A NEW PHYSICAL COMPACT MODEL FOR LATERAL PNP TRANSISTORS

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Abstract

A new lateral pnp compact model, suitable for computer-aided circuit design purposes, is presented. In this new formulation, called MODELLA, the equivalent circuit, analytical equations and model parameters are derived directly from the physics and structure of the lateral pnp. In comparisons with measured device characteristics the performance of this model is shown to be superior to the extended Gummel-Poon model.

Introduction

In the design of bipolar analog integrated circuits, greater flexibility is often achieved when npn and pnp transistors are combined in the circuit design. Many present day bipolar production processes use the conventional *lateral* pnp (see fig. 1) as the standard pnp transistor structure.

In spite of their widespread use, however, literature on lateral pnp compact modeling for computer-aided circuit design purposes is not very abundant[1]. In practice, present day lateral pnp compact models tend to be adaptations of their vertical npn counterparts (c.f. [2]), neglecting the complex 2-D nature of the lateral pnp (see fig. 1). This approach leads to semi-empirical formulations which lack the superiority of a truly physics-based compact model.

In this paper, we present a new compact model, called MODELLA, for the lateral pnp (oxide or junction isolated) which has been derived from device physics. In MODELLA, the basic analytical equations for currents and stored minority charges are derived from an analysis of a 1-D lateral pnp and a 1-D parasitic vertical pnp. This approach was shown to be valid by comparing analytical formulations with 2-D numerical device simulation results, in the case where ohmic voltage drops are excluded. Under these simulation conditions it was found, for example, that the main 2-D hole current density between emitter and collector could be accurately described, at all injection levels, by means of the hole current density of the 1-D lateral pnp device. The scaling factor from the 1-D case to the 2-D case was found to be a function solely of device geometry.

The 2-D aspects of the lateral pnp are then incorporated by modifying and extending these basic equations to include the effects of series resistances, most notably current crowding.

Model derivation

This section describes how the most important basic modeling equations in MODELLA are derived from 1-D lateral pnp device physics and how they are adapted to incorporate 2-D effects. Considering the forward active case, the following physical approach is used to derive the basic equations for the collector current and stored minority base charge.

- High injection effects in the epitaxial layer base region are modeled by relating the collector current, I_c, and the stored minority charge, Q_b, to the bias dependent minority carrier concentration, $p'(x)$, in the base region of a 1-D lateral pnp. Here, $p'(x)$ can be assumed to have a linear distribution in the base at *all injection levels* (see for example [3]). The effective hole diffusion coefficient is therefore defined in the center of the base region. A consequence of relating the currents and charges *independently* to the injected minority carrier concentration (an approach first used in the MEXTRAM [4] compact model) is that the base transit time, $\tau_B(= \frac{dQ_b}{dI_c}|_{dV_{ce}=0})$, is seen to decrease by a factor of two at high injection levels thereby correctly modeling the Webster effect[5]. This contrasts with the extended G-P model[2] (E-GP model) where the use of the charge control principle yields a bias independent base transit time.
- The Early effect[6] is modeled by including the effect of the collector-base depletion width, X_{CB}, on the base width, X_B, in the expression for the collector current :

$$Ic = \frac{Ic'}{1 - X_{CB}/X_B} \tag{1}$$

Here, Ic' is the collector current without Early effect and X_{CB} is obtained by assuming asymmetric abrupt junctions. In this way, the collector-base voltage dependence of the Early voltage is also modeled.

Combining these approaches we obtain a new expression suitable for accurately modeling both the high injection and the forward Early effects in a homogeneously doped base transistor.

$$Ic = \frac{4I_f \,/\, (3 + \sqrt{1 + 16\,\frac{I_f}{\mathbf{I_k}}})}{1 - \sqrt{1 - \frac{V_{cb}}{V_d}} \,/\, (1 + \frac{\mathbf{V_{eaf0}}}{2V_d})} \tag{2}$$

where I_f = the ideal reference current

$= \mathbf{I_{f0}} \exp \frac{V_{eb}}{V_t}$

and V_d = the diffusion voltage

There are three model parameters in this expression: the saturation current $\mathbf{I_{f0}}$, the high injection knee current $\mathbf{I_k}$ and the forward Early voltage at zero collector-base bias $\mathbf{V_{eaf0}}$. By including the effect of the emitter-base depletion width on the base width this equation is extended further, using one extra parameter $\mathbf{V_{ear0}}$, to model the reverse Early effect.

The modeling of 2-D effects such as current crowding is based on the influence of the series resistances shown in fig. 1. This figure shows how the hole current flow lines which make up the collector current can be roughly divided into two distinct components: a purely lateral flow which originates at the emitter sidewall and a flow along curved trajectories which originates from the bottom of the emitter. At low current levels the sidewall component dominates. At high current levels the voltage drop across the lateral emitter resistance, Re_{LAT}, leads to a reduced sidewall junction voltage thereby reducing the contribution from this component. The second component then dominates and current crowding in the region under the emitter contact is observed. Numerical device simulations on 2-D structures have revealed that the larger effective base width associated with these trajectories has the following consequences for device behavior at high current levels.

- the current gain, h_{fe}, decreases.
- the base transit time, τ_B, increases thereby reducing the cut-off frequency, f_t.
- the Early effect is reduced in agreement with the experimentally observed dependence of the Early voltage on the emitter-base voltage, V_{eb} (see fig. 6).

In MODELLA this current crowding effect is modeled using double emitter diodes and current sources to represent the sidewall (I_{FLAT}) and bottom (I_{FVER}) components of I_c (see fig. 2). I_{FLAT} and I_{FVER} are described by means of eqn.(2) using the *internal* junction voltages V_{e1b} and V_{e2b1} respectively. In addition, different saturation current and Early voltage parameters are used in the respective expressions. At low current levels I_{FLAT} dominates due to its larger saturation current, whereas at high current levels I_{FVER} takes over due to the voltage drop across Re_{LAT}. The Early voltage parameter associated with I_{FVER} will be larger than that used with I_{FLAT} thus modeling the dependence of the Early voltage on V_{eb}.

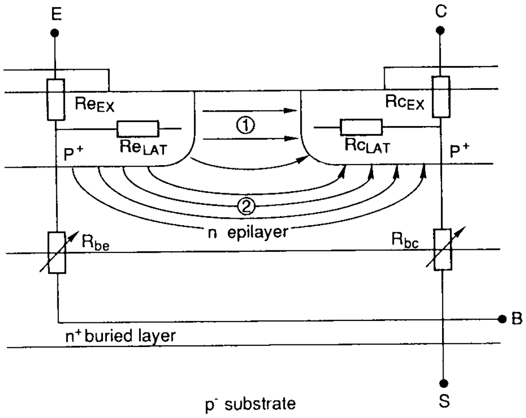


Figure 1: *Schematic cross-section of a lateral pnp transistor, showing the physical origin of the series resistances used in the equivalent circuit of MODELLA. The base resistances Rbe and Rbc both consist of constant and conductivity modulated parts. Also, the 2-D hole current flow in the epitaxial base region is shown to consist of two components: a purely lateral flow originating from the emitter sidewall and a flow along curved trajectories originating from under the emitter.*

In order to model the increase in τ_B due to current crowding, the minority charge storage in the epitaxial base is also split into two components. These components represent charge storage under the emitter (Q_{FVER}) and charge storage between the emitter and collector (Q_{FLAT}). The V_{cb} dependency of the minority charge storage is modeled by adapting the sidewall component, Q_{FLAT}, to include the effect of the collector-base depletion width on the base width. Charge storage under the emitter is not affected by V_{cb}.

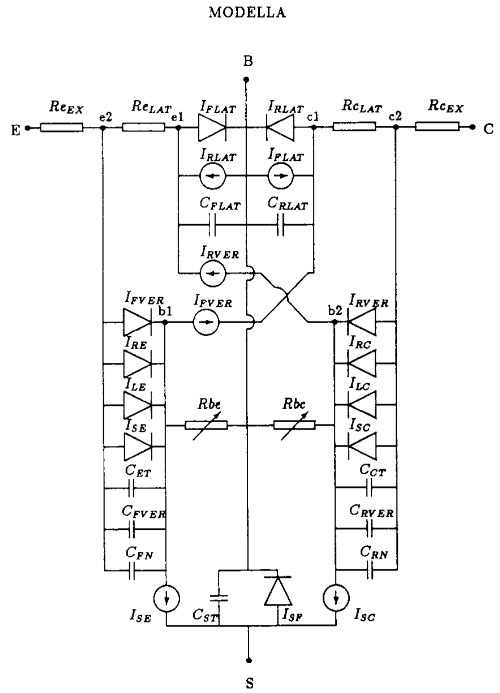


Figure 2: *Equivalent circuit diagram of MODELLA. Note that the emitter resistance is split into Re_{EX} and Re_{LAT} which, in combination with the double emitter diodes and current sources I_{FLAT} and I_{FVER}, models current crowding.*

Discussion and Results

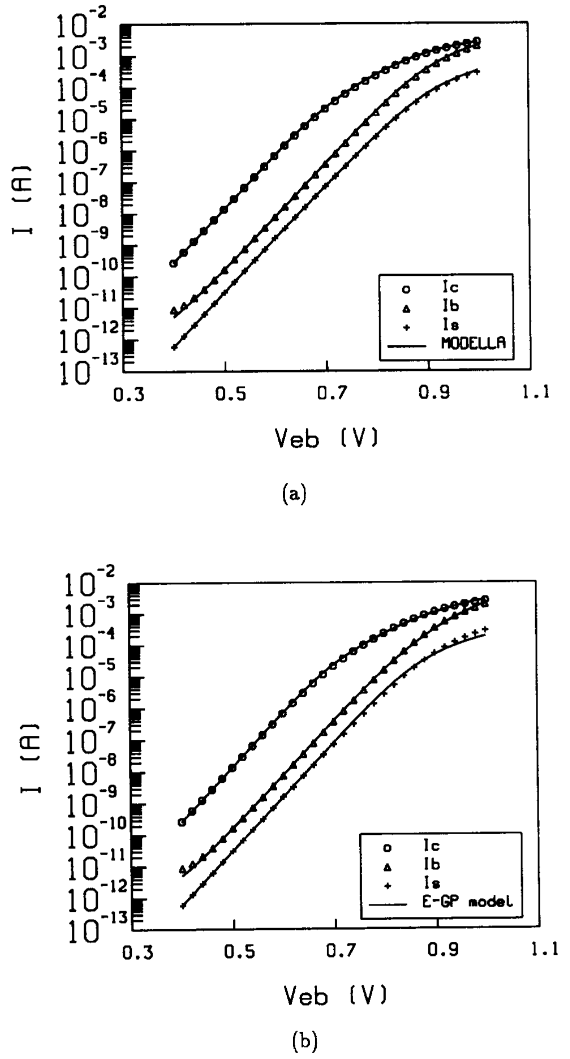
The complete compact model includes ideal and non-ideal base currents, substrate currents with high injection effects, depletion charges, bias dependent base resistances and a substrate-base diode. The location of these elements in the equivalent circuit reflects the location of the underlying physical mechanisms in actual devices. For example, the ideal base current

I_{RE} mainly originates from electrons injected into the emitter which recombine at the emitter contact. Because these minority carriers are injected from the epilayer base region under the emitter contact, the diode I_{RE} is located between nodes $e2$ and $b1$ in fig. 2. This means that the fall off in Ib at high current levels is unaffected by voltage drop across the lateral emitter resistance Re_{LAT}.

MODELLA has 42 parameters with 6 internal nodes which is more complex than the E-GP model (32 parameters with 3 internal nodes). However, due to its symmetry and the explicit nature of its equations which do not require any additional iterative solution procedures, MODELLA has shown excellent convergence properties when implemented in a circuit simulator[7]. In terms of CPU time, MODELLA is only a factor of 1.5 slower than the E-GP model and the number of iterations required for convergence is roughly equal. When compared to the semi-empirical E-GP approach, MODELLA's physical formulation possesses the following advantages:

- model parameters have a physical significance leading to easier, more reliable parameter determination.
- geometrical scaling rules can be applied with confidence.
- the influence of process variations on device behavior can be more accurately forecasted.
- the physical correlation between model parameters facilitates realistic statistical modeling.

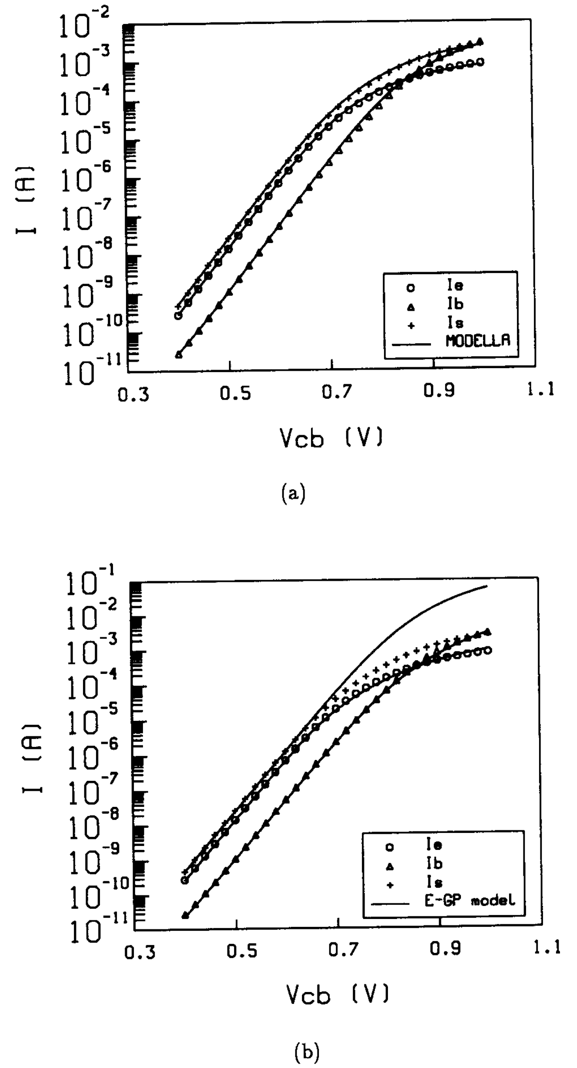
A comparison between MODELLA and the E-GP model using a junction isolated lateral pnp is shown in figs. 3 to 6. In this example, the mask base width is $4\mu m$ and the collector completely surrounds the square $8 \times 8\mu m^2$ emitter. These



(a)

(b)

Figure 3: *Forward active Gummel plots comparing (a) MODELLA and (b) the E-GP model with measured characteristics.*



(a)

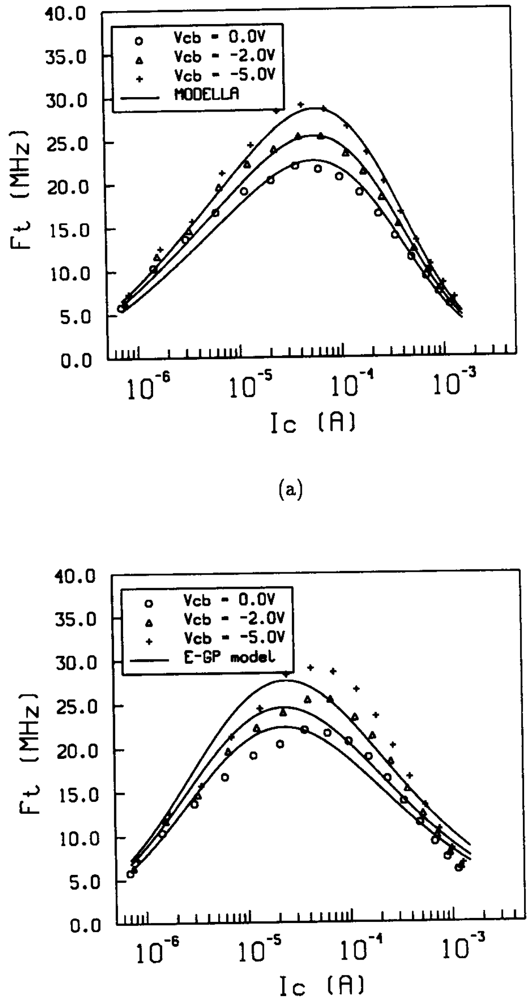
(b)

Figure 4: *Reverse active Gummel plots comparing (a) MODELLA and (b) the E-GP model with measured characteristics.*

comparisons show the improved performance of MODELLA especially with respect to:

- reverse active behavior,
- the bias dependence of the cut-off frequency f_t,
- the bias dependence of the Early effect.

With the E-GP model the Early voltage, V_{eaf}, has a negligible dependence on Veb and is seen to be completely independent of Vcb. MODELLA, on the other hand, shows excellent agreement with measured data due to the physical modeling of both base width modulation by Vcb and current crowding under the emitter. This bias dependence of V_{eaf} is often a critical aspect in lateral pnp compact modeling e.g. in circuit applications involving lateral pnp current sources.



(a)

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Figure 5: *Comparison between (a) MODELLA and (b) E-GP model predictions of the measured cut-off frequency, f_t, as a function of I_c at different V_{cb} values.*

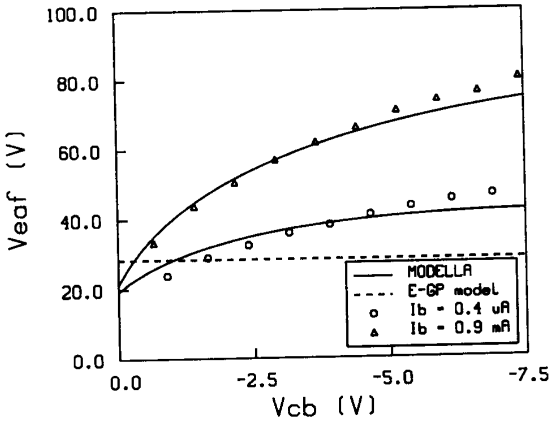

Figure 6: *Comparison between MODELLA and the E-GP model predictions of the measured forward Early voltage, V_{eaf} as a function of V_{cb}. The Early voltage is defined as $V_{eaf} = I_c|\frac{dV_{cb}}{dI_c}|_{I_b=const.} - V_{cb}$. The two I_b values correspond to $V_{eb} = 0.7V$ and $V_{eb} = 0.94V$, respectively.*

Conclusions

A new physical approach to lateral pnp compact modeling, which incorporates high injection effects, current crowding effects and a bias dependent output conductance, has been presented. MODELLA's superior performance has been demonstrated by comparison with the extended Gummel-Poon model using measured device characteristics. Furthermore, MODELLA facilitates a better intuitive understanding of device behavior due to its close link with device physics and to the physical significance of its parameters.

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