SIMULATION OF SEMICONDUCTOR DEVICES AND PROCESSES Vol. 4
Edited by W. Fichtner, D. Aemmer - Zurich (Switzerland) September 12-14, 1991 - Hartung-Gorre

DETERMINATION OF CARRIERS CAPTURE CROSS-SECTIONS OF Si/SiO_2 STATES BY MEANS OF PROCESS/DEVICE SIMULATIONS

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Abstract

The base current modeling remains a difficult task for some bipolar devices such as lateral PNP transistors and I^2L gates. The major problem lies in the difficulty to obtain parameters such as electron and hole capture cross-sections that govern the Si/SiO_2 recombination current. This paper proposes an original technique to determine the carriers capture cross-sections by means of device simulation. It is shown that this method gives far more accurate results than a purely experimental technique such as ERDLTS. The results of simulations are guaranteed by the excellent conservation of the computed currents.

Bipolar devices characteristics are strongly influenced by the quality of the Si/SiO_2 interface. In particular, the surface recombination base current component can lead to a non acceptable gain degradation in low injection regime (especially for I^2L gates and lateral devices). The recombination process at the interface takes place via traps whose energy levels are distributed through the bandgap. The Schockley-Read-Hall (SRH) theory commonly used to model surface recombination requires the knowledge of the traps density and of the electron and hole capture cross-sections. Unfortunately, these last two quantities are not easily accessible: for instance, ERDLTS (Energy Resolved Deep Level Transient Spectroscopy) measurements performed on MOS capacitances are affected of large error bars (up to one decade) [1]. This paper proposes an original method to determine average values of capture cross-sections relevant to accurately calculate the base current in bipolar devices. First, the trap density is measured by a DLTS technique on MOS structures. In a second time, capture cross-sections are determined by means of device simulations performed on specially designed PNP transistors. An additional validation of the results is given through the simulation of a NPN structure biased in reverse mode. The accuracy level obtained on current conservation is also discussed.

1 Experimental results

The bipolar SUBILO-N process [2] is the technological basis used to fabricate the test structures. Figure 1 reports the DLTS results obtained on a large (111) oriented n-Si substrate capacitance: the corresponding density of states in the upper half of the bandgap proves to be very large (minimum is $3\ 10^{11}$ $cm^{-2}\ eV^{-1}$) with a peak value ($2\ 10^{12}\ cm^{-2}\ eV^{-1}$) whose energy level is typical of dangling-bond defects (the so-called P_b center [3]). A schematic representation of the first PNP transistor is given in fig. 2: the emitter contact covers the whole p-type emitter (60x60 μm^2). The second one (fig.3) is designed with a reduced emitter contact (2.8x2.8 μm^2) to enhance the effect of surface recombination. The gain-current characteristics of the two structures are shown in fig.4 and 5 respectively.

2 Simulation: determination of capture cross-sections

Process/device simulations [4] on the first structure is used to ensure a correct description of the doping profiles: the flat current-gain characteristic is only a function of the emitter and base injection currents which are fully determined by the emitter and base impurity distributions (recombination is negligeable). On the other hand, the second vertical PNP transistor exhibits a large gain reduction in low injection regime: two surface recombination components are responsible for the shape of the gain-current curve (fig. 5). The first one takes place along the horizontal interface part (fig.3 region A) and its expression can be given by the following simplified SRH equation which only depends on the electron capture cross-section (σ_n):

$$J_{surf} \sim q \int_{E_v}^{E_c} \sigma_n(E).v_{th}.(n-n_0).D_{it}(E).dE \qquad (1)$$

This contribution is dominant in the medium injection range and lead to a rigid decrease of the gain. The second component, taking place along the isolation structure interface (fig.3 region B), gives rise to a space charge recombination current responsible for the gain drop in low injection regime. In this case, both σ_n and σ_p contribute to the recombination current expressed by:

$$J_{surf} = q \int_{E_v}^{E_c} \frac{(np-n_{ie}^2).D_{it}(E).dE}{\dfrac{(n+n_{ie}.\exp\left[\frac{qE}{kT}\right])}{\sigma_p(E).v_{th}} + \dfrac{(p+n_{ie}.\exp\left[\frac{-qE}{kT}\right])}{\sigma_n(E).v_{th}}} \qquad (2)$$

Following the last observations, σ_n can be chosen independently from σ_p to obtain the correct gain level in medium injection. This point is illustrated in fig.6 where the optimal value for σ_n turns out to be 3.6 10^{-16} cm^2. The sensitivity of the method is proved by the other values of σ_n that represent variations of $\pm 25\%$ and $\pm 50\%$ with respect to the optimal value. Once σ_n is fixed, σ_p can be chosen to fit the gain tail in low injection as indicated in fig.7: σ_p=9 10^{-17} cm^2 gives a satisfactory result while variations of $\pm 25\%$ and $\pm 50\%$ lead to an incorrect description of the gain in low injection. As traps located around midgap give the most important contribution to the recombination rate, σ_n (E) and σ_p (E) were assumed constant ± 0.3 eV around E_i. The last assumption implies that both σ_n and σ_p represent average values within the considered energy interval. Nevertheless, the obtained results are far more accurate than other experimental experimental methods as variations of only $\pm 25\%$ are sufficient to lead to an important variation of the current gain.

3 NPN transistor in reverse active mode

An additional validation has been carried out on a standard NPN transistor used in reverse mode. A good agreement has been found with the previously determined values of σ_n and σ_p (3.6 10^{-16} and 9 10^{-17} cm^2 respectively) (fig.8). For instance, the significant deviation obtained by varying σ_p within the standard error range of other methods [1][5] demonstrates the capabilities of the present technique.

4 Numerical model and accuracy

The basic semiconductor equations are solved through the decoupled Gummel algorithm. In order to accelerate the convergence process and to ensure stability, each current conservation equation is linearized using a Newton loop as the recombination function depends on the carriers concentrations.

Informations concerning the relative error obtained on current conservation is reported in figure 9: the first curve concerns the total current conservation that must obey the Kirchhoff law. The second curve shows the relative error obtained by comparing the electron and hole recombination currents integrated along the Si/SiO_2 interface: their algebraic sum must exactly equal zero. It can be concluded that an excellent accuracy is obtained if a significant current flows in the device: as soon as the current level reaches 1 pA (fig.10), the relative current errors remain below 1% .

Acknowledgments

The author wants to thank M. Lebailly (Philips Components), for providing the bipolar test structures, M. Vuillaume (ISEN) for performing DLTS measurements and M Collard (ISEN) for valuable comments.

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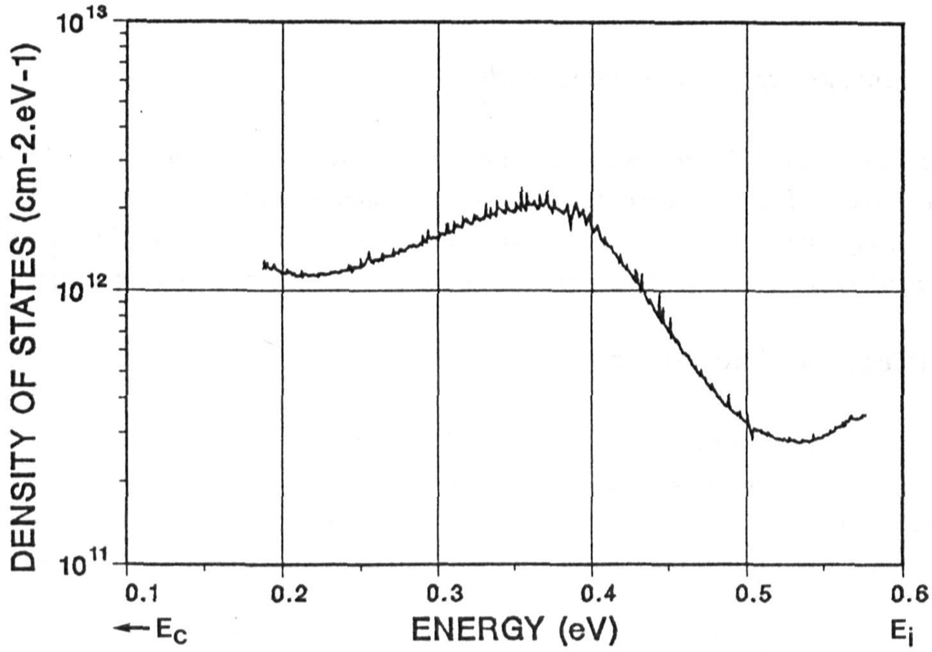

Figure 1: Density of states in the upper half bandgap measured by DLTS

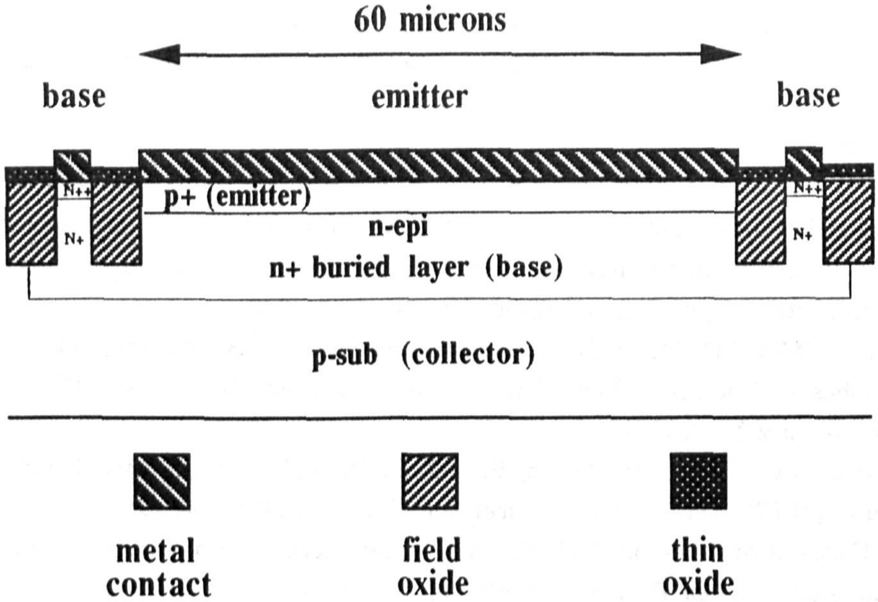

Figure 2: Schematic representation of the first vertical PNP test structure (no surface recombination)

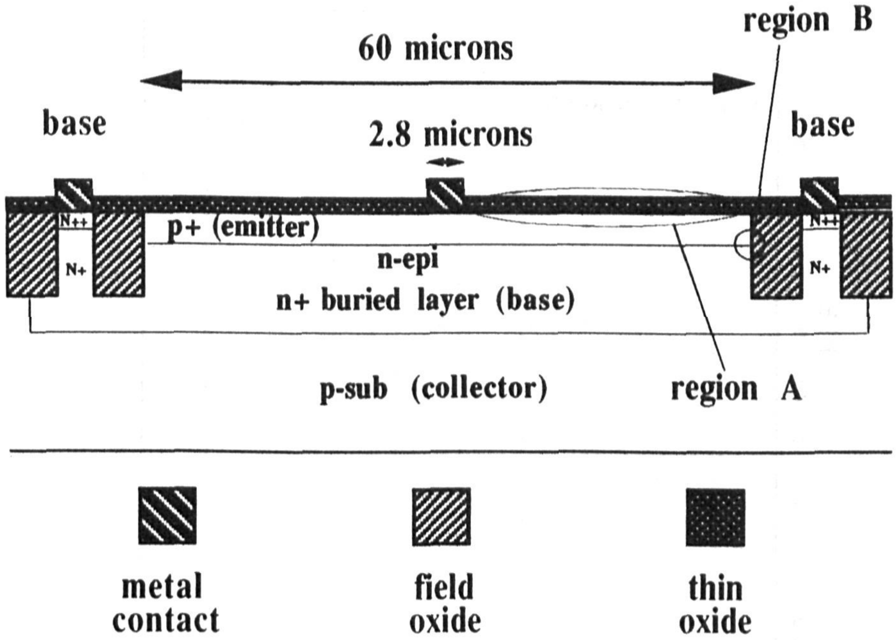

Figure 3: Schematic representation of the second vertical PNP test structure (enhanced surface recombination)

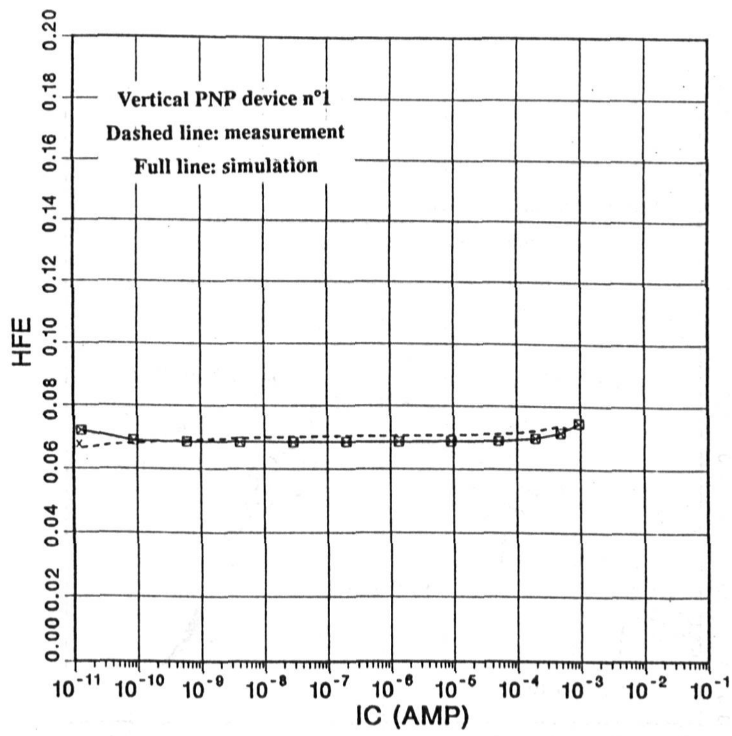

Figure 4: A flat gain-current characteristic is observed for the first PNP structure

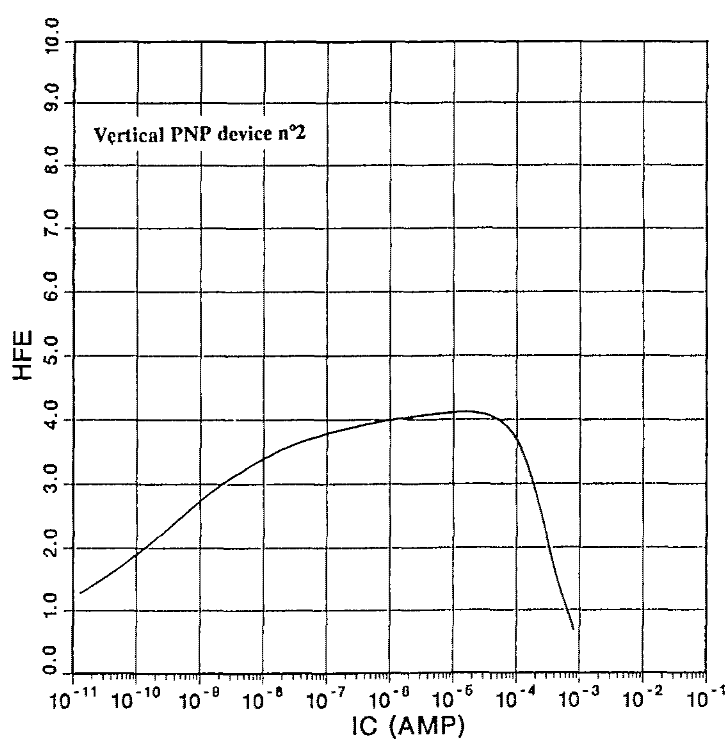

Figure 5: Gain-current characteristic of the second structure

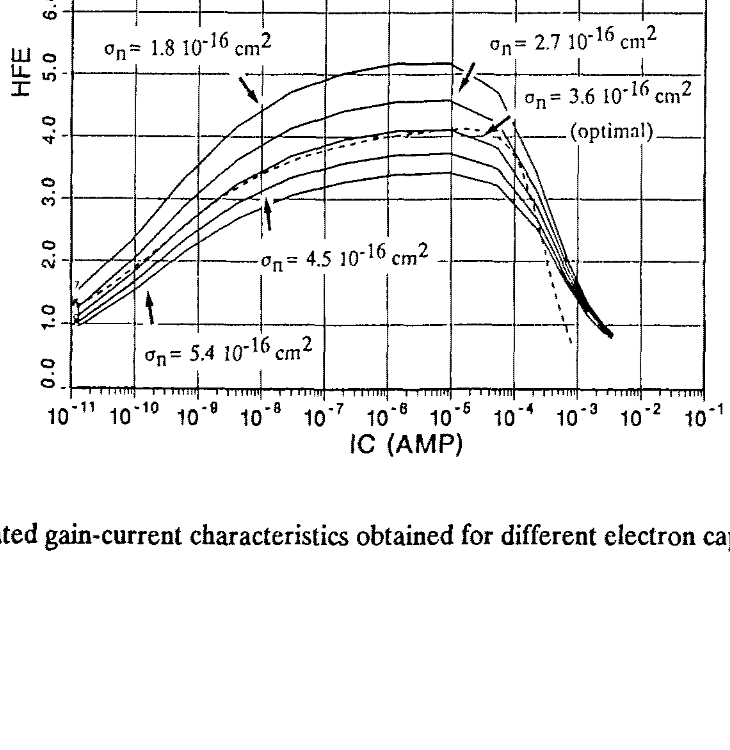

Figure 6: Simulated gain-current characteristics obtained for different electron capture cross-sections

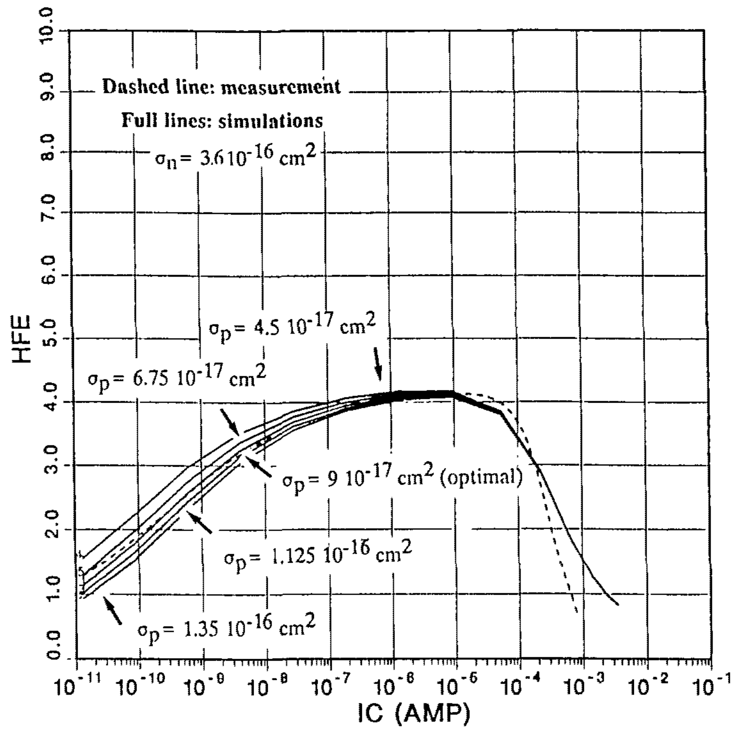

Figure 7: Simulated gain-current characteristics obtained for different hole capture cross-sections

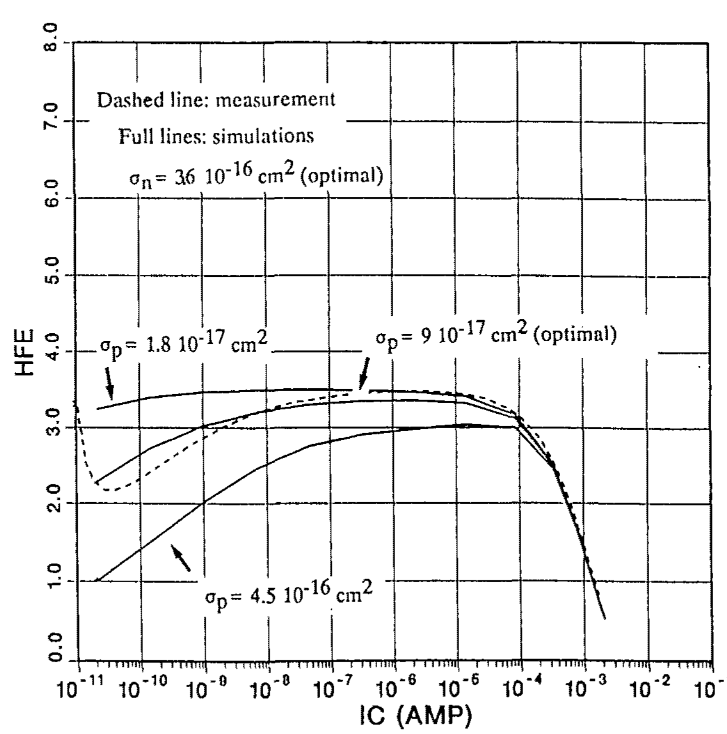

Figure 8: Simulated and measured gain-current characteristics of a NPN transistor in reverse active mode

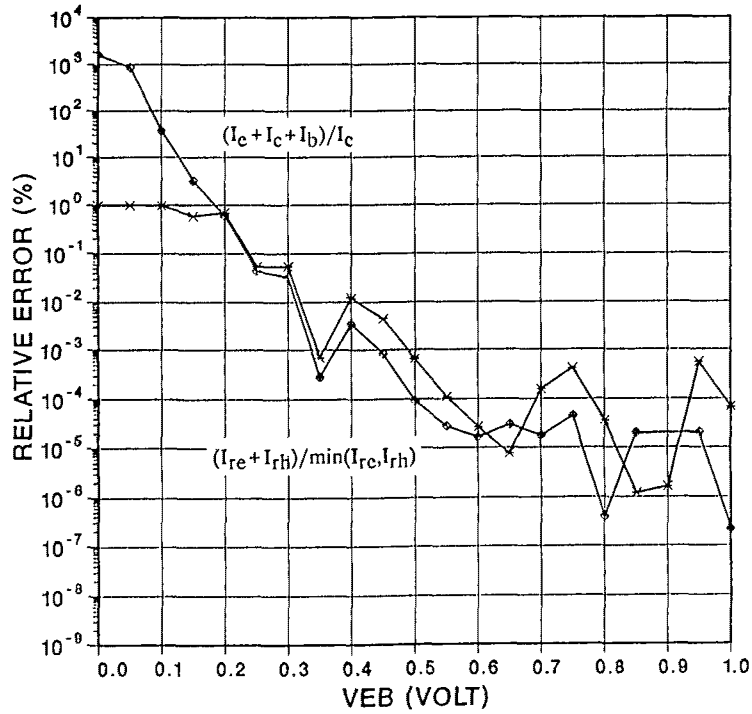

Figure 9: Relative error obtained for the terminal currents and for the surface recombination currents (case of the 2nd vertical PNP structure)

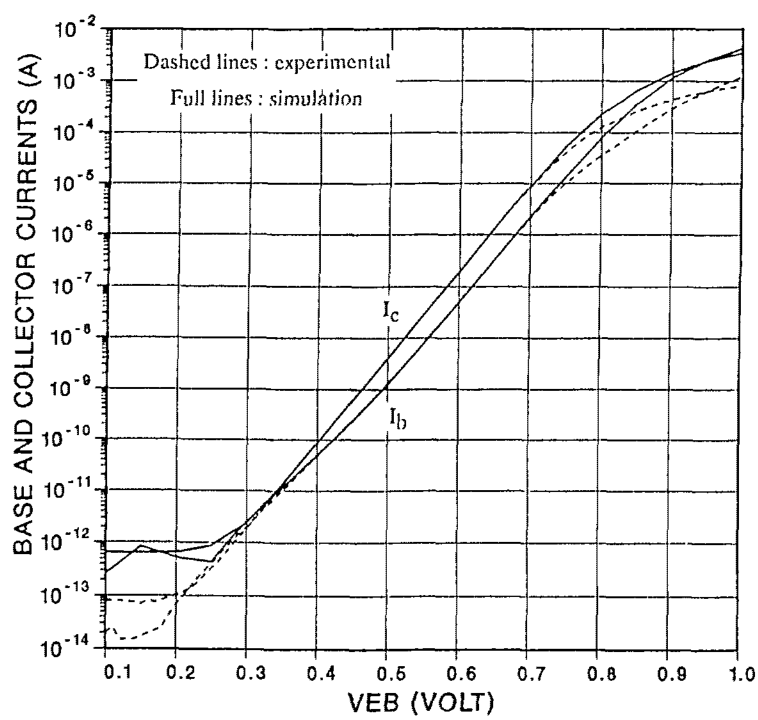

Figure 10: Base and collector currents of the 2nd vertical PNP structure