TEMPERATURE DEPENDENCE SIMULATION OF THE EMISSION COEFFICIENT VIA EMITTER CAPACITANCE

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ABSTRACT

The need to increase accuracy and stability in the design of temperature sensors and bandgap references has lead to recent experimental studies of the emission coefficient n. . In particular an unexplained increase of n at low temperatures has been measured in CMOS vertical bipolar pnp transistors. In this paper a new procedure for the simulation of n is presented using Gummel-Poon's expression of n as a function of Ce, and HICUM's compact model expression of Ce as a function of temperature. This new procedure allows a physical approach to explain temperature dependence of n. Simulation results show that the temperature dependence parameter η of V_{BE} plays a major role in the increase of n at low temperatures.

RESUMEN

La necesidad de aumentar la exactitud y la estabilidad en el diseño de los sensores de temperatura y las referencias de bandgap han dado lugar a estudios experimentales del coeficiente de emisión n. En particular un incremento no explicado de n a bajas temperaturas ha sido medido en transistores bipolares verticales pnp en tecnología CMOS. En este artículo se presenta un nuevo procedimiento para la simulación de n utilizando la expresion de Gummel-Poon para n en función de Ce y la expresión de Ce del modelo compacto HICUM en función de la temperatura. Este nuevo procedimiento enfoca la dependencia de n con la temperatura desde un punto de vista físico. Los resultados de simulación muestran que el parámetro η de la dependencia con la temperatura de V_{BE}, juega un papel importante en el aumento de n a bajas temperaturas.

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ABSTRACT

An unexpected increase of the emission coefficient n of bipolar transistors at low temperature and constant bias current has been experimentally shown recently. In this paper an increase of n at low temperatures is shown in the simulation of a typical bipolar transistor for high values of parameter η and at certain bias current levels. The emission coefficient has been calculated using Gummel-Poon's expression as a function of Ce, and HICUM's compact model expression of Ce as a function of temperature.

1. INTRODUCTION

The need to increase accuracy and stability in the design of temperature sensors and bandgap references has lead to recent experimental studies [1] on the variation with temperature of the emission coefficient n at constant bias current. In particular an unexplained increase of n at low temperatures has been measured in CMOS vertical bipolar pnp transistors.

Many authors [2,3] consider the emission coefficient as in the SPICE-Gummel-Poon model (SGP)[4], with a constant value close to unity to explain the non ideality of the exponential dependence of collector current I_C on emitter base voltage, $\mathbf{I_C \ \alpha \ exp \ (qV_{be}/nkT)}$.

Nevertheless in the original Gummel-Poon model (GP) [5] n is not a parameter and it is defined, at given V_{cb} and T, as the reciprocal of the slope of the Gummel plot . It can be shown that at low level injection n depends on the emitter capacitance and is given by [5], $\mathbf{n \approx 1 + kTC_e / qQ_{b0}}$. Because Ce increases significantly under forward bias conditions [6], n should also increase. The SGP model cannot simulate this behavior because of the constant C_e assumption in its DC model. This assumption was made [7] to obtain a constant output conductance similar to that of the Ebers-Moll model, because at that time the original GP model was not universally accepted.

In this paper a new simulation procedure is presented to obtain the emission coefficient of a bipolar transistor biased at constant collector current. This procedure uses the original Gummel-Poon's expressions [5] as a function of C_e, and HICUM's compact model expressions of C_e as a function of temperature [8]. In this simulation Gummel-Poon's sample transistor [5] is used because the values of its 21 parameters at 300 K are known. At other temperatures the Gummel-Poon model is not adequate [4].

2. THE EMISSION COEFFICIENT

The emission coefficient is defined [5] as the reciprocal of the slope of the Gummel plot ($\ln I_C$ vs qV_{be}/kT) and is given by the analytical expression,

$$\frac{1}{n} \equiv \frac{kT}{qI_C}\frac{dI_C}{dV_{eb}}\bigg|_{V_{cb}=\text{constant}} \qquad (1)$$

The emision coefficient n is not a parameter in the original Gummel-Poon model as can be seen from the collector current expression,

$$I_C = -I_S Q_{b0}\,\frac{\exp\left(\dfrac{qV_{eb}}{kT}\right) - \exp\left(\dfrac{qV_{cb}}{kT}\right)}{Q_b} + I_{bc} \qquad (2)$$

In expression (2) Q_{b0}, the zero-bias charge in the base, can be considered constant and Q_b, the "base charge", includes besides Q_{b0}, capacitive and current charge contributions that depend on junction voltages taking care of the non ideal behavior of ln I_C vs qV_{be}/kT at low and high level injection.

At low level injection and zero biased collector junction, $Q_b = Q_{b0} + Q_e$, and if $Q_{b0} >> Q_e$, n is given by [5],

$$n \approx 1 + \frac{kTC_e}{qQ_{b0}} \qquad (3)$$

where $C_e = \left.\frac{dQ_e}{dV_{eb}}\right|_{V_{cb}=\text{constant}}$ is the emitter capacitance.

3.MODELING EMITTER CAPACITANCE

From expression (3), to simulate n with temperature, adequate modeling of Ce is required. Because GP model is not adequate for temperature variation [4], HICUM's compact model expression [8] for emitter capacitance is used.

Emitter capacitance in HICUM model is also based on clasical depletion capacitance expression,

$$C_{je} = \frac{C_{je0}}{\left(1 - \frac{V_{BE}}{V_{DE}}\right)^{Z}} \qquad (4)$$

whose three parameters are,

V_{DE}: diffusion or built-in voltage

C_{je0}: zero bias emitter capacitance

z: grading coefficient

Under significant forward bias, emitter capacitance increases to a maximum value that can not be explained with expression (4) and in HICUM compact model it has been modified with a four parameters expression that also includes a smoothing function,

$$C_{je} = \frac{C_{je0}}{(1 - V_j/V_{DE})^{z}}\frac{e}{1+e} + a_{je}C_{je0}\frac{1}{1+e} \qquad (5)$$

where **e, V_j, V_f** and the fourth parameter **a_{je}** are given by the expressions,

$$e = \exp\left(\frac{V_j - V_{be}}{V_T}\right) \qquad (6)$$

$$V_j = V_f - V_T \ln(1+e) \qquad (7)$$

$$V_f = V_{DE}\left[1 - a_{je}^{-(1/z)}\right] \qquad (8)$$

$$a_{je} = \frac{C_{jemax}}{C_{je0}} \qquad (9)$$

Temperature dependence in this model is given by expressions,

$$C_{je0}(T) = C_{je0}(T_r)\left(\frac{V_{DE}(T_r)}{V_{DE}(T)}\right)^{z} \qquad (10)$$

$$a_{je}(T) = a_{je}(T_r)\frac{V_{DE}(T)}{V_{DE}(T_r)} \qquad (11)$$

The key parameter for temperature dependence of capacitance is the diffusion (or built-in) voltage **V_{DE}** given in HICUM model by ,

$$V_{DE}(T) = V_{G0}\left(1 - \frac{T}{T_r}\right) + V_{DE}(T_r)\frac{T}{T_r} - 3V_T \ln\left(\frac{T}{T_r}\right) \qquad (12)$$

To model $V_{BE}(T)$, instead of HICUM model, the bandgap linear approximation is used, which based on experimentally measured parameters **η** and **V_{G0}** , is very accurate [9,10],

$$V_{BE}(T) = V_{G0}\left(1 - \frac{T}{T_r}\right) + V_{BE}(T_r)\frac{T}{T_r} - \eta V_T \ln\left(\frac{T}{T_r}\right) \qquad (13)$$

where **T_r** is the reference temperature considered here 300 K. The GP model is not used because it is not adequate for temperature variations [4], and HICUM's V_{BE} model does not consider parameters η and V_{G0} that depend on base impurity concentration [10].

4.SIMULATION OF N WITH GUMMEL-POON'S SAMPLE TRANSISTOR

The simulation of n with temperature uses GP's sample transistor [5] because it is well characterized by the values of its 21 parameters at 300 K [5]. The transistor is biased here at constant collector current.

This simulation is performed in the 240 to 300 K interval using expressions (3) and (5) to (13). The values of Ce parameters of HICUM model $C_{jeo}(T_r)$ = 1.51 pF, $a_{je}(T_r)$= 5.735, z = 0.48, $V_{DE}(T_r)$= 0.700535 V , are obtained from the values v_{oe}= 27.1, m_e= 0.24, a_{e1}= 0.337 and a_{e2}= $1.03 \text{x} 10^{-2}$, of sample transistor.

The value of Q_{b0} calculated from $Q_{b0} = -I_k\tau_f$ [5] is 6.0 pC and its temperature dependence is considered negligible [8].

To simulate the temperature behavior of the base- emitter voltage using expression (13) it is necessary to know the values of **η** , **V_{G0}** and $V_{BE}(T_r)$. The value of $V_{BE}(T_r)$ is obtained solving the full set of GP's equations [5]. Because **η** and **V_{G0}** are not part of GP's model, their values are taken from experimental measurements of transistors in two different technologies: npn transistors of a standard IC bipolar technology [9] and pnp vertical substrate bipolar transistors in a CMOS technology [11].

Two levels of bias current are considered: 100 µA and 200µA, which are not high considering that the knee current I_K of sample transistor is 18.75 mA.

5. SIMULATION RESULTS

The values η=3.618 and V_{G0}=1.1707 V characterize temperature dependence of $V_{BE}(T)$ in npn transistors of a standard bipolar IC process [9].

Simulation is performed at I_C=100µA and I_C=200µA with corresponding values $V_{BE}(T_r)$=0.612265 V and $V_{BE}(T_r)$= 0.630702 V of the sample transistor.

The simulation results are shown in Fig. 1. The emission coefficient shows a decrease at low temperatures.

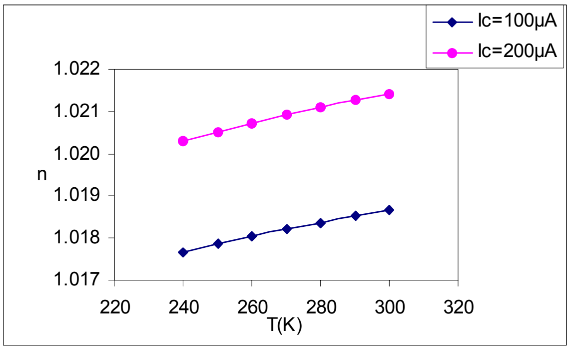

Fig. 1 Emission coefficient temperature dependence of sample transistor with η=3.618, V_{G0}=1.1707 V at two bias current levels.

In vertical pnp transistors of a CMOS technology [11] η shows high values with a spread between 4.8 and 5.2. With a selected value of η=5.1, V_{G0}=1.12046 V was calculated from the linear regression equation [11] between η and V_{G0}.

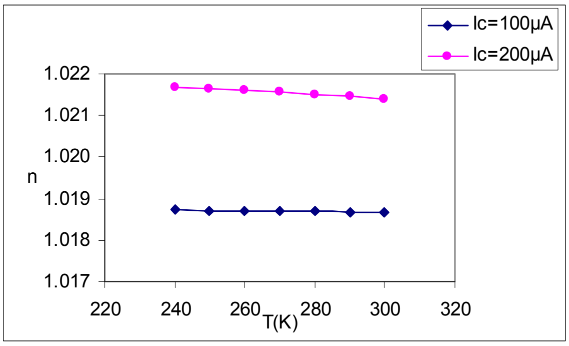

Fig. 2 Emission coefficient temperature dependence of sample transistor with η=5.1, V_{G0}=1.12046 V at two bias current levels

Simulation in this case shows in Fig. 2. an increase of n at low temperature. It can be noticed that at the higher bias current the increase of n is slightly greater.

6. DISCUSSION AND CONCLUSIONS

Simulation results show that for higher values of η, the emission coefficient n increases at low temperatures. This can be explained considering the ideal depletion emitter capacitance expresssion (4). From this expression, if V_{BE} approaches V_{DE} at lower temperatures, C_e will increase rapidly with the possibility to overcome the decrease of T in expression (3) of the emission coefficient.

From expressions (13) and (12) of $V_{BE}(T)$ and $V_{DE}(T)$ it can be seen that at low temperatures, where $T< T_r$, all terms in both equations are positive, and $V_{BE}(T)$ will approach $V_{DE}(T)$ as temperature decreases, only if η>3.

Generally the emission coefficient is obtained from the slope of a Gummel plot.

In this paper the expression (3) of Gummel-Poon is used because in relating n with the emitter capacitance Ce, it allows a physical approach of its behavior with forward bias and temperature which has been widely studied regarding Ce [12,5,6,8].

The use of the expression of n as a function of Ce allows also to see that the constant Ce assumption in the SPICE-Gummel-Poon model is inadequate to characterize n. This constant Ce assumption has also been reported as a limitation to represent the output conductance g_0 [7].

7. REFERENCES

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