DIRECT EXTRACTION OF BASE-COLLECTOR WEAK AVALANCHE HICUM MODEL PARAMETERS

Didier CELI and Dominique BERGER

STMicroelectronics, Device Modelling
850, rue jean Monnet
F-38926 Crolles Cedex

HICUM User's Meeting

September 30, 2001

Minneapolis, MN

DIRECT EXTRACTION OF BASE-COLLECTOR WEAK AVALANCHE HICUM MODEL PARAMETERS

INTRODUCTION

- Whatever the complexity of the model is, we need to find and to develop extraction methods as simple as possible, preferably straightforward, without optimization loop and without initial guess.
- This is the goal that persons who develop extraction routines must have always in their mind.
- This is the key point if we want to obtain physical parameters rather than fitting parameters, uncorrelated to the others and less affected by the measurement accuracy. It will allow, afterward, to have scaleable parameters and parameters well correlated to the process variations, which is important for best and worst case parameter prediction.
- Based on these remarks, a direct extraction method for the HICUM breakdown parameters, F_{AVL} and Q_{AVL}, is described step by step.
- These parameters are determined straightforward, without optimization loop, using only a simple linear regression.
- This method is validated from experimental results, on transistors of various BiCMOS processes, with different structures and geometries.

MODEL EQUATIONS

- The HICUM base-collector (BC) breakdown model is based on a similar approach than those used in MEXTRAM (503) [1] or VBIC [2] and was presented to the BCTM 1998 [3].

- The collector-base weak avalanche current, in parallel with the internal base-collector junction, is based on the well-known relation

$$I_{AVL} = I_{TF} \cdot \alpha_n(x) = I_{TF} \cdot \int_0^{W_{BC}} a_n \cdot \exp\left\{-\frac{b_n}{|E(x)|}\right\} dx \quad (1)$$

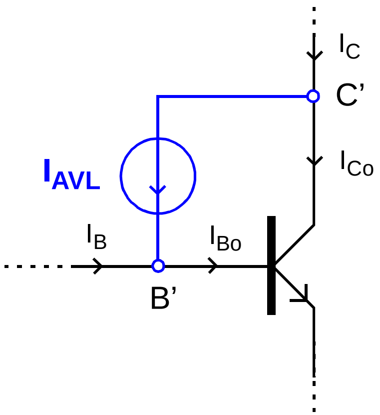
The ionization rate a_n and the critical field b_n are coefficients describing the avalanche process, E(x) is the electric field within the BC space charge layer (SCL), W_{BC} is the width of the BC SCL and I_{TF} is the forward transfer current.

- Substituting the electric field in equation (1) with the internal BC depletion capacitance C_{JCi}, the avalanche generation current can be approximated by

$$I_{AVL} = I_{TF} \cdot \mathbf{F_{AVL}} \cdot (V_{DCi} - V_{B'C'}) \cdot \exp\left\{\frac{-\mathbf{Q_{AVL}}}{C_{JCi} \cdot (V_{DCi} - V_{B'C'})}\right\} \quad (2)$$

the model parameters $\mathbf{F_{AVL}}$ and $\mathbf{Q_{AVL}}$ are related to the ionization coefficients a_n and b_n by

$$\begin{cases} \mathbf{F_{AVL}} = 2 \cdot \dfrac{a_n}{b_n} \\ \mathbf{Q_{AVL}} = \dfrac{\varepsilon_{si} \cdot b_n \cdot A_E}{2} \end{cases} \quad (3)$$



$$I_C = M \cdot I_{Co} = I_{Co} + I_{AVL}$$

$$M = 1 + \frac{I_{AVL}}{I_{Co}}$$

M is the multiplication factor

PARAMETER EXTRACTION STRATEGY (1)

- Assumptions
  - In equation (2) the transfer current I_{TF} is supposed to be equal to the collector current I_{Co}
  - The model parameters of the internal BC junction capacitance are supposed known [4], [5].
  - The internal BC depletion capacitance is approximated by

$$C_{JCi} = \frac{C_{JCi0}}{\left(1 - \frac{V_{B'C'}}{V_{DCi}}\right)^{ZCi}} \qquad (4)$$

- The parameters $\mathbf{F_{AVL}}$ and $\mathbf{Q_{AVL}}$ are determined from the dependence of the multiplication factor M with the BC voltage

- With the above assumptions and from equations (2) we can write

$$M - 1 = \frac{I_{AVL}}{I_{C0}} = \mathbf{F_{AVL}} \cdot (V_{DCi} - V_{B'C'}) \cdot \exp\left\{\frac{-\mathbf{Q_{AVL}}}{C_{JCi} \cdot (V_{DCi} - V_{B'C'})}\right\} \qquad (5)$$

- For M > 1 (avalanche region), and defining $V_j = V_{DCi} - V_{B'C'}$, with Vj the total potential across the BC junction, (5) can be re-written as

$$\ln(M - 1) = \ln(\mathbf{F_{AVL}}) + \ln(V_j) - \frac{\mathbf{Q_{AVL}}}{C_{JCi} \cdot V_j} \qquad (6)$$

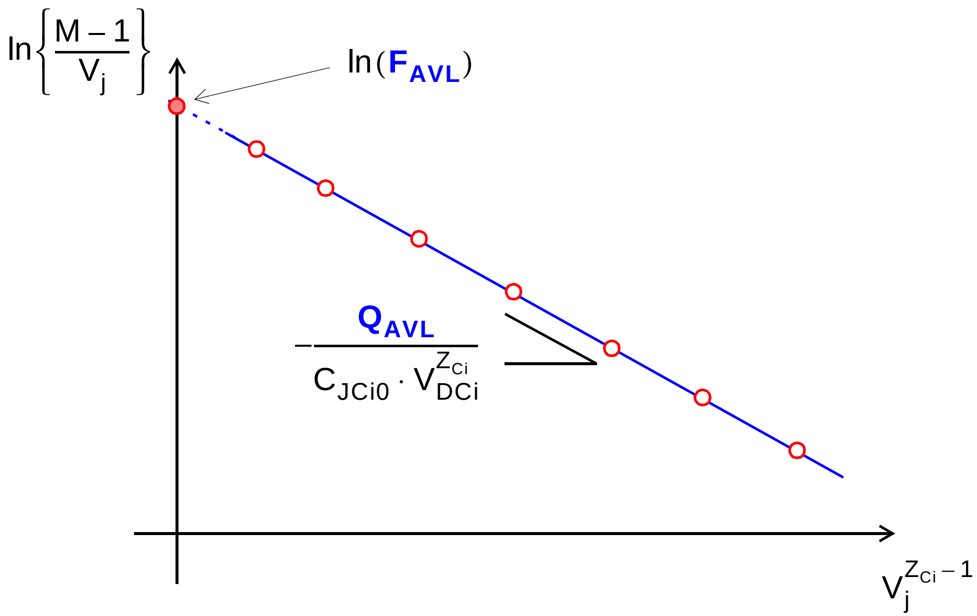
Substituting C_{JCi} in (6) by its expression (4), leads to the final result

$$\ln\left\{\frac{M - 1}{V_j}\right\} = \ln(\mathbf{F_{AVL}}) - \frac{\mathbf{Q_{AVL}}}{C_{JCi0} \cdot V_{DCi}^{Z_{Ci}}} \cdot V_j^{Z_{Ci} - 1} \qquad (7)$$

PARAMETER EXTRACTION STRATEGY (2)

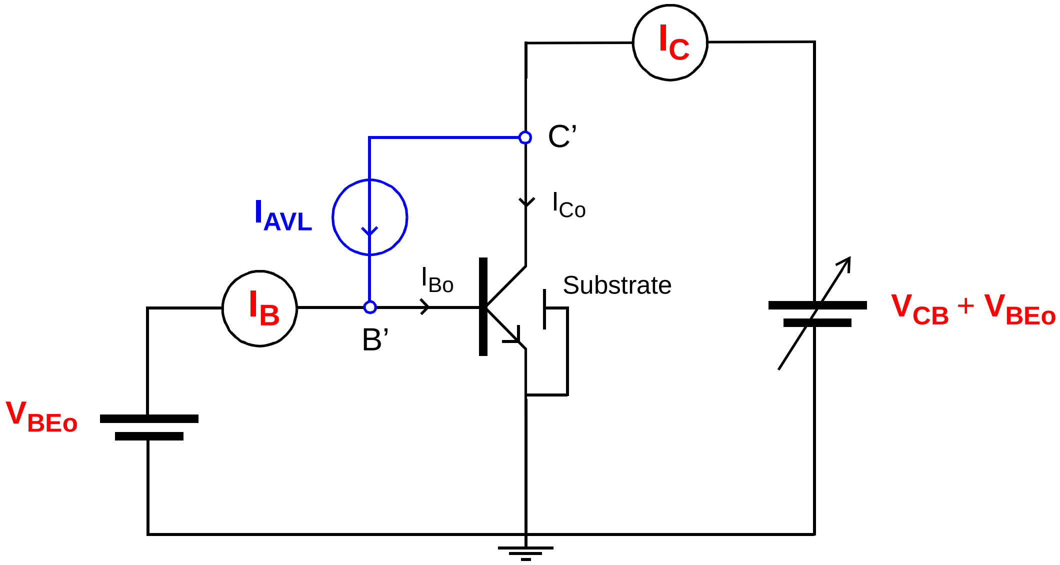
- In conclusion, the characteristic $\ln\left\{\frac{M-1}{V_j}\right\}$ versus $V_j^{Z_{Ci}-1}$, defined by equation (7), is linear. Therefore **Q_{AVL}** can be deduced from the *slope* and **F_{AVL}** from the $y_{intercept}$ of this characteristic

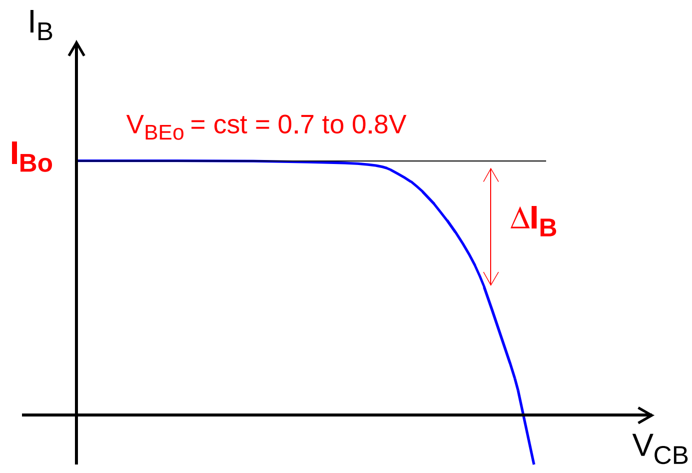
$$\begin{cases} Q_{AVL} = -slope \cdot C_{JCi0} \cdot V_{DCi}^{Z_{Ci}} \\ F_{AVL} = \exp(y_{intercept}) \end{cases}$$



- **Q_{AVL}** and **F_{AVL}** are therefore determined in a straightforward manner, without optimization loop, knowing the parameters of internal BC junction capacitance

MEASUREMENT SETUP





MULTIPLICATION FACTOR DETERMINATION

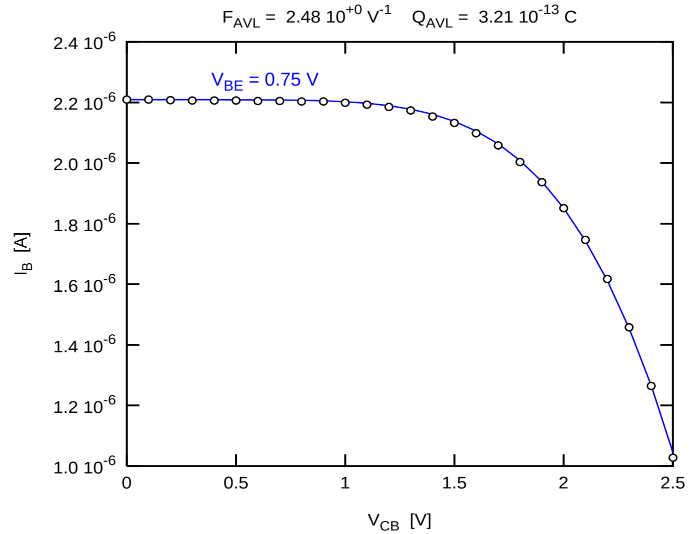
- The multiplication factor M can be easily measured from the collector current I_C and from the decreasing ΔI_B of the base current I_B with the collector voltage V_{CB} at constant V_{BE}. V_{BEo} is chosen low enough to avoid high injection effects, voltage drop in series resistances and self-heating

$$\begin{cases} M = 1 + \dfrac{I_{AVL}}{I_{Co}} \\ I_B = I_{Bo} - I_{AVL} \\ I_C = I_{Co} + I_{AVL} \end{cases} \Leftrightarrow \begin{cases} I_{AVL} = I_{Bo} - I_B = \Delta I_B \\ I_{Co} = I_C - I_{AVL} = I_C - \Delta I_B \\ \boxed{M = \dfrac{I_C}{I_C - \Delta I_B}} \end{cases} \quad (8)$$

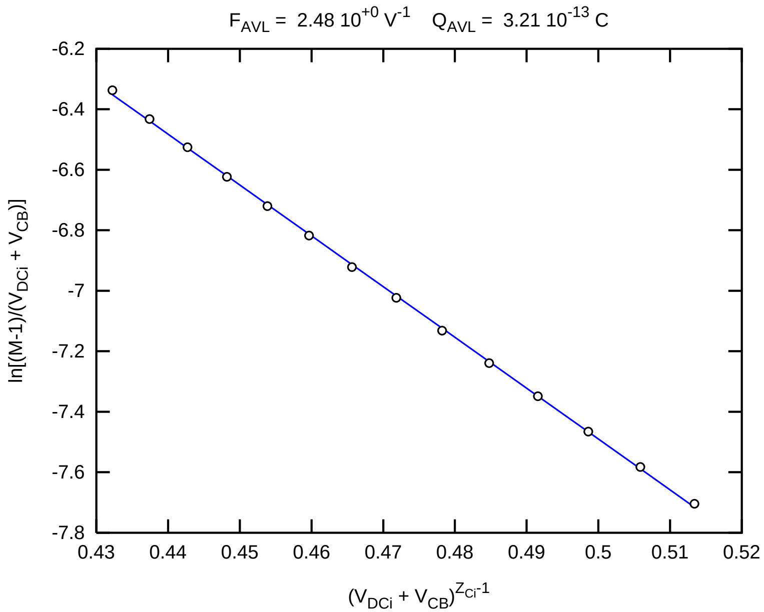
EXPERIMENTAL RESULTS (1)

- This method has been successfully used on various bipolar transistors from low to high voltage processes. Some of these results are given hereafter.
- 0.35 µm 3.6 V BiCMOS process [6]

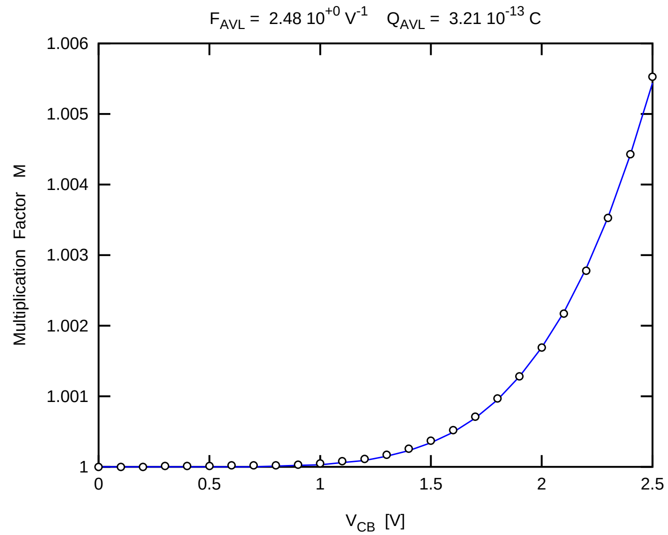
Base Current



Characteristics from which the parameters are extracted



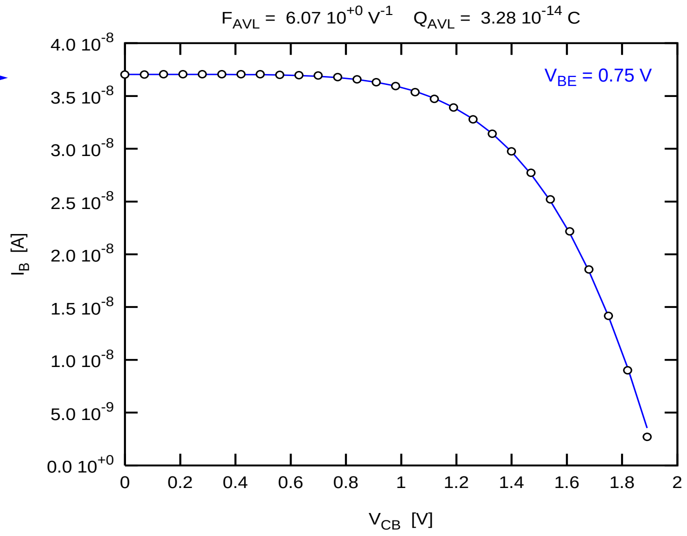
Multiplication Factor



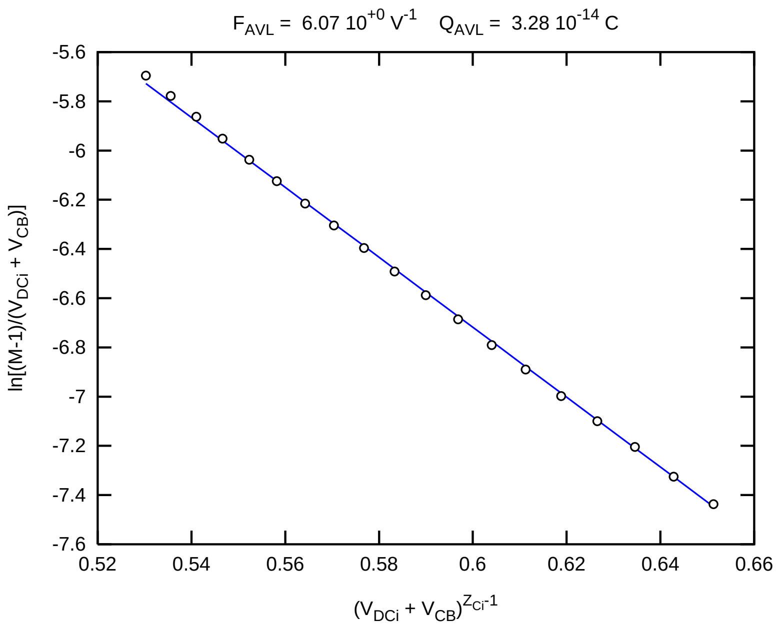
EXPERIMENTAL RESULTS (2)

- 0.25 µm 2.6 V BiCMOS process [7]

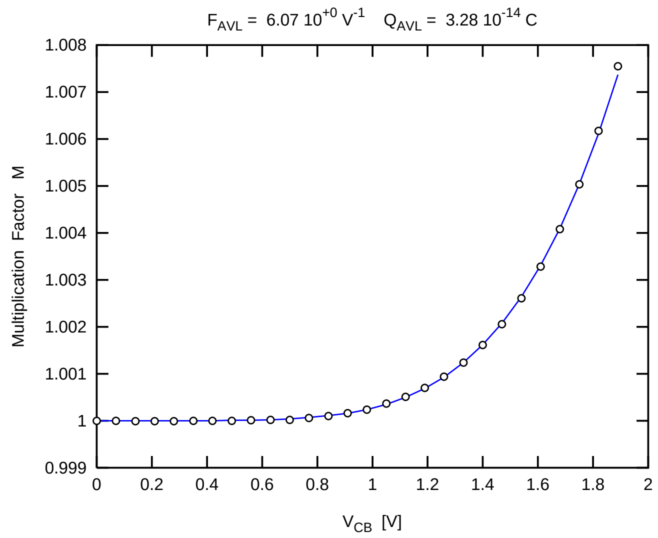
Base Current



Characteristics from which the parameters are extracted



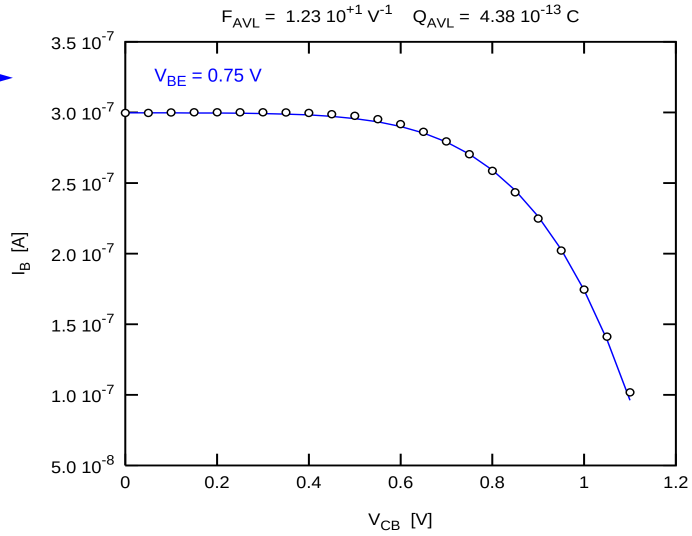
Multiplication Factor



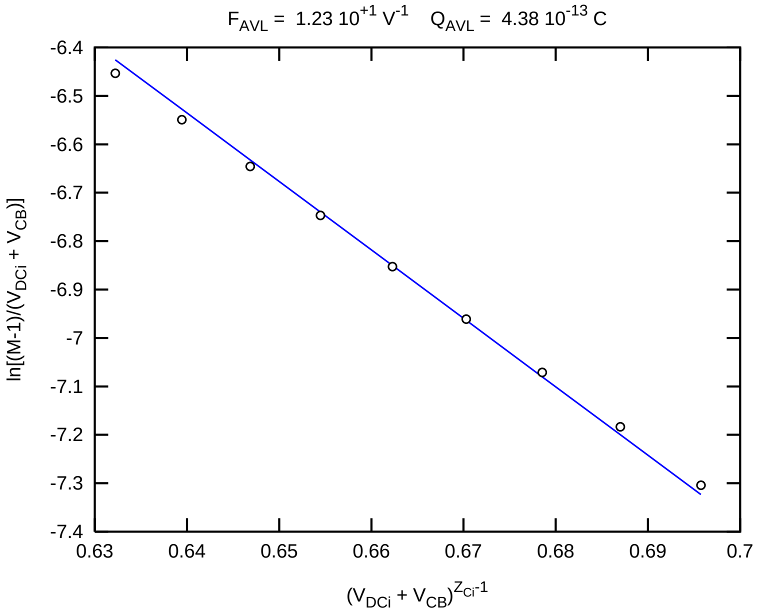
EXPERIMENTAL RESULTS (3)

- 0.13 µm 1.7 V BiCMOS process

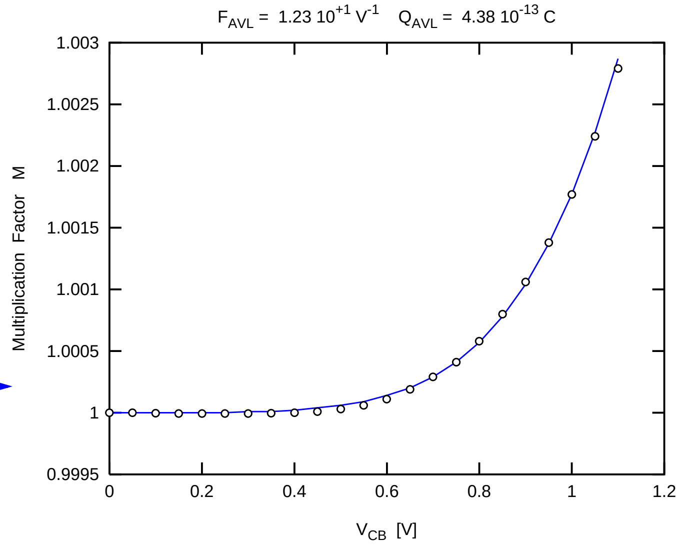
Base Current



Characteristics from which the parameters are extracted



Multiplication Factor



CONCLUSION AND COMMENTS

- A novel straightforward extraction methodology for the HICUM weak avalanche parameters has been described step by step.
- This method can be easily implemented in extraction tools like ICCAP or UTMOS, requiring only a linear regression, without optimization loop, and knowing the parameters of the internal part of the BC junction capacitance.
- This method was successfully used and validated on different type of transistors (low and high voltage).
- The scalability of $\mathbf{F_{AVL}}$ and $\mathbf{Q_{AVL}}$ has to be tested.
- We have notice that the parameters $\mathbf{F_{AVL}}$ and $\mathbf{Q_{AVL}}$ are very sensitive to the values of the internal BC depletion capacitance parameters, but not the accuracy of the fitted characteristics. Whatever the values of C_{JCI0}, V_{DCi}, $Z_{Ei,}$ equation (7) is always linear.
- As consequence, the scalability of $\mathbf{F_{AVL}}$ and $\mathbf{Q_{AVL}}$ depends on the correctness of the internal BC junction capacitance parameters.
- Validation of the HICUM weak avalanche model at higher density of currents has to be done, as this present model does not include the case where the maximum electric field occurs at the buried layer rather than at the BC junction (Kirk effect).

REFERENCES

[1] W. J. Kloosterman and H. C. de Graaff, "Avalanche Multiplication in a Compact Bipolar Transistor Model for Circuit Simulation", *Proceedings BCTM*, Minneapolis, 1988.

[2] C. McAndrew et al., "VBIC95 : An Improved Vertical, IC Bipolar Transistor Model", *Proceedings BCTM*, Minneapolis, 1995.

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

[4] D. Berger, N. Gambetta, D. Céli, D. Duffaza, "Extraction of the Base-Collector Capacitance Splitting Along the Base resistance", *Proceedings BCTM*, Minneapolis, 2000.

[5] B. Ardouin et al., "Direct Method for Bipolar Base-Emitter and Base-Collector Capacitance Splitting Using High Frequency Measurements", *Proceedings BCTM*, Minneapolis, 2001.

[6] A. Monroy et al., "BiCMOS6G : A High Performance 0.35 mm SiGe Technology for Wireless Applications", *Proceedings BCTM*, Minneapolis, 1999.

[7] H. Baudry et al., "High Performance 0.25 µm SiGe and SiGe:C HBTs using Non Selective Epitaxy", *Proceedings BCTM*, Minneapolis, 2001.