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D.C. Electrothermal Hybrid BJT Model for SPICE

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Abstract

SPICE - built-in models are the isothermal models with the temperature as a parameter. Electrothermal interactions caused that the device (junction) temperature changes due to changes of dissipated power. In the paper the new BJT electrothermal model which includes the thermal effects is proposed. This model is represented by combination of SPICE-built-in isothermal model and any additionaly controlling generators modelling selfheating and some other electrical effects nonmodeled by SPICE.

1. Introduction

The strong temperature influence on the electrical characteristics of bipolar transistors is observed. On the other hand, the electrical power dissipated in BJT causes the increase of the inside temperature above the ambient one, as a result of non-ideal conditions of the heat abstraction. Therefore, the mutual interactions between the electrical and the thermal phenomena in BJT, commonly called - the electrothermal interactions, exist. Inclusion of the electrothermal interactions to modelling makes the model of a semiconductor device more adequate.

SPICE program - commonly used for circuit analysis, can not be directly applied to the electrothermal case, because there is no possibility to consider the change of device (junction) temperature caused by power dissipation. On the other hand, there were some attempts made to use SPICE to the electrothermal analysis, e.g. [1, 2]. Unfortunately, these analyses are inaccurate because of the use of too simple electrothermal device models.

In this paper an electrothermal hybrid model of BJT with much better accuracy in the whole operating range is presented. This model is represented by combination of SPICE-built-in isothermal model and additionally control generators. These generators model changes of BJT currents and voltages caused by the change of the junction temperature due to the electrothermal interactions and by other isothermal effects, like current gain factors changing and avalanche effects, which are not modelled directly by SPICE.

2. The fundamental dependences

The starting point to formulate the electrothermal hybrid model (EHM) of BJT are dependences describing GETM2 model given in [3]. Choosing the collector current i_C, the base-to-emitter voltage u_{BE} and the base-to-collector voltage u_{BC} as the independent variables, one can write for the active-normal region:

$$i_C = \beta_F \cdot i_B + I_S \cdot \left(1 + \frac{\beta_F + 1}{\beta_R}\right) \tag{1}$$

$$u_{BE} = V_T \cdot \ln\left(\frac{i_B \cdot \beta_F}{I_S} + 1 + \frac{\beta_F}{\beta_R}\right) \tag{2}$$

and for the active-inverse region:

$$i_C = -(\beta_R + 1) \cdot i_B - I_S \cdot \left(\frac{1}{\beta_R} + \frac{\beta_R + 1}{\beta_F}\right) \tag{3}$$

$$u_{BC} = V_T \cdot \ln\left(\frac{i_B \cdot \beta_R}{I_S} + 1 + \frac{\beta_R}{\beta_F}\right) \tag{4}$$

where i_B is the base current .

In Eqs (1-4) the temperature dependent parameters: the saturation current I_S, the thermal potential V_T and the current-gain factor for the active-normal region (β_F) and for the active-inverse region (β_R), respectively are given as follows:

$$I_S = I_0 \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(\frac{-U_{go}}{V_T}\right) \tag{5}$$

$$V_T = {}^{k}\!/_{q} \cdot T_j \tag{6}$$

$$\beta_F = \frac{\beta_{0F} \cdot \left(1 + a \cdot \left(T_j - T_a\right)\right)}{1 + b \cdot \left(1 + c \cdot \left(T_j - T_a\right)\right) \cdot \left|i_C\right|} \tag{7}$$

$$\beta_R = \frac{\beta_{0R}}{\beta_{0F}} \cdot \beta_F \tag{8}$$

where k, q - are the phisical constants, I_0, T_0, β_{0F}, β_{0R}, a, b, c are the model parameters and T_a is the ambient temperature. The junction temperature T_j is given by the following dependence

$$T_j = T_a + K_t \cdot \left(u_{CE} \cdot i_C + u_{BE} \cdot i_B\right) \tag{9}$$

where the u_{CE} is the collector-to-emitter voltage, and K_t denotes the thermal resistance of the BJT. Eqs (7) and (8) denote that β_F and β_R are described by the dependences of the same form, but with different values of the coefficients β_{0F}, β_{0R}. It was assumed that parameters a, b, c are the same for β_F and β_R. So, β_F (Eq. 7) or β_R (Eq. 8) can be given as follows

$$\beta = \beta_0 \cdot f\left(u_{CE}, i_C\right) \tag{10}$$

Now, it is easy to observe that the multiplications $\beta_F \cdot i_B$ (Eq 2) and $\beta_R \cdot i_B$ (Eq 4) can be presented as the multiplication of the isothermal collector current i_{CO} (represented by SPICE-built-in model) and the function $f(u_{CE}, i_C)$, of the form

$$\beta \cdot i_B = |i_{CO}| \cdot f(u_{CE}, i_C). \tag{11}$$

The absolute value of i_{CO} in Eq. (11) and i_C in Eq (7) is to secure the rightness of the model, both in the active-normal region ($i_C > 0$) and in the active-inverse region ($i_C < 0$).

3. The electrothermal hybrid BJT model (EHM)

The electrothermal hybrid model results directly from the transformation of the dependences from Sec. 2 to the form

$$i_C = i_{CO} + \Delta i_C \tag{12}$$

$$u_B = u_{BO} + \Delta u_B \tag{13}$$

where, i_{CO}, u_{BO} are described by the standard SPICE-built-in model with the ambient temperature as a parameter ($u_{BO} = u_{BEO}$ for the active-normal region and $u_{BO} = u_{BCO}$ for the active-inverse region). The remain part of the so transformed dependences describes the change of the collector current (Δi_C) and the base-to-emitter or the base-to-collector voltages (Δu_B), caused by the increase of the junction temperature and by the decrease of the current gain factor (both β_F and β_R) for high current density simultanously. Assuming that $\beta_F >> \beta_R$ and $\beta_F >> 1$, we get

$$\Delta u_B = T_j \cdot \frac{k}{q} \cdot \ln\left(\frac{|i_{CO}| \cdot f(u_{CE}, i_C)}{I_S} + 1 + \left(\frac{\beta_{0F}}{\beta_{0R}} \right)^{\varphi} \right) - T_a \cdot \frac{k}{q} \cdot \ln\left(\frac{i_{CO}}{I_{S0}} + 1 + \left(\frac{\beta_{0F}}{\beta_{0R}} \right)^{\varphi} \right) \tag{14}$$

$$\begin{aligned} \Delta i_C = {} & -b \cdot \left(1 + c \cdot (T_j - T_a)\right) \cdot |i_C| \cdot i_C + i_{CO} \cdot a \cdot (T_j - T_a) + \\ & + \varphi \cdot I_S \cdot \left(\frac{1}{\beta_R} + \left(\frac{\beta_{0F}}{\beta_{0R}} \right)^{\varphi} \right) \cdot \left[1 + b \cdot \left(1 + c \cdot (T_j - T_a)\right) \cdot |i_C| \right] \end{aligned} \tag{15}$$

where I_{SO} is the value of I_S for the ambient temperature and $\varphi = 1$ for $i_C \geq 0$ and $\varphi = -1$ for $i_C < 0$.

The finally circular form of EHM is shown in Figure 1. Additionally, in EHM the avalanche effects existing in the both BJT junctions for the appropriate high values of the junction-voltages (modelled by the additionally connected p-n diodes with satisfactory built parameters) are taken into account. The part of EHM marked as T-iso is the SPICE-built-in BJT model. The independent voltage sources (u = 0) allow the use of the values of the appropriate currents, with much better accuracy than in the case of resistors use.

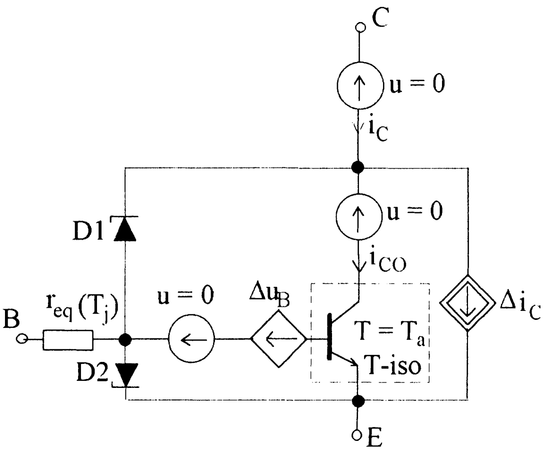

Figure 1: The circular form of EHM

To include the temperature dependence of the series BJT resistances, the linear temperature dependent equivalent resistance of the form

$$r_{eq}\left(T_j\right) = r_0 \cdot \frac{T_j}{T_a} \qquad (16)$$

where r_0 is the value of r_{eq} for $T_j = T_a$, is introduced. In this case the proper SPICE parameters represented the series BJT resistances are equal to zero.

4. Example

To illustrate the usefulness of the presented model to modelling of BJT in the electrothermal case, in Figure 2 nonisothermal $i_C(u_{CE})$ characteristics of 2N2193 transistor obtained by the use of EHM, a model proposed in [1] and by measurements, are presented. At it is seen, EHM gives a good accuracy, much better than the known model presented in [1].

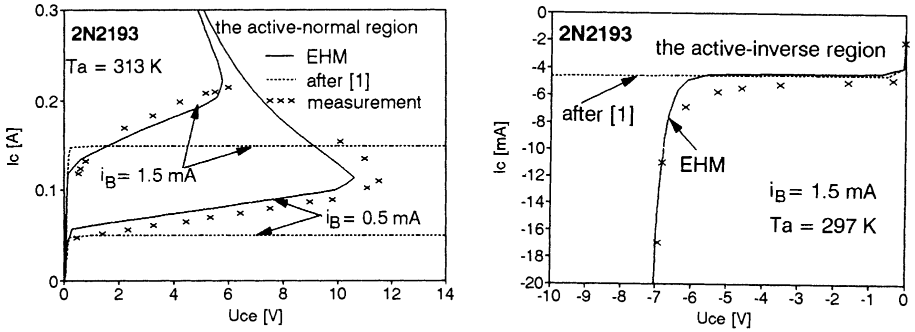

Figure 2: Nonisothermal $i_C(u_{CE})$ BJT characteristics

5. Concluding remarks

In this paper the new form of the electrothermal BJT model has been presented. This model gives a good accuracy in the whole range of the work of BJT. In EHM, apart from electrothermal interactions, also dependence of the current gain factors on the collector current and avalanche effects in the both junctions are included.

References

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