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A new physical compact model of CLBTs for circuit simulation including two-dimensional calculations

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Abstract

A new, physics-based compact model for CMOS-compatible, lateral bipolar transistors is presented. For the calculation of DC collector and base currents including the influence of gate-voltage, Early- and Late-effect and the extended base resistance, a specially developed, fully 2-dimensional analysis is used resulting in closed-form analytical equations that only need device geometry and technological data as parameters. In this way, parameter extraction is drastically simplified. Together with state-of-the-art AC components, the complete model has been implemented in ELDO; its predictive abilities favourably compare with measurements on devices fabricated in different technologies, where standard models tend to fail.

1. Introduction

CLBTs (CMOS-compatible lateral bipolar transistors, see Figure 1) have gained an important position in analog circuit design during the last years. They can be found to be used in numerous applications all over the field of MOS-based analog low-power circuitry. In contrast to their favoured use, an appropriate physical compact model has not been presented for state-of-the-art simulation tools. Model approaches by Ankele [1] and Arreguit [2] are neither as physics-based as necessary to reflect the complete device behaviour nor do they offer the possibility of an inclusion in other than in-house simulators. In this paper, we present a new compact model of CLBTs which is able to describe all the important, mostly 2-dimensional, features of device operation in an analytical, physics-based form and can be incorporated in the commercial simulator ELDO.

2. Outline of the model conception

To stay related to the internal device physics and geometry, the equations for the *collector currents* in flatband operation have to solve the underlying 2D-boundary problem. For this reason, in [1] the authors introduced a special application of conformal mapping techniques to the base region of the transistors which give rise to the definition of geometrical factors, depending only on process and geometry parameters in the following generalized form for npn-CLBTs (see Fig.1):

$$I_{CLFB} = en_i^2 \frac{W_E}{N_B} K_L(W_E, N_B, g, h, \alpha, x_j) \; e^{\frac{V_{BE}}{V_T}} \quad (1)$$

$$I_{CV} = en_i^2 \frac{W_E}{N_B} K_V(W_E, N_B, g, h, \alpha, x_j) \; e^{\frac{V_{BE}}{V_T}} \quad (2)$$

The two-dimensional aspects of the device operation are described by K_L and K_V, where the transistor geometry and the bias voltages V_{BE},V_{BCL} and V_{BCV} influence the space-charge extensions and hence g and h (see Figure 1). To include the effect of a *variable gate-voltage* on the lateral collector current in (1), an analytical solution of Poisson's equation applied to the MOS-structure has been derived. For this, it can be shown that a one-dimensional approach is sufficient for all realistic device configurations and can finally be combined with (1) in the following way (Debye-length $L_D = \sqrt{\frac{\varepsilon_{Si} U_T}{eN_B}}$, (3) and (4) still hold for npn-CLBTs):

$$\psi_S = -U_T \ln\left(\frac{\varepsilon_{ox} L_D}{\sqrt{2}\varepsilon_{Si} d_{ox}} \left(\frac{V_{GB} - V_{FB}}{U_T}\right)^2 + 1\right) \quad (3)$$

$$I_{CL} = I_{CLFB} + 4 \frac{en_i^2 W_E D_N L_D}{\sqrt{2}\; g N_B} \left(e^{\frac{\psi_S}{U_T}} - 1\right) e^{\frac{V_{BE}}{U_T}} \quad (4)$$

A 2D equation for the *base current* component due to diffusion in the emitter again results from conformal mapping calculations. The recombination current in the base volume is calculated by solving the corresponding differential equations analytically under use of specially derived mathematical decomposition techniques. Altogether, this allows the introduction of new coefficients in the equation for the base current which include all two-dimensional aspects of diffusion (K_{EB}) and recombination (K_{BB}) in the device.

$$I_B = en_i^2 \left(\frac{W_E}{N_E} K_{EB}(W_E, \alpha, x_j) + \frac{1}{\tau_{rec} N_B} K_{BB}(W_E, h, g)\right) \; e^{\frac{V_{BE}}{V_T}} \quad (5)$$

Emitter doping N_E and base minority lifetime τ_{rec} are the controlling parameters.

Early- and Late-Effect have a comparatively high influence on the collector currents due to the low well (base) doping. This causes a strong bias-dependence of both, leading to a variable output conductance (Early-Effect) and a variable transconductance (Late-Effect). In our model, these features are taken into account by employing appropriate equations for the extensions of the space-charge regions at emitter and both collectors into the base, which both affect the geometrical factors K_L and K_V and hence the collector currents.

Again due to the extended configuration and the low doping of the base in CLBTs, the *base resistance* has to be modelled significantly different to the usual approaches developed for vertical devices. The model uses new equations for the resistance including spreading effects in a typical rectangular or concentric CLBT-layout as well.

These model equations describe the transistor action by only using process- and layout-related parameters without the inclusion of numerical fitting factors at all. Thus, the conception of our model ensures that the two-dimensionality of the device operation is reflected as accurate as analytical approaches allow, leading to an outstanding performance related to existing other approaches which are not extensive enough to obtain the same thorough and powerful predictive abilities.

3. Model implementation and performance in ELDO

The complete model is implemented by adding existing model components to the features from section 2. Figure 2 shows the equivalent circuit for the CLBT. The currents I_{CE}, I_{EC}, I_{CVN}, I_{CVI} represent the lateral and vertical collector currents in active and inverse operation, respectively. I_{BEN}, I_{BCI}, I_{BBN}, I_{BBI} denote the base current components due to diffusion and recombination. R_{BD}, R_{BM}, R_{BI} add up to the base resistance. The equations for these model elements employ the analytical results of the calculations outlined in Section 2. The capacitances and the G/R-components of the base current are modelled comparable to SPICE; the series resistances at emitter and both collectors are chosen to be lumped elements without relation to the underlying process environment.

The model has been implemented in the simulator ELDO using the CFAS-interface[4]. According to Figure 2, all in all 60 parameters are needed. Compared to Ankele's [1] and Arreguit's [2] approaches, in which the CLBT is described by a parallel combination of two Gummel/Poon- models for the BJT-components and an additional MOS model for the gate effect, our model needs less parameters with reduced extraction effort due to the two-dimensional conception, so that fitting is only necessary to adjust the high-current behaviour of the device via an appropriate determination of series resistances and high-injection parameters.

To show the technology-dependent predictive performance of the model, measurements on CLBTs fabricated in different processes have been performed to obtain the DC-characteristics (Fig. 3-5). Evidently, a close correspondence of measured data and model predictions has been obtained. Due to the basic conception of the model even the fitting results for the high-current parameters remain physically reasonable.

The simplified extraction procedure demonstrates the success of the physics-related outline of the new model, which ensures that the parameters establish a tight correlation between electrical device behaviour and process- and layout-parameters, hence being predictively able to keep track with changes in both, layout and technology.

4. Conclusion

In this paper, we presented a new process- and layout-related compact model for CLBTs under use of two-dimensional calculations which led to analytical, closed-form equations for the DC-behaviour of the devices. Parameter extraction for our model is very easy. Due to the strong links to device physics, their majority can be taken straight from process- and layout data without fitting, making the model very useful for analysis tasks as well as for an application in layout-generating synthesis tools. Good accordance between model predictions and measurements could be shown for different technologies. The implementation in ELDO requires less parameters than other approaches, but describes the device operation more thoroughly. In the AC-domain, up to the moment, our model does not differ from others. By deriving more physics-based equations for the capacitances, the number of parameters can be finally restricted even further, resulting in a model with a minimum of needed parameters and very easy extraction rules.

References

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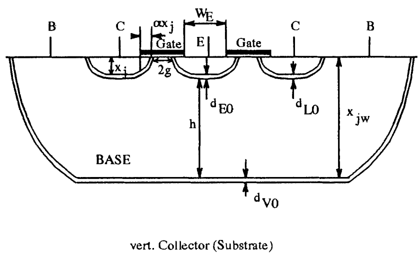

Fig. 1: Cross-section of a CLBT. d_{L0}, d_{V0}, d_{E0} denote the space-charge extensions into the base region at collectors and emitter, α the lateral diffusion coefficient.

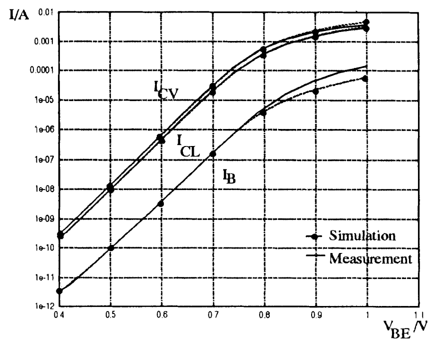

Fig. 3: Gummel-Plot of the base and collector currents in a npn-CLBT ($V_{CLB} = V_{CVB} = 3V, V_{GB} = -3V$)

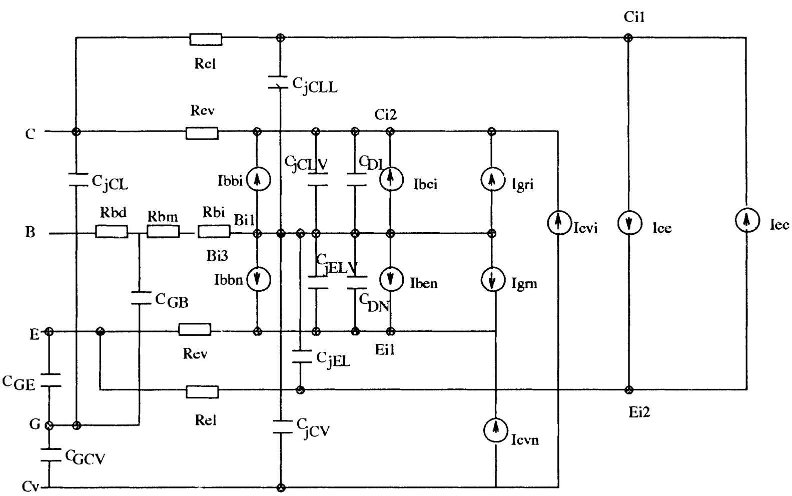

Fig. 2: Equivalent circuit for a CLBT

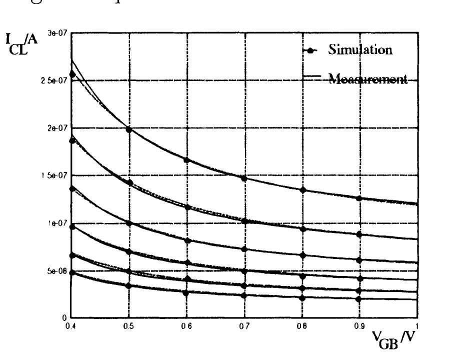

Fig. 4: Gate effect in a pnp-CLBT ($0.45V < V_{EB} < 0.5V, V_{CLB} = -3V, V_{CVB} = -3V$)

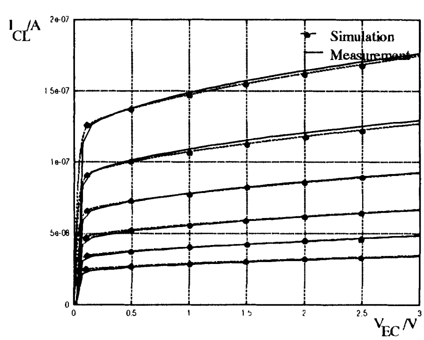

Fig. 5: I_C/V_{EC}-curves of a pnp-CLBT ($0.5V < V_{EB} < 0.55V, V_{GB} = 3V, V_{CVB} = -3V$)