Scalability of the avalanche phenomenon in bipolar transistors

5th European HICUM Worskshop, June 6/7, 2005

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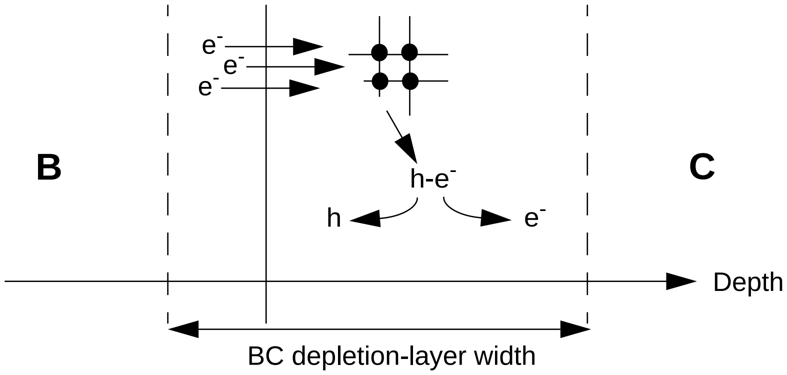
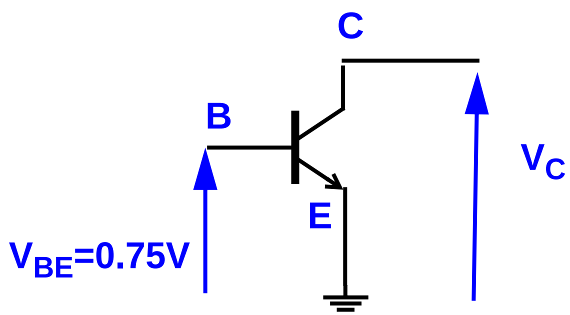
Outline

- ❒ **Introduction on the soft avalanche breakdown characterization and motivation of this work.**
- ❒ **Study of the geometrical dependence of the avalanche current.**
- ❒ **Modeling proposal and parameters extraction.**
- ❒ **Validation for HICUM 2.2 using VerilogA capabilities.**

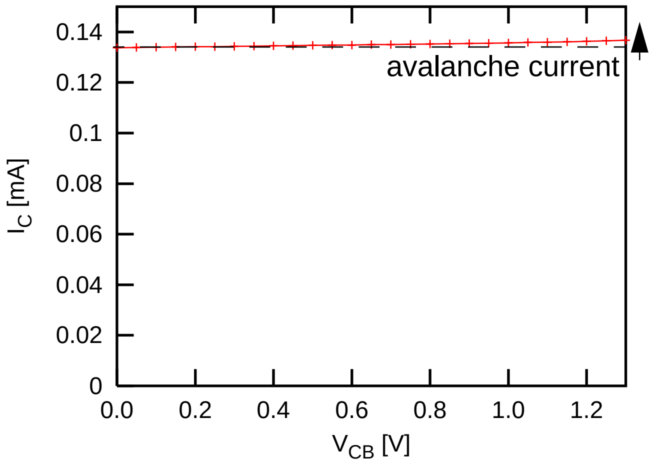
Soft breakdown characterization

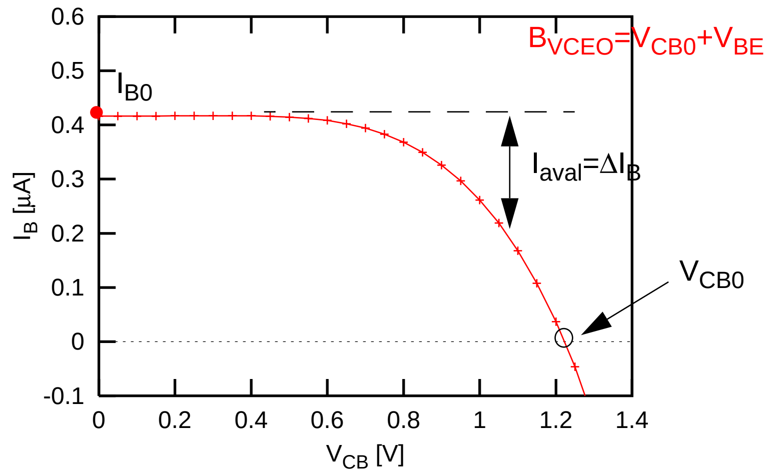
❒ **impact ionization phenomenon (NPN transistor):**





❒ **impact ionization phenomenon (NPN transistor):**





Avalanche current and multiplication factor M:

- The avalanche current is defined as:

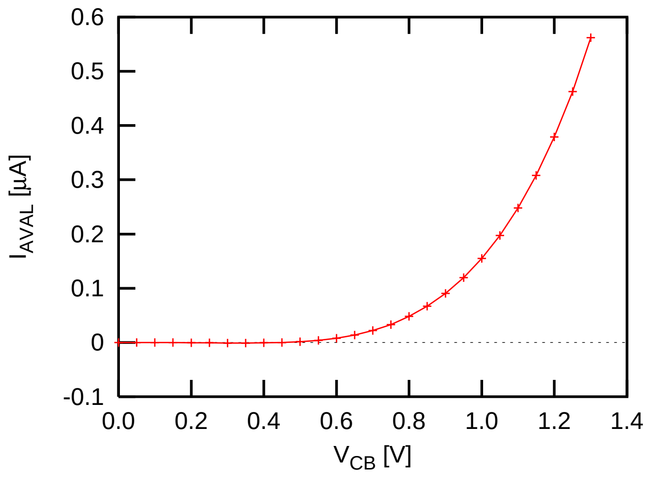
$$I_{aval} = I_{B0} - I_B(V_{CB})$$

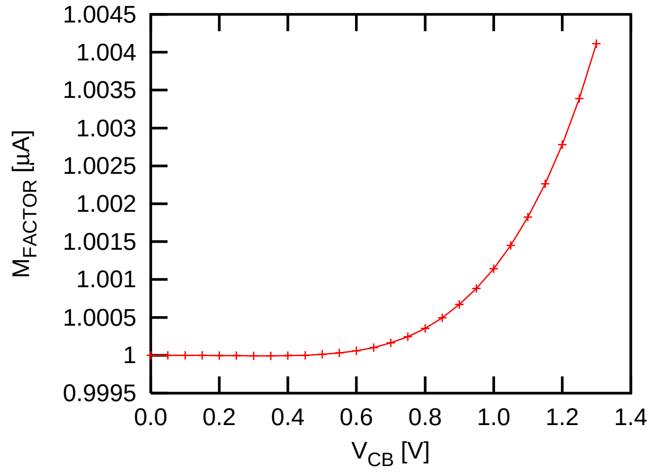
- The multiplication factor M is defined as:

$$I_C = M \cdot I_{C0} = I_{C0} + I_{aval}$$

thus

$$M = 1 + \frac{I_{aval}}{I_{C0}} = 1 + \frac{I_{aval}}{I_C - I_{aval}}$$





What about avalanche in HICUM?

❐ Presented at the BCTM 1998 [1]:

❍ planar breakdown occurring in the BC junction of the internal transistor below the emitter, the collector-base weak avalanche current is expressed as:

$$I_{AVL} = I_{TF} \cdot \alpha_n(x) = I_{TF} \cdot \int_0^{W_{BC}} a_n \cdot \exp\left\{-\frac{b_n}{|E(x)|}\right\} dx$$

W_{BC}, the width of the BC depleted region could be expressed with the internal BC depletion capacitance C_{JCi} leading to (with $\mathbf{F_{AVL}}$ and $\mathbf{Q_{AVL}}$ model parameters):

$$I_{AVL} = I_{TF} \cdot \mathbf{F_{AVL}} \cdot (V_{DCi} - V_{B'C'}) \cdot \exp\left\{\frac{-\mathbf{Q_{AVL}}}{C_{JCi} \cdot (V_{DCi} - V_{B'C'})}\right\}$$

❐ Geometry dependence of M factor:

$$M = 1 + \frac{I_{AVL}}{I_{C0}} = 1 + \mathbf{F_{AVL}} \cdot (V_{DCi} - V_{B'C'}) \cdot \exp\left\{\frac{-\mathbf{Q_{AVL}}}{C_{JCi} \cdot (V_{DCi} - V_{B'C'})}\right\}$$

❍ Q_{AVL} and C_{JCi} are both proportional to A_E, the effective area (I_{TF} as well):

M is geometrically independent!
(and for a scalable model I_{AVL} is proportional to A_E)

Measurements from ST tech.

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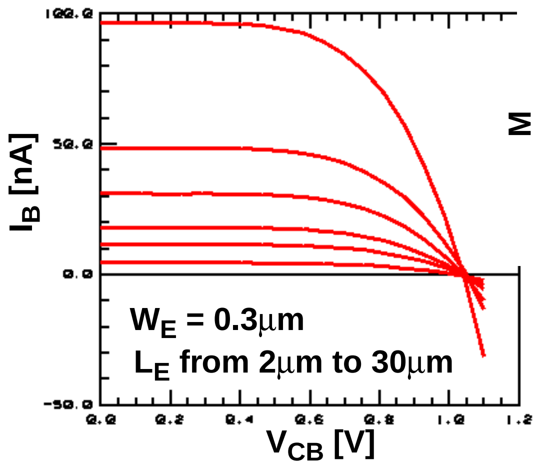
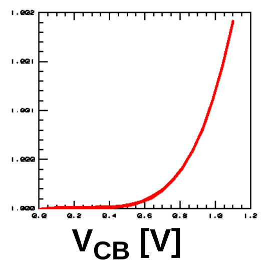
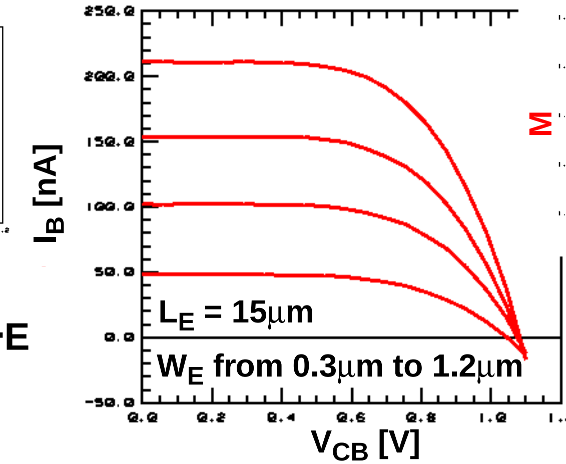
- Geometrical dependence of the avalanche current
- Modeling and extraction
- Model validation
- Conclusion

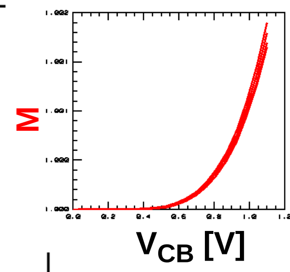
❒ 0.13µm technology, Bvceo=1.8V:





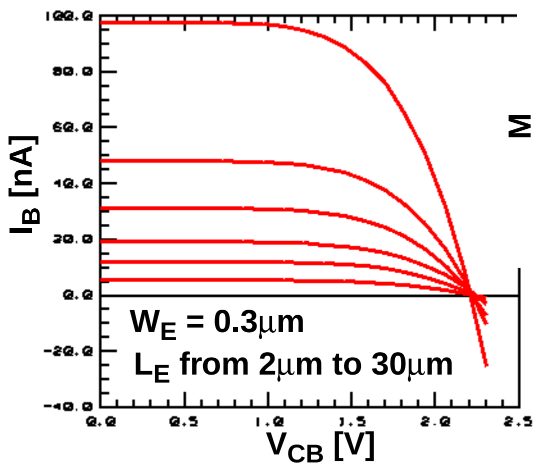
M = with L_E

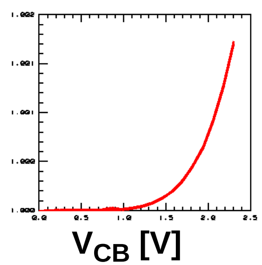




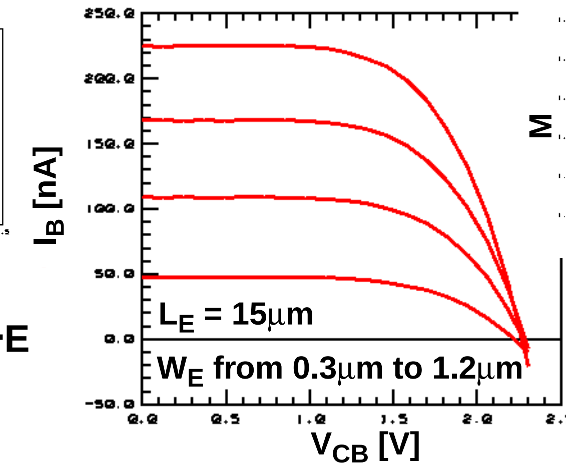
M ≈ with W_E

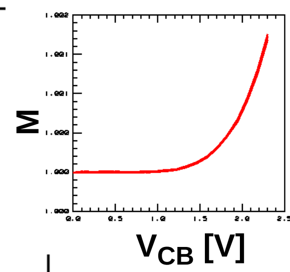
❒ 0.13µm technology, Bvceo=3.0V:





M = with L_E





M ≈ with W_E

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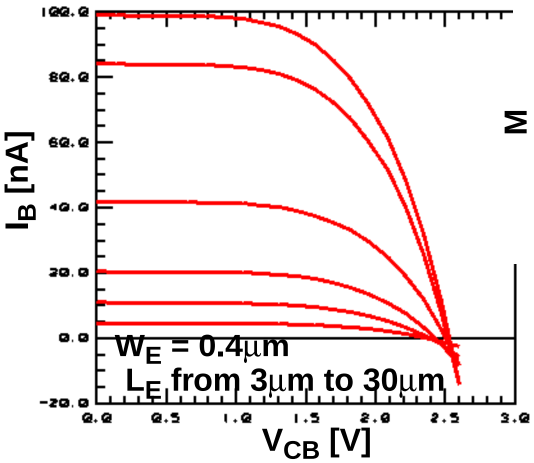
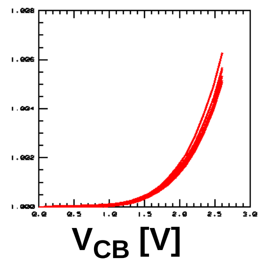
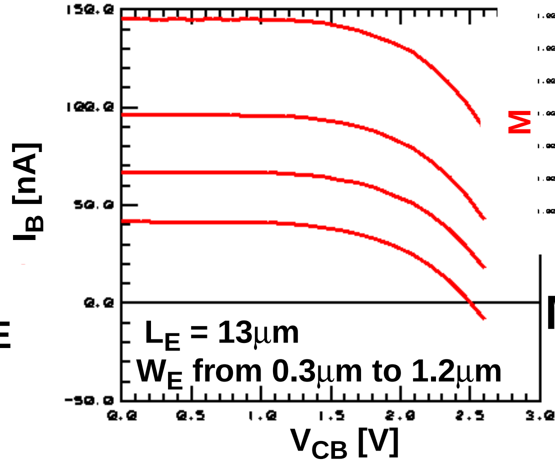
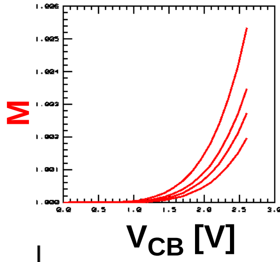
❐ 0.25µm technology, Bvceo=3.3V:





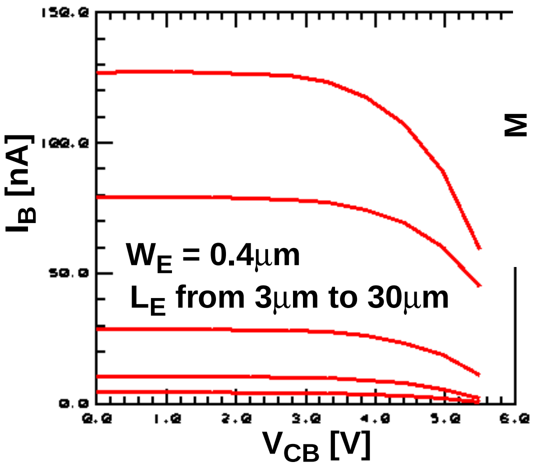
M ↓ with L_E

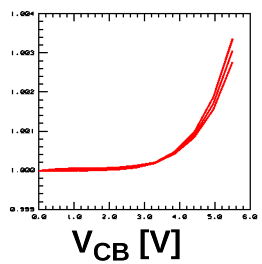




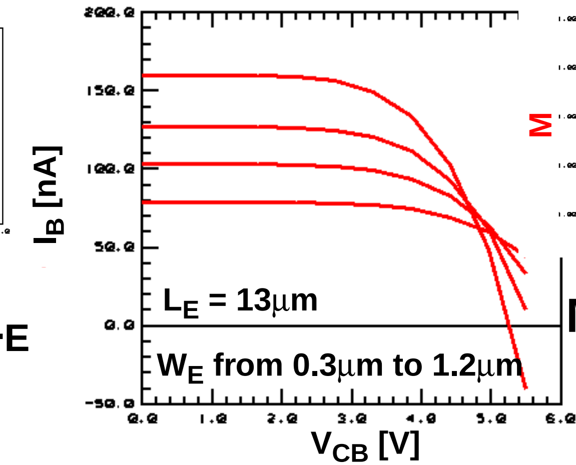
M ↓ with W_E!

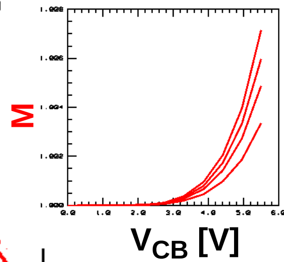
❐ 0.25µm technology, Bvceo=6.0V:





M = with L_E





M ↑ with W_E!

❐ **Unfortunately, the M factor does not overlay for every bipolar transistors of every technologies, clear trends could be noticed!**

Geometrical dependence of I_{aval}

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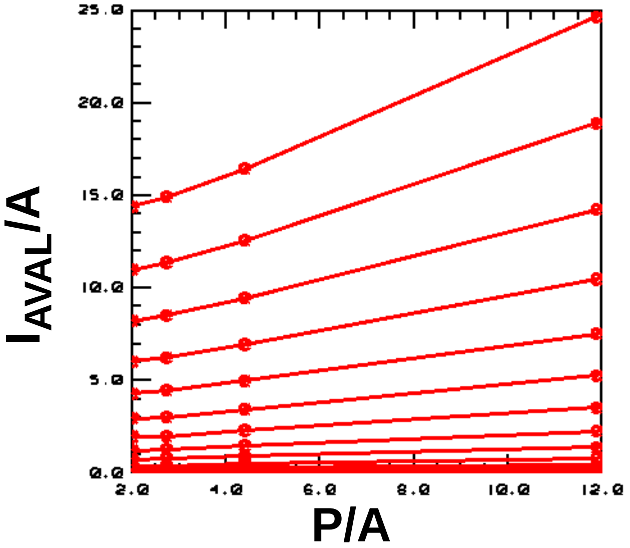
❒ **To study the geometrical dependence of the avalanche current, area and peripheral components could be extracted, assuming:**

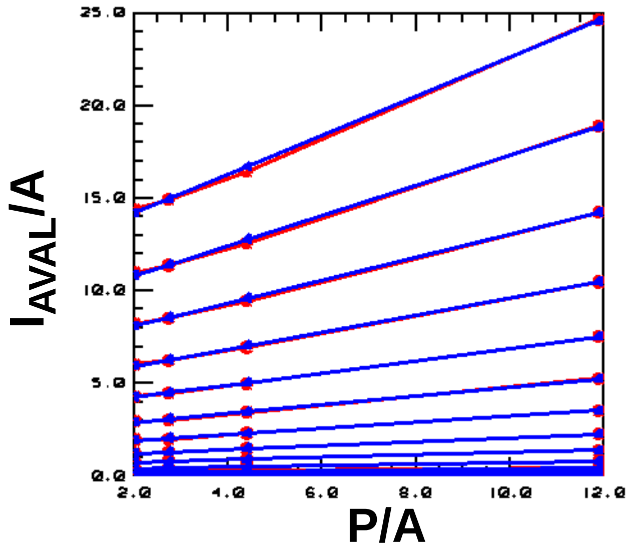
$$I_{aval} = I_{avalPERI} \cdot P + I_{avalAREA} \cdot A \quad (1)$$

leads to: $$\frac{I_{aval}}{A} = I_{avalPERI}\,\frac{P}{A} + I_{avalAREA} \quad (2)$$

allows an 'Y=a.X+b' type of direct extraction with $Y = \frac{I_{aval}}{A}$ and $X = \frac{P}{A}$!

❒ **0.13µm technology with Bvceo=1.8V, extraction performed with 4 devices with different W_E (L_E =15µm) for the whole V_{BC} range:**





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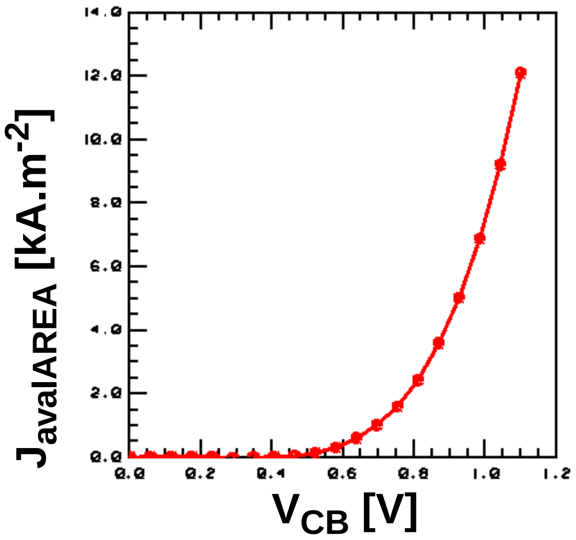
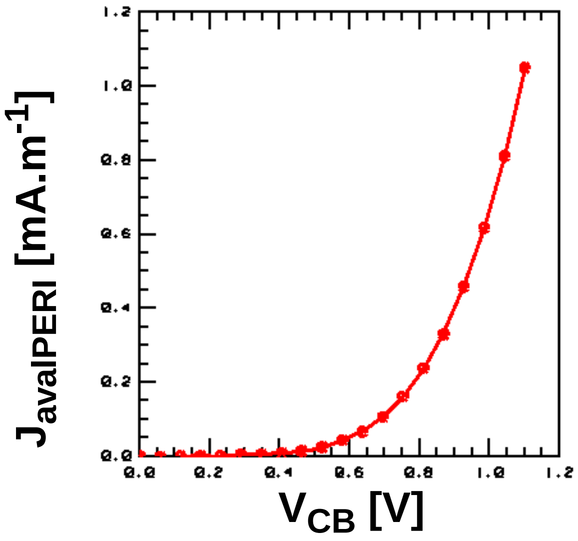
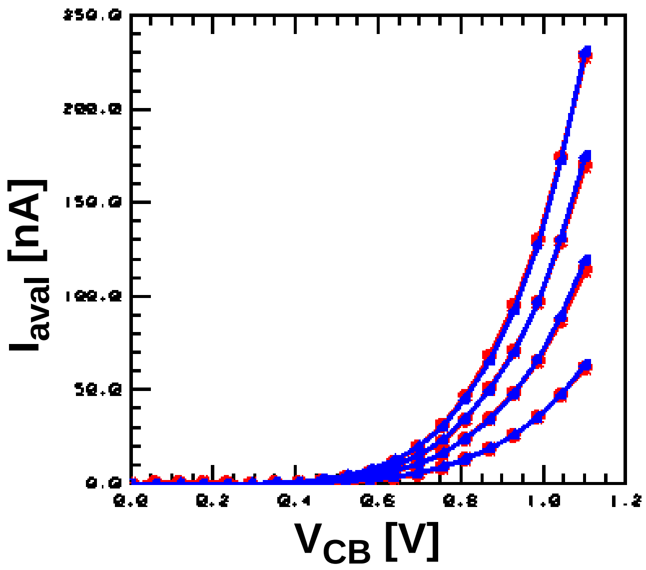
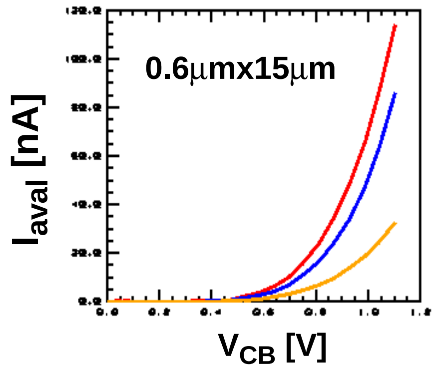
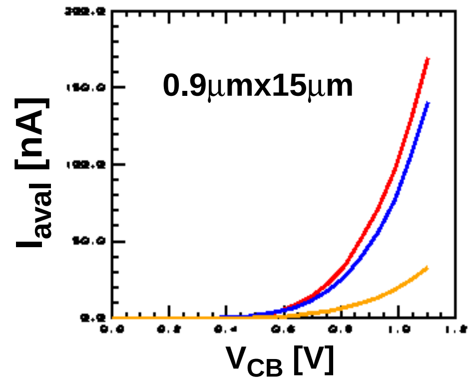




❍ Validation on the avalanche current data:

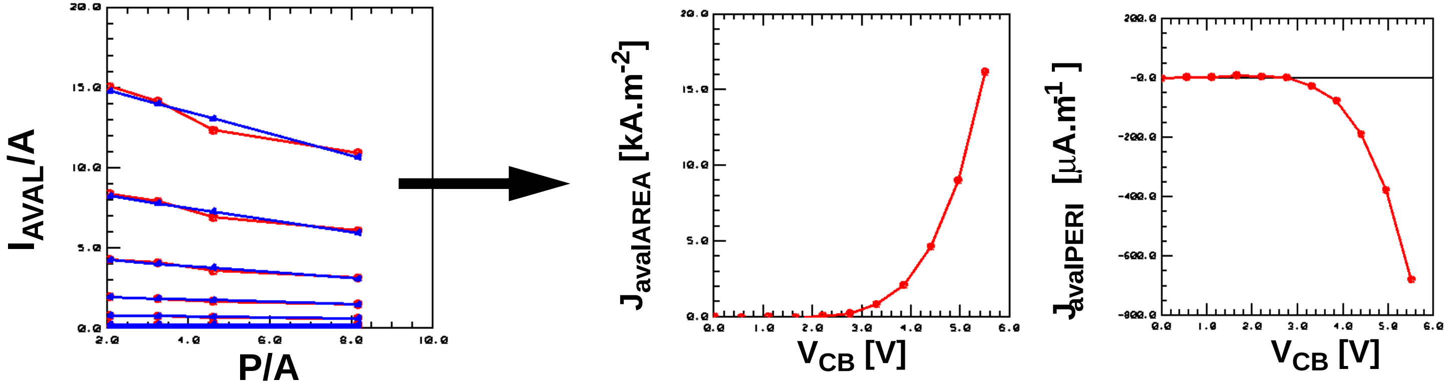






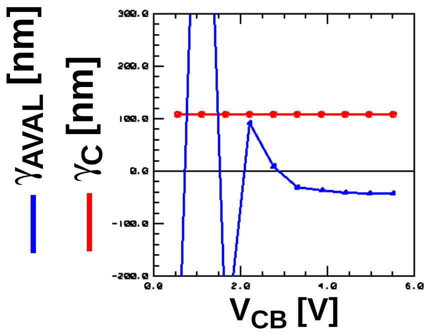
Influence of the dimensions

❒ **Extraction for a 0.25µm technology, f_T=30GHz and Bvceo=6.0V using the real emitter dimensions (drawn dimensions-spacer with):**



❍ Peripheral component could be negative, not physical! The area considered is too large!

❍ Which dimensions have to be used?... ➪ extraction of γ_{AVAL} which defines a surface collecting all the avalanche current (identically to γ_C for I_C):



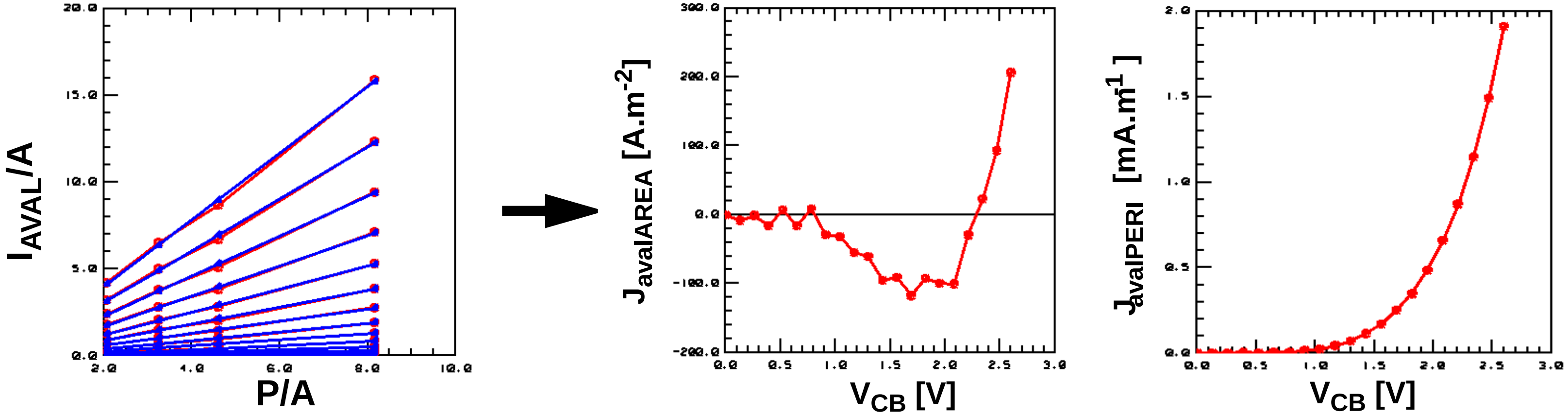
➪ γ_{AVAL} <0, area is too large! If real dimensions are reduced by 2xγ_{AVAL} peripheral component ≈ 0

➪ $\gamma_{AVAL} \neq \gamma_C$, I_{aval} has not the same lateral distribution than I_C!

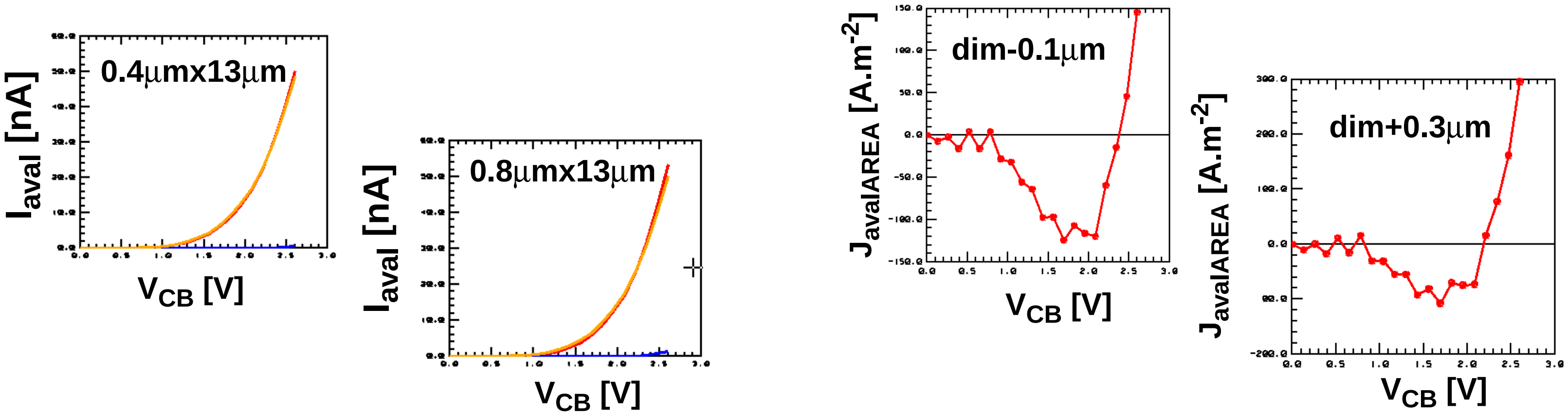
➪ γ_{AVAL} varies with V_{BC}

Particular case

❒ **Extraction for a 0.25µm technology, Bvceo=3.3V with real dimensions (4 devices with different W_E and L_E =13µm):**



❍ Area component is negligible! Avalanche current is mostly peripheral whatever the chosen dimensions!



Intermediate conclusions

❐ In most of the case I_{aval} is both area and peripheral:

❍ Difficult to determine their respective contribution!... both currents are dependent of the dimensions considered (the peripheral component compensates the overestimation of the area!): emitter cut (local collector implant=SIC), real emitter dimensions, other dimensions...difficult to have physical results!

❍ γ_{AVAL} helps to define the minimum area in order to get a positive peripheral avalanche current.

❍ $\gamma_{AVAL} \neq \gamma_C$ indicates that I_{aval} has not the same lateral distribution than I_C! ➪ I_{aval} could not be proportional to the effective area!

if M varies with transistor geometry two current sources are required to modelled accurately the avalanche current!

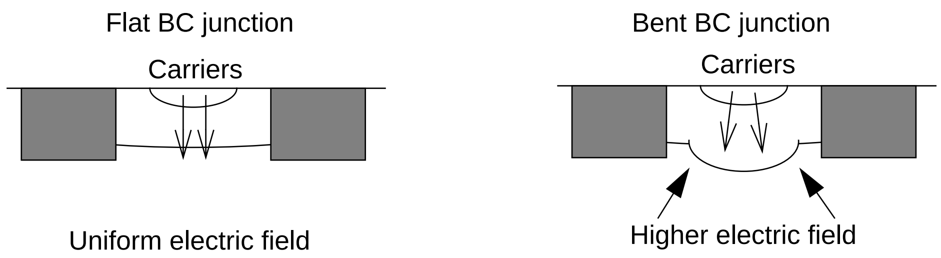
❐ If I_{aval} is mostly peripheral:

A current source proportional to the perimeter is required!

❐ What could physically explained this differences between technologies?

❍ The generation of avalanche current is the result of both the electric field in the BC depleted region and the collector current distribution over this junction.

❍ The electric field distribution is sensitive to the bending of the junction (SIC or not...):



❍ The lateral extension of the collector current flow through the BC junction depends on the 2D junction profile (could be different from the lateral extension in the BE junction)

➩ The distribution of the generated avalanche current in the BC depleted region depends strongly on the device architecture!

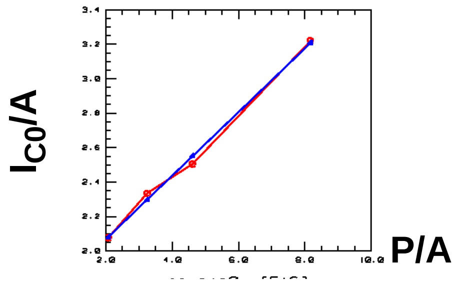
Modeling and extraction

- **Both area and peripheral avalanche current have been extracted, the M factor needs to be defined,** $M = 1 + \frac{I_{AVL}}{I_{C0}}$ **, so I_{C0} be has to defined!**

- **The I_{C0} value should be coherent with the avalanche current extraction so:**
  - assuming $I_{c0} = I_C(V_{CB} = 0) = I_{C0P} \cdot P + I_{C0A} A$ (Early effect neglected) leads to:

$$\frac{I_{c0}}{A} = I_{C0P}\frac{P}{A} + I_{C0A}$$

➪ direct extraction



I_{C0P} = slope

I_{C0A} = cut

  - The approach is validated, I_{C0A} and I_{C0P} are extracted!
  - M_A and M_P could be defined:

$$M_A = 1 + \frac{I_{avalAREA}}{I_{C0A}} \quad \text{and} \quad M_P = 1 + \frac{I_{avalPERI}}{I_{C0P}}$$

- **M needs to be modelled with a simple equation, Miller has defined M with an empirical law as [2]:**

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BVC}\right)^{MF}} \qquad (3)$$

where MF is the exponent multiplication factor and BVC is assumed to be the BC planar junction breakdown.

- **Convergence problem for V_{CB}=BVC! Thus as M is very close to 1, using the Taylor's series, M could be approximated by:**

$$M = \exp\left(\left(\frac{V_{CB}}{BVC}\right)^{MF}\right) \qquad (4)$$

- **MF and BVC direct extraction (similar method extended to HICUM avalanche model explained in [3]):**

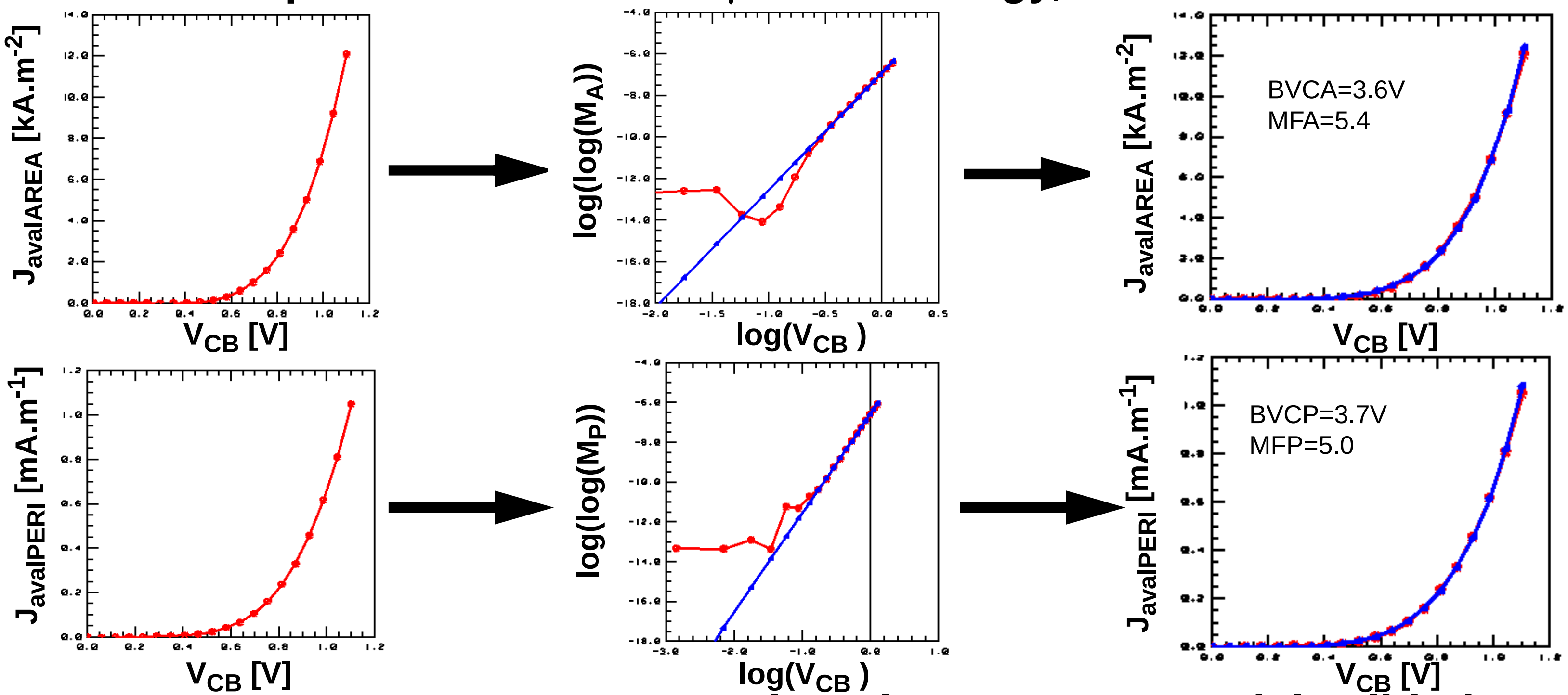
$$\log(\log(M))M = MF \cdot \log(V_{CB}) - MF \cdot \log(BVC)$$

- **Linear fit on log(log(M))=f(log(V_{CB})) characteristic yields:**

$$MF = slope$$

$$BVC = \exp(-cut/slope)$$

- **extraction performed for a 0.13µm technology, Bvceo=1.8V:**



measurement **extraction plot** **model validation**

- **The total avalanche current could be calculated as:**

$$I_{aval} = I_{avalPERI} \cdot P + I_{avalAREA} \cdot A$$

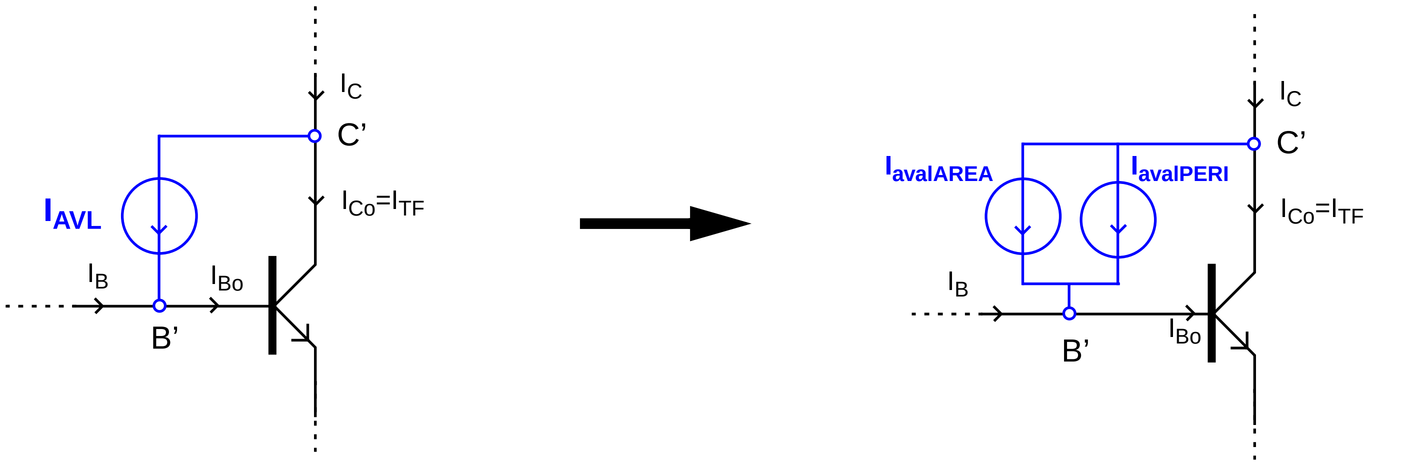
with

$$I_{avalAREA} \cdot A = I_{C0A} \cdot A \cdot (M_A - 1) = I_A \cdot \left(\exp\left(\left(\frac{V_{CB}}{BVCA}\right)^{MFA}\right) - 1\right) \qquad (5)$$

$$I_{avalPERI} \cdot P = I_{C0P} \cdot P \cdot (M_P - 1) = I_P \cdot \left(\exp\left(\left(\frac{V_{CB}}{BVCP}\right)^{MFP}\right) - 1\right) \qquad (6)$$

Model validation

- Availability of a new verilogA code for HICUM 2.2!
- In verilogA code, the HICUM avalanche current generator has been replaced by two current generators in parallel:



- The previous new parameters **QAVL** and **FAVL** are replaced by 6 new ones I_A, **BVCA**, **MFA** and I_P, **BVCP**, **MFP**.
- Within the ICCAP environment, simulation can be performed with the verilogA code with ADS simulator!

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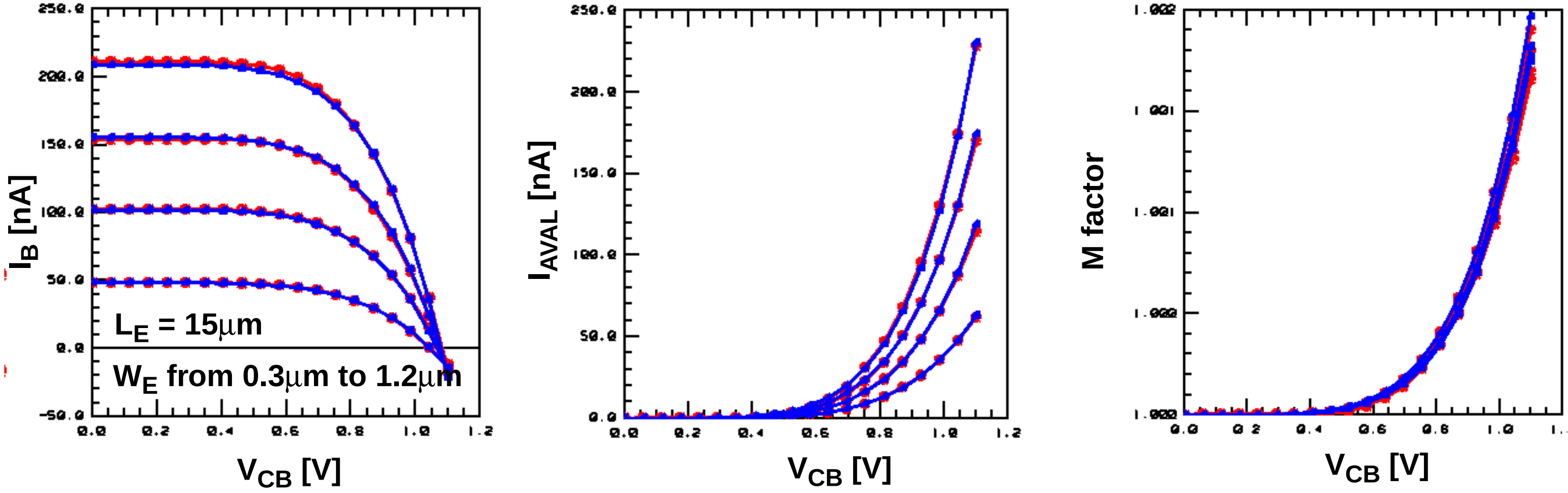
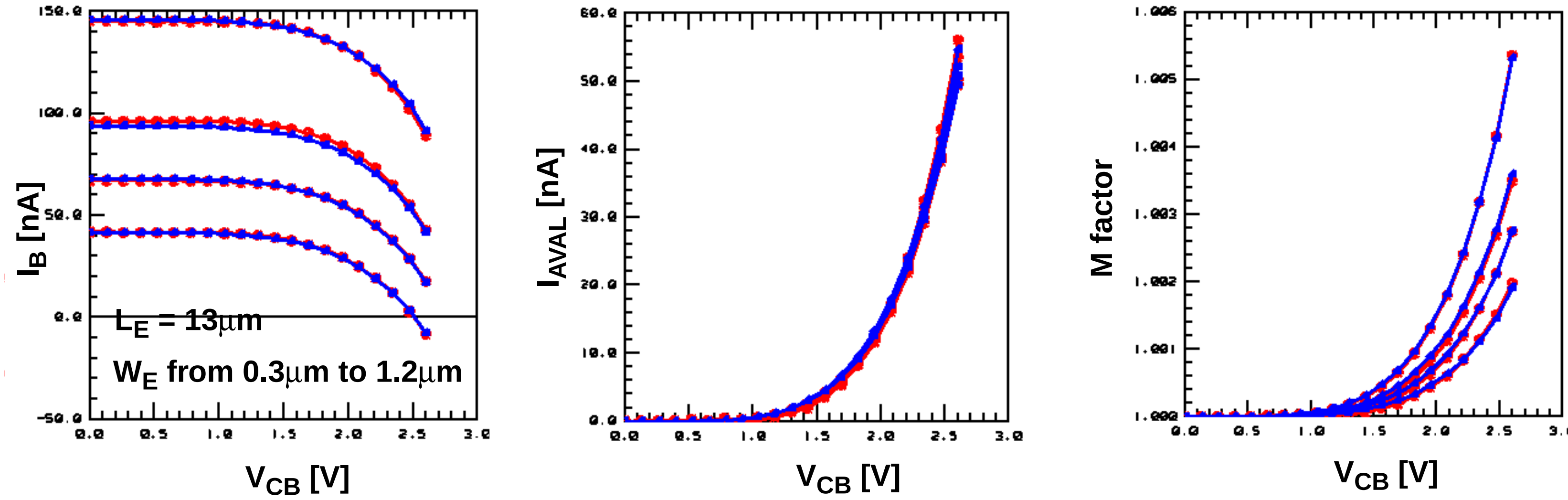
❐ Experimental results for a 0.13µm technology, Bvceo=1.8V:



❐ Results for a 0.25µm technology, Bvceo=3.3V:



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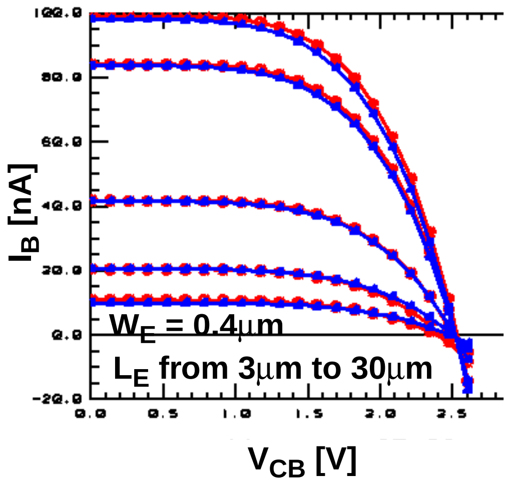
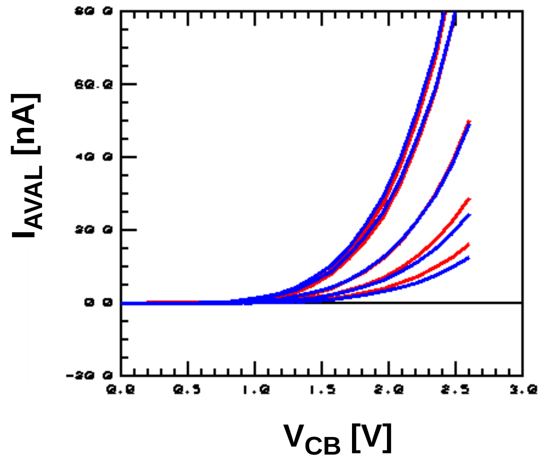
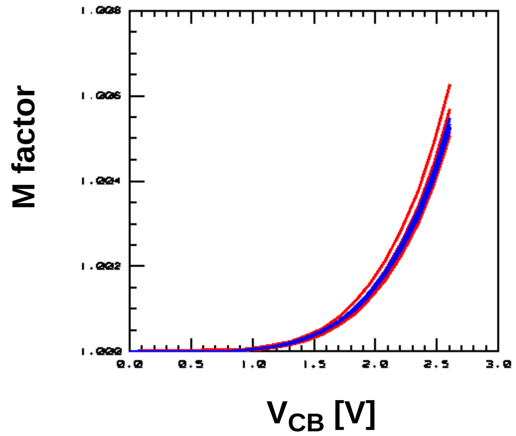
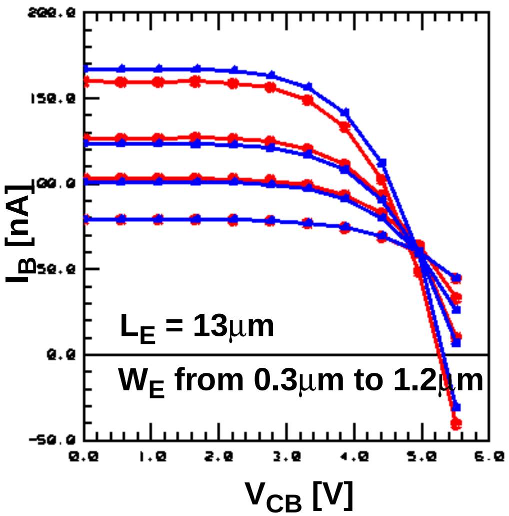
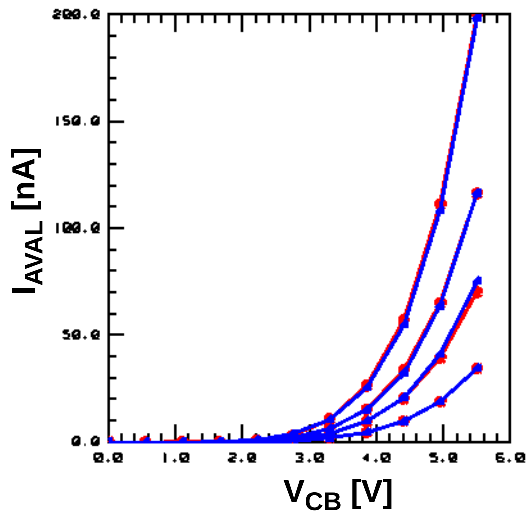


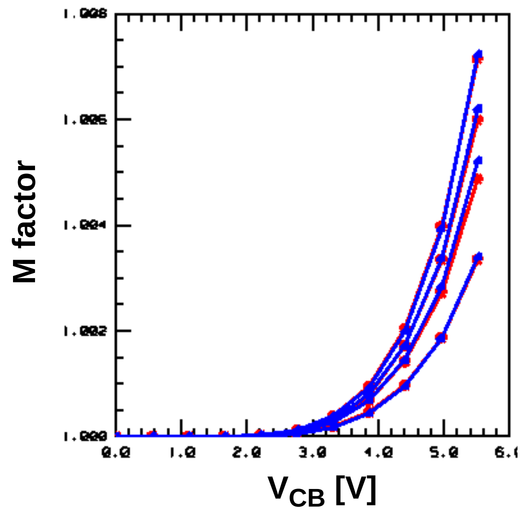




❒ **Results for a 0.25µm technology, Bvceo=6.0V:**







❒ **This approach allows to model with accuracy all type of weak avalanche breakdown!**

Conclusion

- **Proposal and validation of a area/peripheral model of avalanche current for scalable model improvement (for technologies with a geometry dependent M factor).**
- **Possible improvement in term of more physical formulation of the avalanche currents?...split of I_{TF} for avalanche current generation?**
- **Possibility to split the two current generators along R_{BX}?**
- **How to introduce this effect in current HICUM model for scalable libraries?**
- **Do others users face the same issues in soft breakdown modeling?**

Thanks and Reference

Thanks to:

- Christian Raya for his help in programming ICCAP.
- Anjan Chakravorty for his HICUM 2.2 verilogA code.
- Franz Sischka for his ICCAP .mdl file to simulate with verilogA code.
- Didier Céli for his help and explanations about avalanche modeling.

References:

[1] M. Schröter, Z. Yan, T.Y. Lee and W. Shi, “A Compact Tunneling Current and Collector Breakdown Model”, Proceedings BCTM, Minneapolis, 1998.

[2] S. L. Miller, “Ionization rates for electrons and holes in Silicon”, Phys. Rev, vol. 105, pp1246-1249, 1957.

[3] D. Céli, D. Berger, “Direct extraction of base-collector weak avalanche HICUM model parameters”, HICUM users’ meeting, Minneapolis, 1998.