COMPARITIVE STUDY ON MODELLING OF TRANSISTOR: BJT

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***Abstract*: The paper includes the comparison and study of different models being employed on bipolar junction transistor. The Ebers-Moll transistor model is an attempt to create an electrical model of the device as two diodes whose currents are determined by the normal diode law but with additional transfer ratios to quantify the interdependency of the junctions This document presents the definition of the CMC world standard model Mextram, for vertical bipolar transistors. The goal of this document is to present the full definition of the model, including the parameter set, the equivalent circuit and all the equations for currents, charges and noise sources. Apart from the definition also an introduction into the physical background is given[9]. We have given also a very basic parameter extraction procedure. Both the background and the parameter extraction are documented separately in dedicated documents. The transition from Mextram 503 to Mextram 504 is described, to enable the translation of a 503 parameter-set to a 504 parameter set. At last we have given some numerical examples that can act as a test of implementation. It should be mentioned that the Gummel-Poon model itself covers only the internal part of a real-transistor. Therefore, on-wafer parasitic like a parasitic pnp transistor are not covered. Also, packaging parasitics and other non-ideal effects are not part of the model. However, they can be added by using a sub-circuit rather than just the stand-alone model.**

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Keywords:Ebers-moll,Gummel Poon,Mextram,Cutoff,Saturation,Active,reverse

I. Introduction :

Modeling of a transistor begins with solving the basic device equations for carrier transport in semiconductors. For an accurate solution, the equations can be solved numerically using a computer with donor and acceptor profiles and appropriate boundary conditions as the input data. The numerical solutions not only predict the terminal behavior, but also describe the electron-hole distribution in the device, and thus provide a detailed study of the device behavior. These solutions though accurate, require a large amount of computational time. For this reason, analytical expressions for the solutions of the device equations have been derived using different approximations .Here the models included are Ebers-Moll model,the charge control model,and the integral charge control model proposed by Gummel and Poon.The Ebers moll model is the simple model for intrinsic transistors. PN junction theory,continuity equation are basis of this theory. The Mextram model is a physical device model and defining model equations are derived directly from the device physics.Such Physical models offer forecasting capabilities, allowing geometrical scaling rules to be applied.Gummel poon includes the effect of dc bias on current and optical gains

II. OPERATING MODES OF THE BIPOLAR TRANSISTOR

There are four operating modes of a bipolar transistor as illustrated in figure 1. The saturation region, for example, the region $v_{CE}<0.3V$ in the DC output characteristics, is described by the ohmic resistors[6]. The DC and AC extraction procedures that are proposed in this manual cover mainly the forward region. Since the model is symmetrical, the reverse parameters can be extracted following the same ideas, but applied to the reverse measurements.

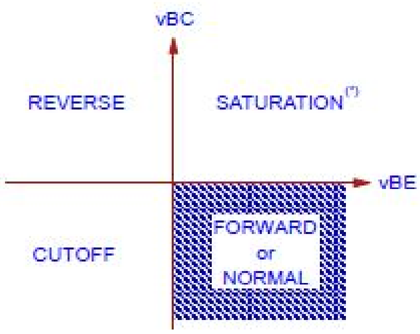

Fig.1: operating modes of a bipolar npn transistor

III. EBER MOLLS MODEL

The bipolar junction transistor can be considered essentially as two pn junctions placed back-to-back, with the base p-type region being common to both diodes[7]. This can be viewed as two diodes having a common third terminal as shown in Fig. 2.1.

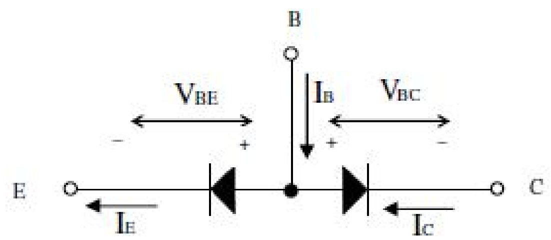

Fig.2

However, the two diodes are not in isolation, but are interdependent.This means that the total current flowing in each diode is influenced by the conditions prevailing in the other. In isolation, the two junctions would be characterized by the normal Diode Equation with a suitable notation used to differentiate between the two junctions as can be seen in Fig. 2.2. When the two junctions are combined, however, to form a transistor, the base region is shared internally by both diodes even though there is an external connection to it. As seen previously, in the forward active mode, aF of the emitter current reaches the collector. This means that aF of the diode current passing through the base-emitter junction contributes to the current flowing through the base-collector junction. Typically, aF has a value of between 0.98 and 0.99. This is shown as the forward component of current as it applies to the normal forward active mode of operation of the device. Note this current is shown as a conventional current in Fig. 2.2. It is equally possible to reverse the biases on the junctions to operate the transistor in the "reverse active mode". In this case, aR times the collector current will contribute to the emitter current. For the doping ratios normally used the transistor will be much less efficient in the reverse mode and aR would typically be in the range 0.1 to 0.5.

a.Ebers-Moll Equations

The Ebers-Moll transistor model is an attempt to create an electrical model of the device as two diodes whose currents are determined by the normal diode law but with additional transfer ratios to quantify the interdependency of the junctions as shown in Fig. 2.3. Two dependent current sources are used to indicate the interaction of the junctions.The interdependency is quantified by the forward and reverse transfer ratios, aF and aR. The diode currents are given as[5]:

$$I_F = I_{ES}(e^{V_{BE}/V_T} - 1) \text{ where } I_{ES} = qA\left(\frac{D_e p_{e0}}{L_e} + \frac{D_b n_{b0}}{W_b}\right) = qA\left(\frac{D_e n_i^2}{L_e N_e} + \frac{D_b n_i^2}{W_b N_b}\right)$$

$$I_R = I_{CS}(e^{V_{BC}/V_T} - 1) \text{ where } I_{CS} = qA\left(\frac{D_c p_{c0}}{L_c} + \frac{D_b n_{b0}}{W_b}\right) = qA\left(\frac{D_c n_i^2}{L_c N_c} + \frac{D_b n_i^2}{W_b N_b}\right)$$

Applying Kirchoff's laws to the model gives the terminal currents as:

This gives:

$$I_E = I_F - \alpha_R I_R \qquad \alpha_F = 0.98 - 0.99 \text{ typically}$$
$$I_C = \alpha_F I_F - I_R \qquad \alpha_R = 0.1 - 0.5 \text{ typically}$$
$$I_B = I_E - I_C$$

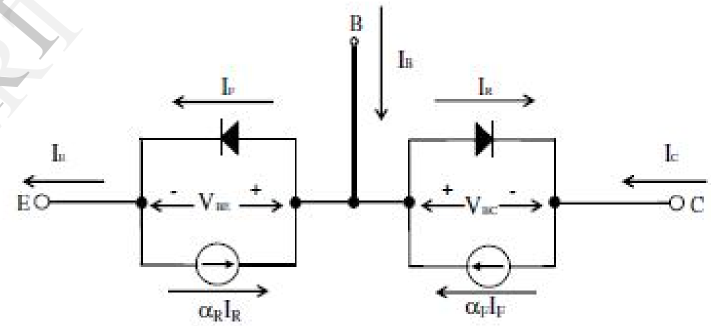

Fig. 3 The Ebers-Moll Model of an n-p-n Bipolar Junction Transistor

$$I_E = I_{ES}(e^{V_{BE}/V_T} - 1) - \alpha_R I_{CS}(e^{V_{BC}/V_T} - 1)$$

$$I_C = \alpha_F I_{ES}(e^{V_{BE}/V_T} - 1) - I_{CS}(e^{V_{BC}/V_T} - 1)$$

$$I_B = (1 - \alpha_F) I_{ES}(e^{V_{BE}/V_T} - 1) + (1 - \alpha_R) I_{CS}(e^{V_{BC}/V_T} - 1)$$

These are called the Ebers-Moll Equations for the bipolar transistor(see Fig. 2.3).

IV. GUMMEL POON MODEL

The *Gummel-Poon* model is a compact model for bipolar junction transistors (BJT) which also takes into account effects of low currents and at high-level injection[12]. A Gummel–Poon model for abrupt, single heterojunction Npn bipolar phototransistors is described including the effects of the dc base bias on the current and optical gains. Initially, the excess electron concentration at the emitter end of the quasi neutral base is determined by matching the thermionic field emission across the emitter–base heterojunction with the diffusion current at the emitter end of the base and including the effects of optical generation. The result is used in determining the electron profile in the base from which the base charge and the electron component to the emitter and collector currents are calculated following the Gummel–Poon model. The photocurrent's components due to optical absorption in the quasineutral base, the base–collector space charge region, and the collector region are determined taking into account the nonuniform optical generation assuming topside illumination. A comprehensive description of the recombination current components is incorporated including the effects of optical absorption on recombination. The model is then used to calculate the dc and small signal current gain and the device's optical gain, and to examine the effects of dc biasing and the optical power level[8].The structure of the model is derived from the transport model (figure below)

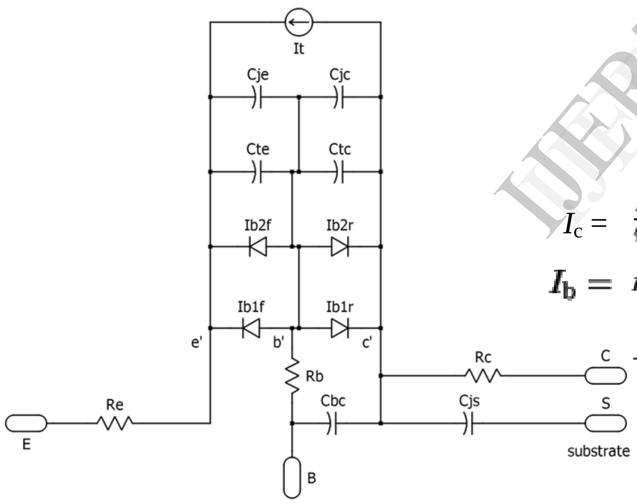

Fig.4 Transport model of Gummel Poon

The *Gummel-Poon* model is a compact model for bipolar junction transistors (BJT) which also takes into account effects of low currents and at high-level injection. Fig .shows the equivalent circuit of the *Gummel-Poon* model.

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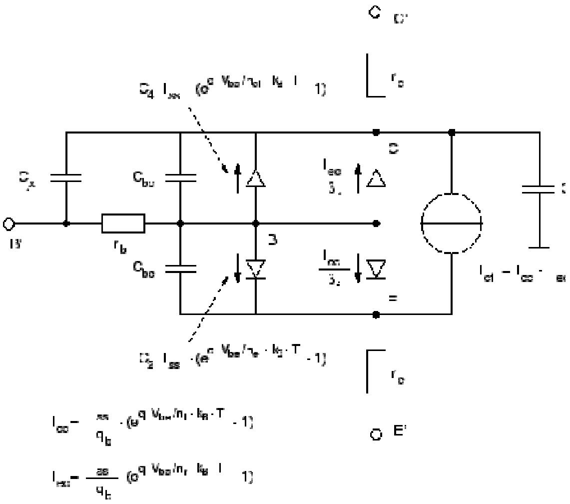

Fig.5 Equivalent circuit of the Gummel-Poon model.

The model distinguishes four operating regions. The base and collector current as they are implemented in *SPICE* are as follows.

a. *Normal Active Region*:

$$V_{be} > -\frac{5 \cdot n_f \cdot k_B \cdot T}{q}$$

and

$$V_{bc} \leq \frac{5 \cdot n_r \cdot k_B \cdot T}{q}$$

$$I_c = \frac{I_s}{q_b} \cdot \left(\exp\left(\frac{q \cdot V_{be}}{n_f \cdot k_B \cdot T}\right) + \frac{q_b}{\beta_r}\right) + C_4 \cdot I_s + \left(\frac{V_{be}}{q_b} - \left(\frac{1}{q_b} + \frac{1}{\beta_r}\right) \cdot V_{bc}\right) \cdot G_{min} \quad (3.1)$$

$$I_b = I_s \cdot \left(\frac{1}{\beta_f} \cdot \left(\exp\left(\frac{q \cdot V_{be}}{n_f \cdot k_B \cdot T}\right) - 1\right) - \frac{1}{\beta_r}\right) + C_2 \cdot I_s \cdot \left(\exp\left(\frac{q \cdot V_{be}}{n_{el} \cdot k_B \cdot T}\right) - 1\right)$$

$$-C_4 \cdot I_s + \left(\frac{V_{be}}{\beta_f} + \frac{V_{bc}}{\beta_r}\right) \cdot G_{min} \quad (3.2)$$

b. *Inverse Region*:

$$V_{be} \leq -\frac{5 \cdot n_f \cdot k_B \cdot T}{q}$$

and

$$V_{bc} > -\frac{5 \cdot n_r \cdot k_B \cdot T}{q}$$

$$I_c = -\frac{I_s}{q_b} \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_r \cdot k_B \cdot T}\right) + \frac{q_b}{\beta_r} \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_r \cdot k_B \cdot T}\right) - 1\right)\right)$$

$$-C_4 \cdot I_s \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_{cl} \cdot k_B}\right) - 1\right) + \left(\frac{V_{be}}{q_b} - \left(\frac{1}{q_b} + \frac{1}{\beta_r}\right) \cdot V_{bc}\right) \cdot G_{min} \quad (3.3)$$

$$I_b = -I_s \cdot \left(\frac{1}{\beta_f} - \frac{1}{\beta_r} \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_r \cdot k_B \cdot T}\right) - 1\right)\right) - C_2 \cdot I_s$$

$$+C_4 \cdot I_s \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_{cl} \cdot k_B \cdot T}\right) - 1\right) + \left(\frac{V_{be}}{\beta_f} + \frac{V_{bc}}{\beta_r}\right) \cdot G_{min} \quad (34)$$

b. *Saturated Region*:

$V_{be} > -\frac{5 \cdot n_f \cdot k_B \cdot T}{q}$ and

$$V_{bc} > -\frac{5 \cdot n_r \cdot k_B \cdot T}{q}$$

$$I_c = \frac{I_s}{q_b} \cdot \left(\left(\exp\left(\frac{q \cdot V_{be}}{n_f \cdot k_B \cdot T}\right) - \exp\left(\frac{q \cdot V_{bc}}{n_r \cdot k_B \cdot T}\right)\right) - \frac{q_b}{\beta_r} \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_r \cdot k_B \cdot T}\right) - 1\right)\right)$$

$$-C_4 \cdot I_s \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_{cl} \cdot k_B}\right) - 1\right) + \left(\frac{V_{be}}{q_b} - \left(\frac{1}{q_b} + \frac{1}{\beta_r}\right) \cdot V_{bc}\right) \cdot G_{min} \quad (3.5)$$

$$I_b = I_s \cdot \left(\frac{1}{\beta_f} \cdot \left(\exp\left(\frac{q \cdot V_{be}}{n_f \cdot k_B \cdot T}\right) - 1\right) + \frac{1}{\beta_r} \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_r \cdot k_B \cdot T}\right) - 1\right)\right)$$

$$+C_2 \cdot I_s \cdot \left(\exp\left(\frac{q \cdot V_{be}}{n_{el} \cdot k_B \cdot t}\right) - 1\right) + C_4 \cdot I_s \cdot \left(\exp\left(\frac{q \cdot V_{bc}}{n_{cl} \cdot k_B \cdot T}\right) - 1\right) + \left(\frac{V_{be}}{\beta_f} + \frac{V_{bc}}{\beta_r}\right) \cdot G_{min}$$

$$+\left(\frac{V_{be}}{\beta_f} + \frac{V_{bc}}{\beta_r}\right) \cdot G_{min} \quad (3.6)$$

d. *off region*: $V_{be} \leq -\frac{5 \cdot n_f \cdot k_B \cdot T}{q}$ and

$$V_{bc} \leq -\frac{5 \cdot n_r \cdot k_B \cdot T}{q}$$

$$I_c = \frac{I_s}{\beta_r} + C_4 \cdot I_s + \left(\frac{V_{be}}{q_b} - \left(\frac{1}{q_b} + \frac{1}{\beta_r}\right) \cdot V_{bc}\right) \cdot G_{min} \quad (3.7)$$

$$I_b = -I_s \cdot \frac{\beta_f + \beta_r}{\beta_f \cdot \beta_r} - (C_2 + C_4) \cdot I_s + \left(\frac{V_{be}}{\beta_f} + \frac{V_{bc}}{\beta_r}\right) \cdot G_{min} \quad (3.8)$$

In these equations G_{min} is the minimum conductance which is automatically switched in parallel to each pn-junction.

V. MEXTRAM MODEL

Mextram is an advanced compact model for the description of bipolar transistors. It contains many features that the widely-used Gummel-Poon model lacks. Mextram can be used for advanced processes like double-poly or even SiGe transistors, for high-voltage power devices, and even for uncommon situations like lateral NPN-transistors in LDMOS technology. Mextram level 503 has been put in the public domain [1] by Koninklijke Philips Electronics N.V. in 1994. Since the model update of 1995 it had been unchanged[13]. A successor, Mextram level 504, was developed in the late nineties of the 20th century for several reasons,the main ones being the need for even better description of transistor characteristics and the need for an easier parameter extraction. In the fall of 2004, Mextram was elected as a world standard transistor model by the *Compact Model Council (CMC)*, a consortium of representatives from over 20 major semiconductor manufacturers.The goal of this document is to give the model definition of Mextram 504. Since especially section 4 is also meant as an implementation guide, the structure of our presentation will be more along the lines of implemented code than structured in a didactical way. But we have also added an introduction of the physics behind the model and an introduction to the parameter extraction. The improved description of transistor characteristics of Mextram 504 compared to Mextram 503 were achieved by changing some of the formulations of the model. For instance Mextram 504 contains the Early voltages as separate parameters, whereas in Mextram 503 they were calculated from other parameters. This is needed for the description of SiGe processes and improves the parameter extraction (and hence the description) in the case of normal transistors. An even more important improvement is the description of the epilayer. Although the physical description has not changed, the order in which some of the equations are used to get compact model formulations has been modified[3]. The result is a much smoother behaviour of the model characteristics, i.e. the model formulations are now such that the first and higher-order derivatives are better. This is important for the output-characteristics and cut-off frequency, but also for (low-frequency) third order harmonic distortion. For the same reason of smoothness some other formulations, like that of the depletion capacitances, have been changed. In Mextram almost all of the parameters have a physical meaning.[4]This has been used in Mextram 503 to relate different parts of the model to each other by using the same parameters. Although this is the most physical way to go, it makes it difficult to do parameter extraction, since some parameters have an influence on more than one physical effect. Therefore we tried in Mextram 504 to remove as much of this interdependence as possible, without losing the physical basis of the model. To do this we added some extra parameters. At the same time we removed some parameters of Mextram 503 that were introduced long ago but which had a limited influence on the characteristics, and were therefore difficult to extract.

a.*Mextram contains descriptions for the following effects[14]:*

• Bias-dependent Early effect

• Low-level non-ideal base currents

• High-injection effects

• Ohmic resistance of the epilayer

• Velocity saturation effects on the resistance of the epilayer

• Hard and quasi-saturation (including Kirk effect)

• Weak avalanche (optionally including snap-back behaviour)

• Charge storage effects

• Split base-collector and base-emitter depletion capacitance

• Substrate effects and parasitic PNP

• Explicit modelling of inactive regions

• Current crowding and conductivity modulation of the base resistance

• First order approximation of distributed high frequency effects in the intrinsic base (high-frequency current crowding and excess phase-shift)

• Recombination in the base (meant for SiGe transistors)

• Early effect in the case of a graded band gap (meant for SiGe transistors)

• Temperature scaling

Mextram does not contain extensive geometrical or process scaling rules (only a multiplication factor to put transistors in parallel). The model is well scalable, however, especially since it contains descriptions for the various intrinsic and extrinsic regions of the transistor. Some parts of the model are optional and can be switched on or off by setting flags[1]. These are the extended modelling of reverse behaviour, the distributed high-frequency effects, and the increase of the avalanche current when the current density in the epilayer exceeds the doping level. Besides the NPN transistor also a PNP model description is available. Both three-terminal devices (discrete transistors) and four-terminal devices (IC-processes which also have a substrate) can be described.

a..***Physical description of the model***

Mextram, as any other bipolar compact model, describes the various currents and charges that form the equivalent circuit, given in Fig. 1 on page 32. In tables 1 and 2 we have given a list of the currents and charges of this equivalent circuit.We will first describe the active transistor. This is the intrinsic part of the transistor, which is also modelled by the Gummel-Poon model. Next we will discuss the extrinsic regions.

In the Mextram model the generalisation of the Moll-Ross relation, better known as the integral charge control relation (ICCR), is used to take into account the influence of the depletion charges *QtE* and *QtC* and the diffusion charges *QBE* and *QBC* on the main current. The basic relation is Convergency and computation time[14]
Mextram is a more complex model than Gummel-Poon. Therefore, the computing time is larger, especially when self-heating is included.[5] For the same reason the convergency will be less, although we cannot give any quantitative comparison. The computation time of Mextram 504 is comparable to that of Mextram 503. However, tests show that Mextram 504 has better convergency than Mextram 503. This is probably mainly due to improved smoothness of the model

Mextram does not contain a substrate resistance. We know that this substrate resistance can have an influence on transistor characteristics. This is mainly seen in the real part of *Y*22. For optimimum flexibility we did not make it a part of the model itself, because in the technology it is also not part of the transistor itself[13]. It depends very much on the layout. The layout in a final design might be different from the layout used in parameter extraction. Also complicated substrate resistance/capacitance networks are sometimes needed. Therefore we chose to let the substrate resistance not be part of the model[14]

b.*Possible improvements*

Mextram does not contain a reverse emitter-base breakdown mechanism, because it was not deemed relevant enough. This could be either an avalanche breakdown or, more probable, a tunnel breakdown. The forward current of the parasitic PNP transistor is modelled. Mextram, however, does not contain a full description of the reverse current of the PNP since we believe that this is not important for designers. The output conductance d*IC/*d*V*CE at the point where hard saturation starts seems to be too abrupt for high current levels, compared to measurements[1]. At present it is not possible to improve this, without losing some of the other features of the model. The clarity of the extrinsic current model describing *XI*ex and *XI*sub could be improved by adding an extra node and an extra contact base resistance[7]. Since the quality of the description does not improve, the parameter extraction would be more difficult, and the model topology would become dependent on a parameter (EXMOD) we choose not to do this.

VI CONCLUSION:

The bipolar models discussed include the Ebers-Moll model, Gummel-Poon model, MEXTRAM model. The Ebers-Moll model is a simple model for the "intrinsic" transistor, first developed in 1954. It is based on the pn-junctions theory where the continuity equation for the narrow-base region is solved using the excess minority carrier concentrations at the edges of the neutral base as boundary conditions[5].The Mextram model is a physical device model developed for CACD purposes.The defining model equations are derived directly from the device physics,and empirical fit functionsare avoided whenever possible. Physical models offer forecasting capabilities, allowing geometrical scaling rules to be applied confidently. The parameter values used in Mextram model, including the temperature dependencies, are not simply fitted values but have physical significance. Because statistical correlation between model parameters is also determined by device physics, the physical models faciliate realistic statistical modeling , which is doubtful for empirical curve-fitting models.

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