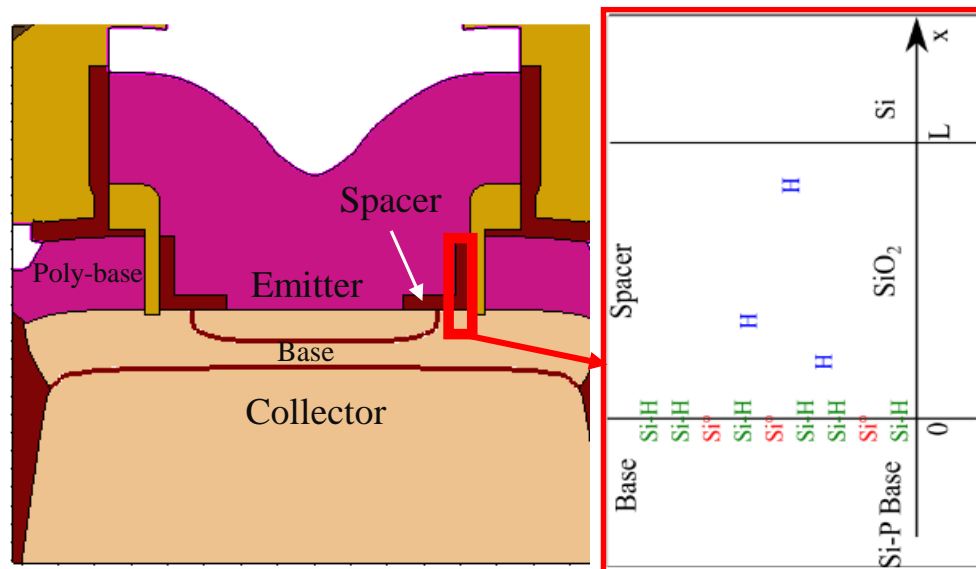
$$g_T(t) = K_F(N_F - N_T(t)) - K_R N_T(t) N_H(0, t)$$

- When a Si-H breaks, every dangling Si bond is associated with a free H atom in the oxide.

$$g_T(t) = \frac{dN_T}{dt} = \Phi_H(0, t)$$

- In the oxide volume, the flow of hydrogen is related to the density by Fick's diffusion law

$$\Phi_H(x, t) = -D_H \frac{\partial N_H(x, t)}{\partial x}$$



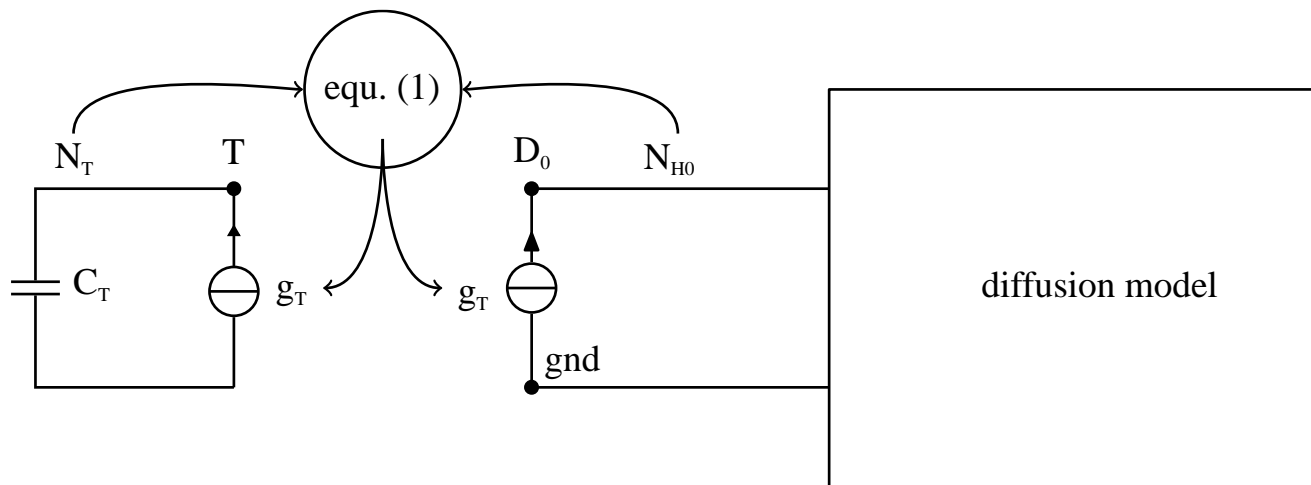
- Adding the hydrogen conservation law when $x > 0$, Fick's second law reads

$$\frac{\partial N_H(x, t)}{\partial t} - D_H \frac{\partial^2 N_H(x, t)}{\partial x^2} = 0$$



Implementation of the R-D Model

- In order to introduce in the compact model the time-invariance property and the memory effect necessary for dynamic stress simulation, we introduce a new structure of the compact model compared to HiCUM_AL V1*
- Aging model implemented in HiCuM compact model => HiCuM_AL V2
 - through recombination current parameter in the periphery, I_{REPS}
 - similar evolution as the trap density $N_T(x, t)$.
 - K_F (s^{-1}), K_R (cm^3s^{-1}) are represented by their corresponding compact model parameters $K_{F,I}$ (s^{-1}), $K_{R,I}$ ($cm.A^{-1}.s^{-1}$), respectively, and N_F by I_F (A) which is the final value of ΔI_{REPS} , (A).

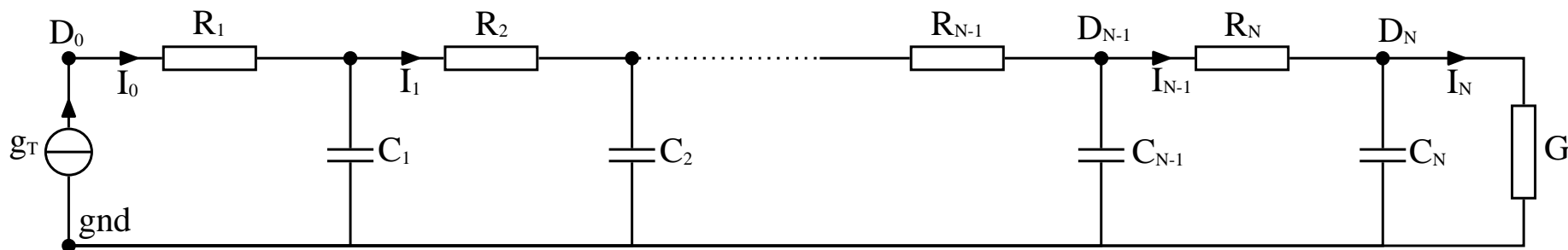


*C. Mukherjee, T. Jacquet, G. G. Fischer, T. Zimmer, and C. Maneux, " Hot Carrier Degradation in SiGeHBTs: A Physical and Versatile Aging Compact Model," IEEE Transactions on Electron Devices, vol. 64, no. 12, pp. 4861-4867, Dec. 2017.DOI: 10.1109/TED.2017.2766457.



Implementation in a Spice-like circuit simulator

- To simulate the diffusion model in a Spice-like circuit simulator
 - => organized around a finite set of nodes or variables.
- To obtain a time-invariant model
 - => the time does not appear explicitly in the equations but only in time derivatives.
 - => the distributed partial derivative equations are replaced by a finite set of first order differential equations implemented by a resistor-capacitor (R-C) network.
 - => As the physical system can only be considered for one dimension, an R-C ladder network is used.



R-C ladder network representing Hydrogen diffusion model.



Verilog-A model

- Hydrogen flow density is presented as currents I_N (ensuring conservation law)
- Hydrogen density as potential V_N at node D_N
- Voltage at D_0 is $V_0 = N_H(0, t)$, Input current is $I_0 = \Phi_H(0, t) = g_T(t)$.
- In frequency representation, introducing admittances $\tilde{Y}_n = \tilde{I}_N / \tilde{V}_N$, we have the recurrence:

$$\tilde{Y}_N = G$$

$$\tilde{Y}_{n-1} = \frac{1}{R_n + \frac{1}{j2\pi f C_n + \tilde{Y}_n}}; n = 1..N$$

- To reduce model parameter number, values of R_n and C_n follow geometrical sequences

$$R_n = R_1 \alpha_R^{n-1}, \quad C_n = C_1 \alpha_C^{n-1}$$

- Sequence identified to a finite difference approximation along the x axis, considering a geometrically increasing sequence of x.
 - => One dimensional system => same common ratio $\alpha_R = \alpha_C$.
 - => Identification of the diffusion compact model parameters => diffusion model equations => Fick's second law translated into the frequency domain

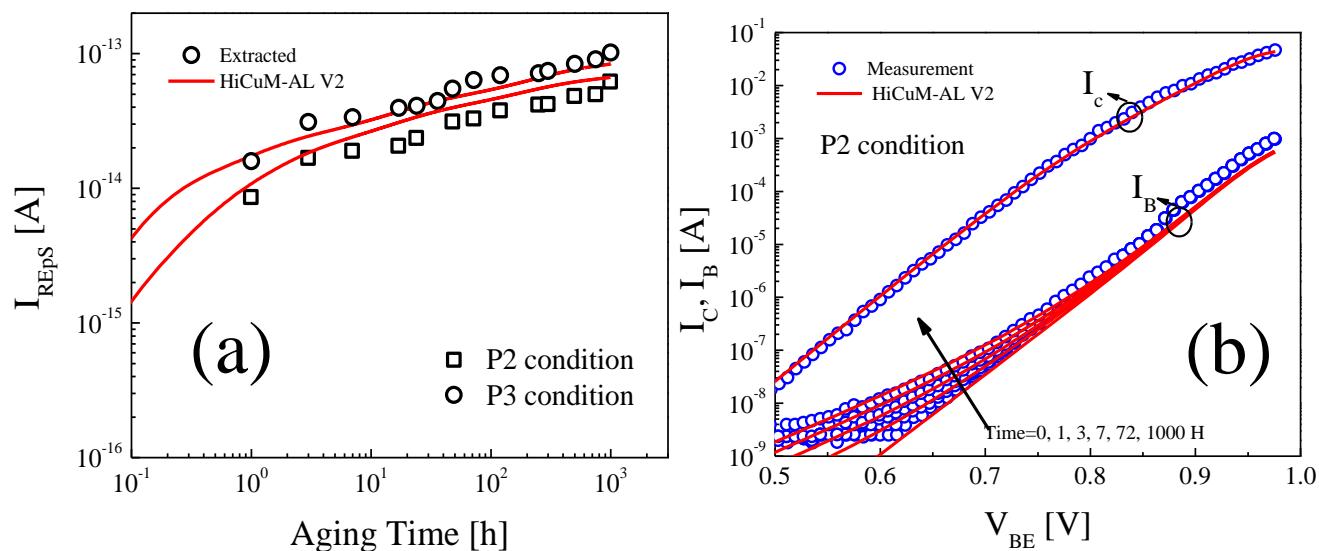
Limit conditions		$\tilde{Y}(f) = \tilde{\Phi}_H(0, f) / \tilde{N}_H(0, f)$
Very thick oxide	$L \rightarrow \infty; A_H = 0$	$(1 + j)\sqrt{\pi f D_H}$
Finite thickness: Hydrogen barrier at L	$\Phi_H(L, t) = 0$	$(1 + j)\sqrt{\pi f D_H} \tanh((1 + j)\sqrt{\pi f D_H} L)$
Finite thickness: Free hydrogen at L	$N_H(L, t) = 0$	$(1 + j)\sqrt{\pi f D_H} \coth((1 + j)\sqrt{\pi f D_H} L)$

LIMIT CONDITIONS FOR HYDROGEN DIFFUSION MODEL



Results : Infineon technology

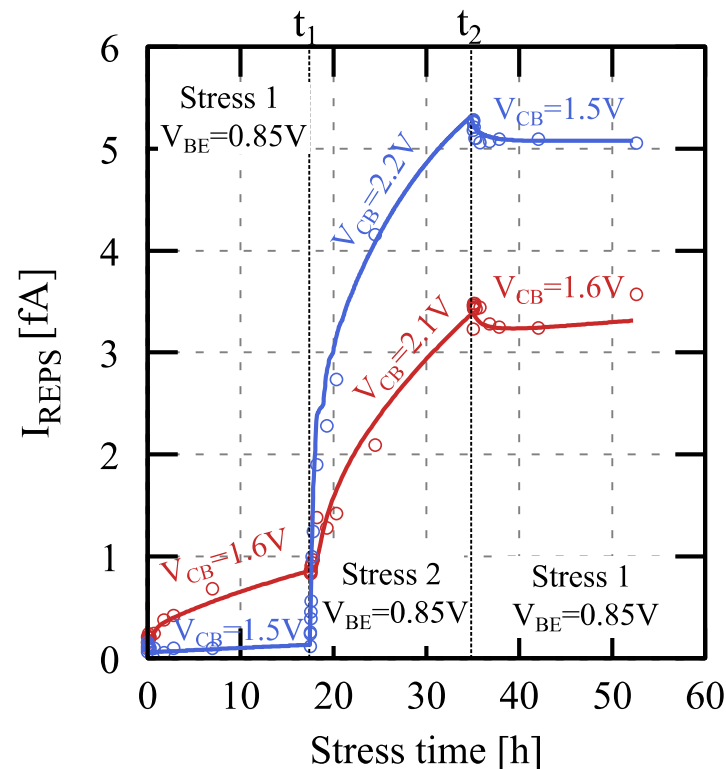
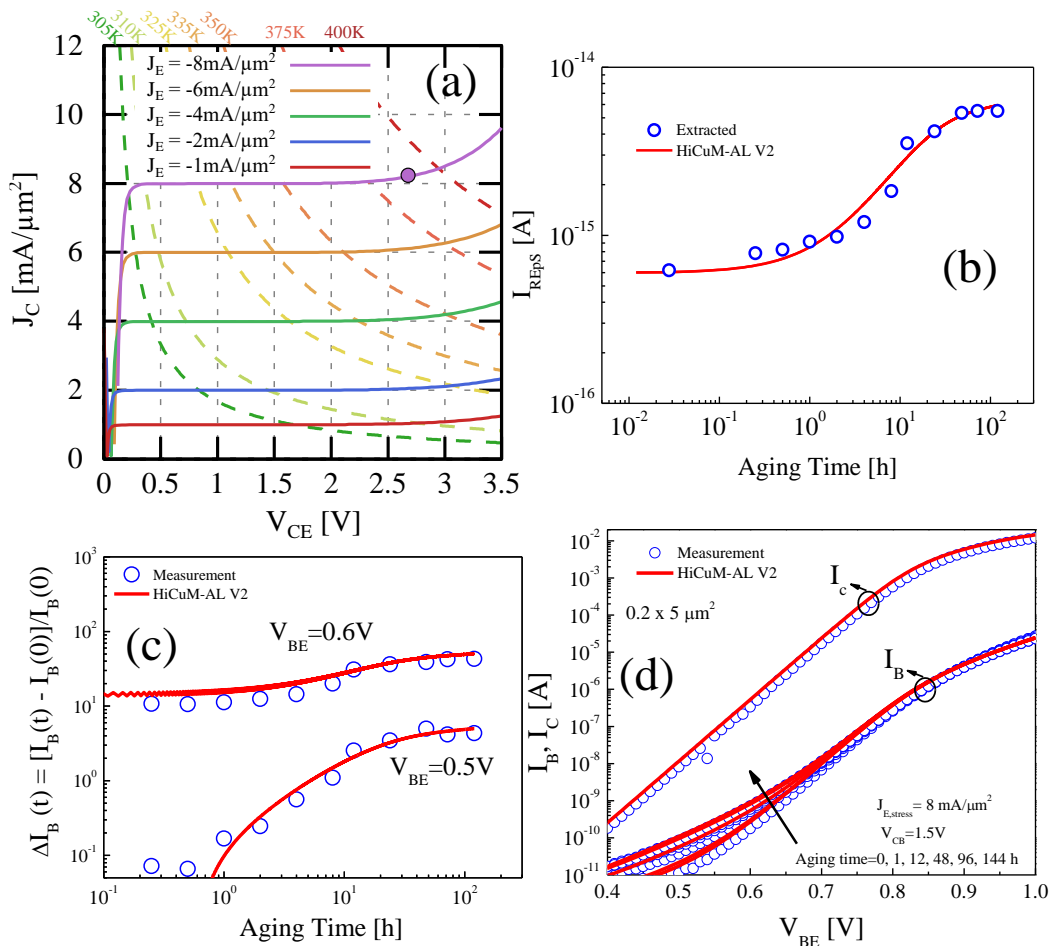
- Aging-tests were performed on SiGe NPN HBTs from Infineon Technologies.
- DUTs of drawn emitter dimension $0.2 \times 10 \mu\text{m}^2$ exhibit peak f_T/f_{MAX} of 240/380 GHz and a BV_{CEO} of 1.3V.
- Stress conditions P2 and P3 (above BV_{CEO} with $V_{CE} = 2\text{V}$, $J_C = 5 \text{ mA}/\mu\text{m}^2$ and $V_{CE} = 3\text{V}$, $J_C = 1 \text{ mA}/\mu\text{m}^2$, respectively)





Results : STMicroelectronics technology

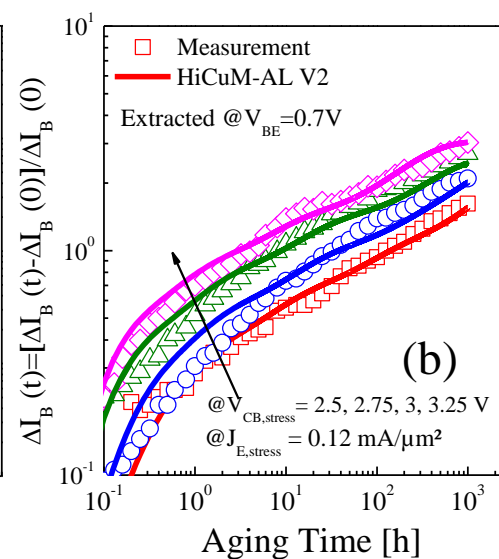
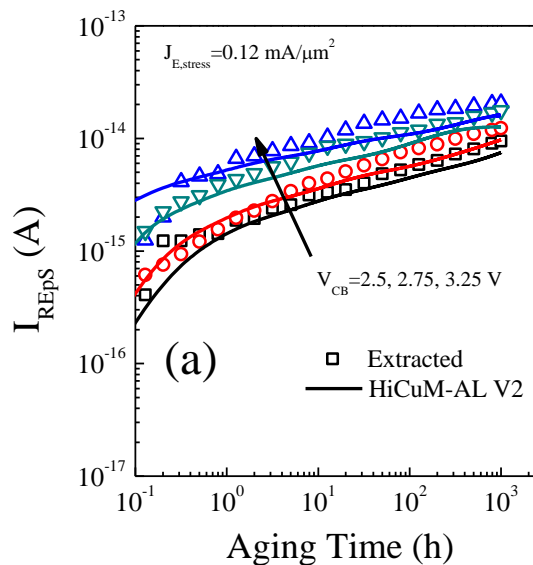
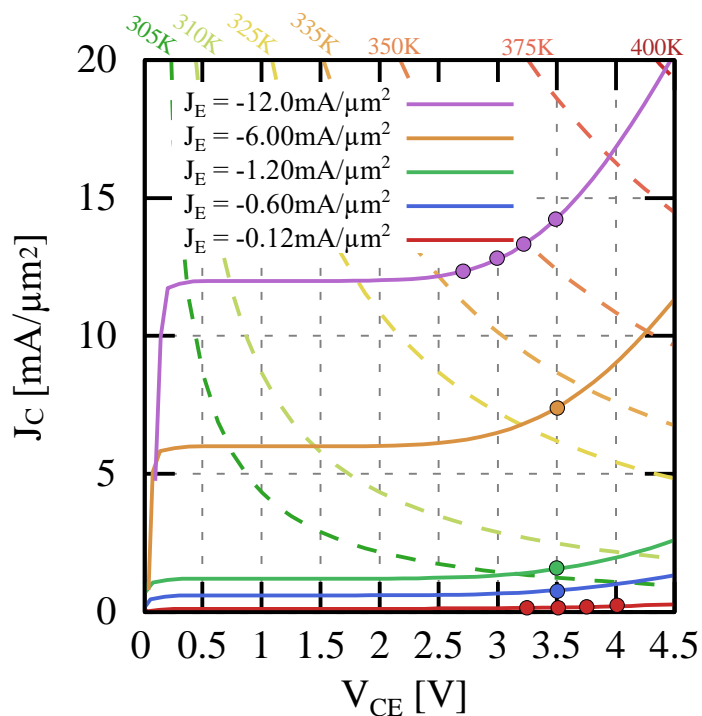
NPN SiGe HBTs based on an advanced BICMOS 55nm technology from STMicroelectronics featuring devices with a drawn emitter size of $0.2 \times 5 \mu\text{m}^2$ in CBECB configuration





Results : IHP technology 1/2

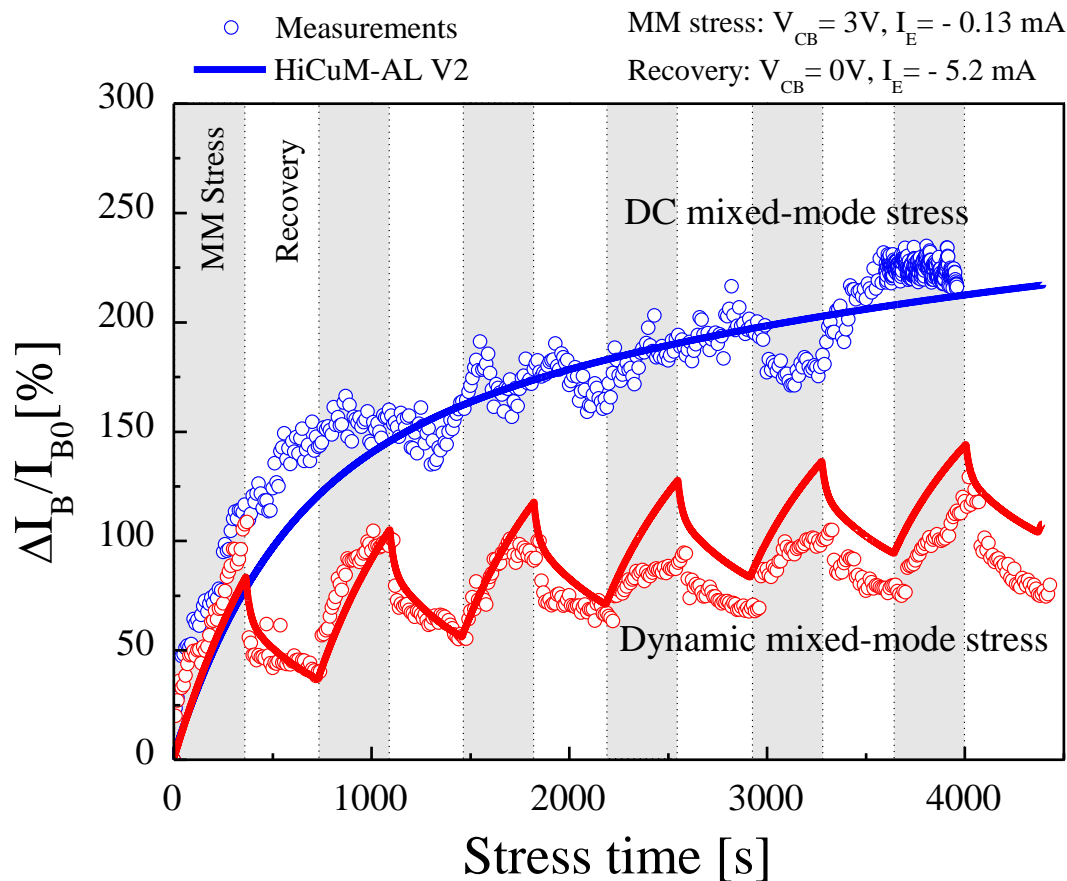
- Aging model validated on SG13S IHP technology featuring transistors in BEC configuration with an effective emitter area of $8 \times 0.16 \times 0.52 \mu\text{m}^2$.
- Aging tests were performed under various mixed-mode stress conditions.
- Very large spectrum of aging tests allowing analysis of hot-carrier degradation governed by the two accelerating factors: V_{CB} and J_E .
- In all cases, aging tests were performed up to 1000h of stress time.





Results : IHP technology 2/2

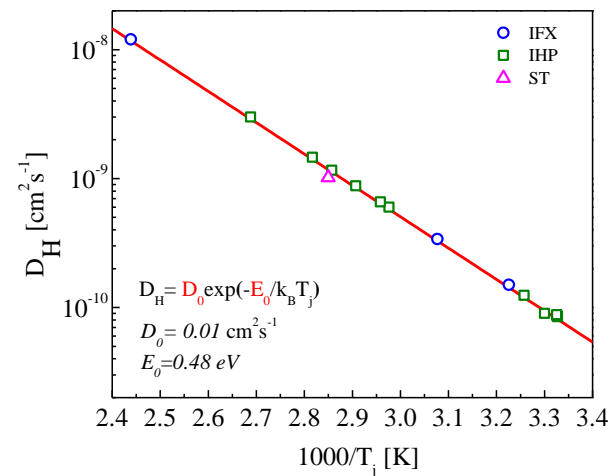
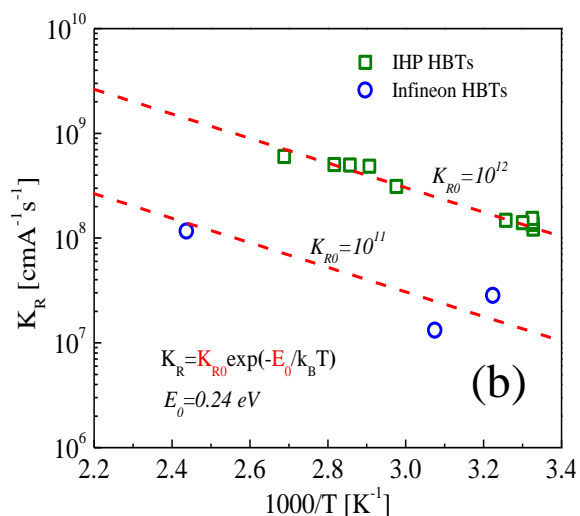
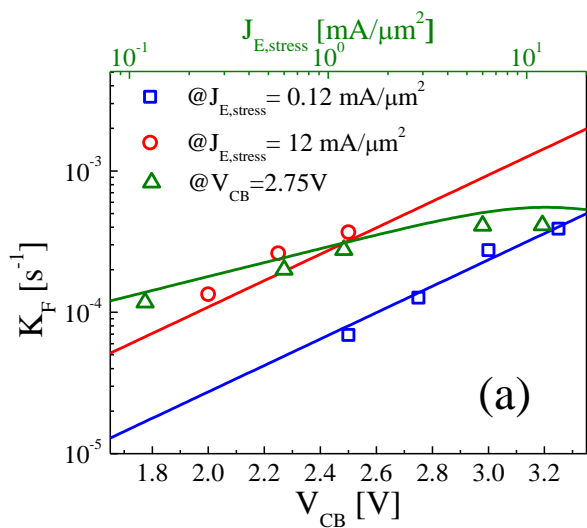
Evolution of excess base current for IHP technology under dynamic mixed-mode stress conditions comparing the measurements and HiCuM_AL V2





Model parameters analysis

- Forward rate, $K_{F,I}$, increases with $V_{CB, stress}$ following an exponential dependence while $J_{E, stress}$ is kept constant
- On the other hand, while $V_{CB, stress}$ is kept constant, $K_{F,I}$ demonstrates a peak value before starting to roll off.
 - => explained by a decrease in the C-B electric field at the onset of the Kirk effect at such high stress current densities
 - => resulting in a reduction in ΔI_B

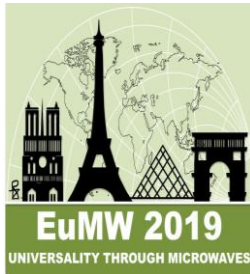




Conclusion

- A new physical and accurate aging compact model implementation for modern SiGe HBTs based on
 - the reaction-diffusion theory of hot-carrier degradation
 - a differential form of Fick's law of diffusion.
- The model implementation, although complex compared to its predecessor while employing additional transistor nodes in simulation, ensures invariance in time of the degradation characteristics.
- The aging model has been compared with long-term aging tests on various SiGe HBT technologies, yielding very good agreement thus confirming its accuracy and versatility.
- The proposed model formulation can easily be co-integrated with existing circuit design framework.
- With its strong physical basis, the proposed model can prove to be indispensable for ensuring stable circuit operation close to the SOA of the technology, through prediction of reliability-aware circuit architectures.

Thank you

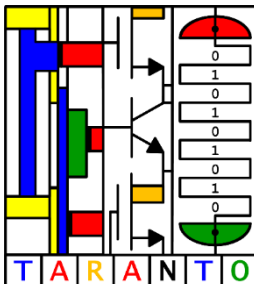


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