SIMULATION OF SEMICONDUCTOR DEVICES AND PROCESSES Vol. 5
Edited by S. Selberherr, H. Stippel, E. Strasser – September 1993

Semianalytical Universal Simulation of the Electrical Properties of the Permeable Base Transistor

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Abstract

Using only a few numerical calculations, we give the analytical current-voltage and charge-voltage characteristics valid for any PBT. The highest unity current gain frequency (f_T) corresponding to the current technology is on the order of 30 GHz ; nevertheless, the oscillation frequency can be higher than 100 GHz.

1. Introduction

There are two types of PBT : the buried base PBT, and the etched groove PBT [1].
The PBT is essentially a two dimensional structure ; it is so impossible to find *ab initio* analytical expressions for its characteristics. The optimization of the device needs time consuming 2-D programs, and in particular, concerning its frequency limits.
In this paper, we show, for the first time, that the modelization of the PBT do not require to have a continuous recourse to a 2-D numerical simulation program, and we give a definitive answer to the high frequency performances of the device. To reach these results : (i) we have worked in the buried base PBT, and (ii) we have utilized the 2-D numerical program (TITAN+JUPIN) of CNET/CNS. Evidently, the PBT is a short channel MESFET. So, we have studied the half period of the structure $\left(L = \frac{a+d}{2} \text{ ; Fig. 1}\right)$, and we have supposed that the device is limited in its active zone : $W_E + W_C$; the device bias are then applied on the limits of these zones (V'_{BE} and V'_{CE}).

2. Similitude Laws for Low Collector Bias

We suppose here that in the electron velocity expression : $\vec{V}_n = \mu_n \vec{E}$, the mobility is constant. Besides, we adopt the classical hypothesis : (i) SCR totally depleted, (ii) at SCR boundaries, $\frac{\partial\phi}{\partial\vec{n}} = 0$, and (iii) into the channel $n \approx N_D$.

The study of Poisson equation with its boundary conditions shows that, if one takes $\frac{d}{2}$ as the length unity, and $\frac{qN_D}{\varepsilon}\frac{d^2}{4}$ as the potential unity, the potential $\phi(X,Y)$ depends only on the two dimensionless parameters $X=\frac{2W_E}{d}\,;Y=\frac{2W_C}{d}$, where W_E and W_C are the lengths of SCR around the base :

$$W_E=\left[\frac{2\varepsilon}{qN_D}\left(V_D-V'_{BE}\right)\right]^{1/2}\;;W_C=\left[\frac{2\varepsilon}{qN_D}\left(V_D-V'_{BE}+V'_{CE}\right)\right]^{1/2} \qquad (1)$$

We show then that the transistor current can be written as :

$$I_C=-\frac{q^2N_D^2\mu_n Zd^2}{4\varepsilon}\,f\left(\frac{2W_E}{d},\frac{2W_C}{d}\right) \qquad (2)$$

To determine the function $f(X,Y)$, it is sufficient to plot the $I_C\left(V'_{BE},V'_{CE}\right)$ characteristics for only one set of technological parameters $\left(\frac{d}{2},N_D,\mu_n\right)$. Therefore, using the 2-D numerical program for calculating the current characteristics of only one (non particular) PBT, we can calculate analytically the characteristics of any other device.

The threshold voltage of PBT (for $V_{CE}=0$) can also be calculated :

$$l(0)=H(0)W_E\,;V_{BET}=V_T \text{ for } \frac{d}{2}-l(0)=0, \text{ so, } V_T=V_D-\frac{q}{2\varepsilon H^2}N_Dd^2 \qquad (3)$$

The simulated characteristics give : $H(0)\approx 0{,}7$.

3. High Collector Bias Regime

The used model takes $\vec{V}_n=V_S\frac{\vec{E}}{E+E_C}$ with $V_S=1.04\times10^7\,cm\cdot s^{-1};E_C=1.04\times10^4\,Vcm^{-1}$

The current I_C can be written :

$$I_C=-qN_DZV_m\left[\left(\frac{d}{2}-h\right)\right] \qquad (4)$$

where V_m is an average velocity ; V_m and h are, *a priori*, dependent from bias, doping (N_D) and $\frac{d}{2}$. Using the 2-D program, we show that : (i) V_m and h are independent from $\frac{d}{2}$, (ii) V_m is independent from V'_{BE}, (iii) we can write : $h=H\left(N_D,V'_{CE}\right)W_E$,

(iv) $H=0.705-0.0525\,V'_{CE}$ (5)

so H is, in a first approximation, independent from N_D,

(v) satisfactory analytical expression for V_m is :

$$V_m=\frac{V'_{CE}}{V'_{CE}+E_C\left(W_{E_0}+W_{C_0}\right)} \qquad (6)$$

W_{E_0} and W_{C_0} being the values for $V'_{BE}=0$.

We establish so a universal expression for I_C :

$$I_C=-qN_DZV_m\left[\frac{d}{2}-HW_E\right] \qquad (7)$$

with V_m and H given by (6) and (5).

These analytical expressions fit very satisfactorily the 2-D simulations (Fig. 2 for example, where the dots correspond to the analytically calculated current). The 2-D simulations allow us to find also an analytical expression for the total charge in the SCR :

$$Q_{SC} = qN_D ZS = qN_D Z(W_E + W_C)\left[\frac{a}{2} + \alpha_0 \frac{W_E(W_E + W_E)}{3W_E + W_C}\right] \tag{8}$$

we find $\alpha_0 = 0.77$.

4. Small Signal Parameters; Frequency Limits

Using the analytical expressions of current (7) and charge (8), we can calculate : the conductance g_D, the transconductance g_m and the interelectrode capacitances C_{BE} and C_{BC}. The unity current gain (transition) frequency is then calculated :

$$f_T = \frac{g_m}{2\pi\left(C_{BE}\left(C_{BE} + 2C_{BC}\right)\right)^{1/2}} \tag{9}$$

$$g_m = Z\frac{\varepsilon}{W_E} V_m H$$

$$C_{BE} = Z\frac{\varepsilon}{W_E}\left[\left(\frac{a}{2}\right) + \alpha_0 W_C \frac{(1+\gamma)}{(1+3\gamma)^2}\left(6\gamma^2 + 3\gamma + 1\right)\right] \qquad)$$

$$C_{BC} = Z\frac{\varepsilon}{W_E}\left[\left(\frac{a}{2}\right)\gamma + \alpha_0 W_C \frac{(1+\gamma)}{(1+3\gamma)^2}\gamma^2(5\gamma + 1)\right] \qquad) \tag{10}$$

$$\gamma = \frac{W_E}{W_C} = \left[\frac{V_D - V'_{BE}}{V_D - V'_{BE} + V'_{CE}}\right]^{1/2} \qquad)$$

5. Conclusion and Remarks

The f_T, corresponding to the Fig. 2 parameters, is not higher than 30 GHz (Fig. 3). This result is confirmed by all the published experimental works [2,3,4,5,6,7] ; the PBT on GaAs has the same limits (V_S is nearly the same for Si and GaAs) ; the etched groove PBT can be slightly better (C_{BE} is lower) ; the maximum frequency oscillations, according to our estimations, must be higher than 100 GHz ; so, the PBT, as it can deliver an important power, can be an interesting device for high frequency power amplification [8].

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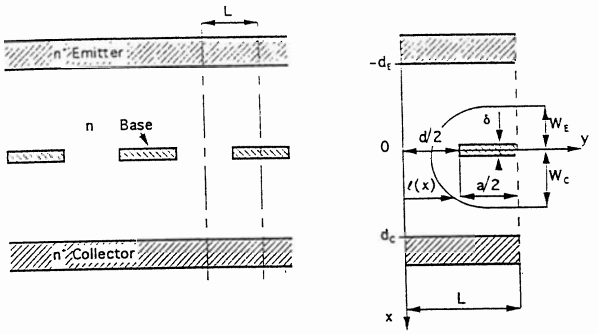

Fig. 1

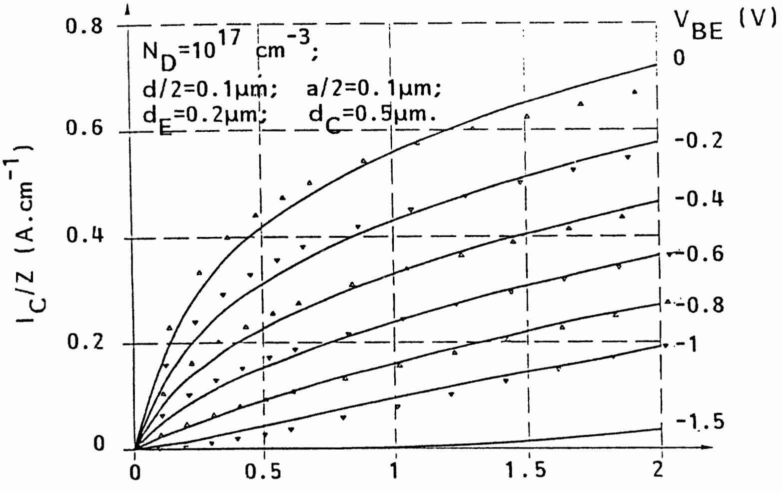

Fig. 2

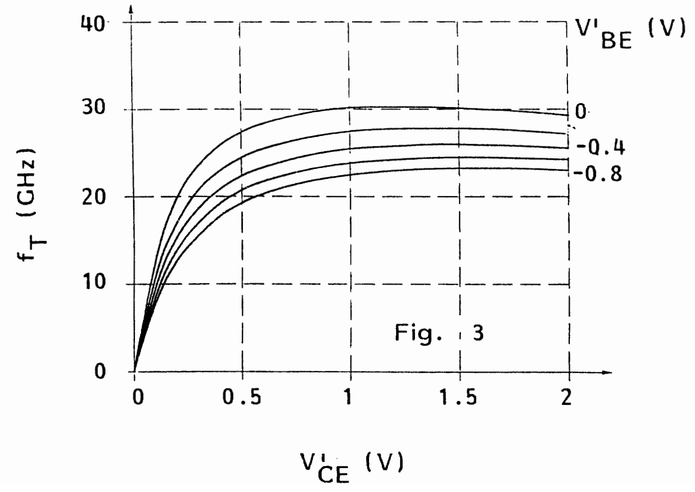

Fig. 3