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NOTE

C_{jc} AND THE OUTPUT CONDUCTANCE OF ADVANCED BIPOLAR JUNCTION TRANSISTORS UNDER NONLOCAL IMPACT IONIZATION CONDITIONS

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1. INTRODUCTION

With the advancement of integrated circuit process technology, as bipolar junction transistors are scaled down, the doping densities in the base and collector are increased. To prevent base stretching and its consequent performance degradation at high current densities, the collector doping is raised[1]. As a consequence, the collector junction breakdown voltage (BV_{ceo}) decreases. Hence under normal operating bias conditions, advanced bipolar transistors are required to operate at a quiescent point that is susceptible to the avalanche effect. The collector capacitance (C_{jc}) which becomes significant at high collector dopings plays a significant role in determining the switching speed and high frequency response of the bipolar transistors. The output conductance and early voltage are also very important SPICE model parameters in CAD of VLSI circuits. As impact ionization generates large number of free electrons and holes in collector–base space charge layer when the transistor operates near avalanche breakdown regime, C_{jc}, output conductance and early voltage of the device are affected significantly.

The aim of the present paper is therefore to study the above parameters in terms of multiplication factor M which changes considerably in the avalanche region. The avalanche effect is due to the impact ionization which may be local or nonlocal[2] depending on the collector–base space charge layer thickness and the electric field distributions over this region. In a local model, locality of ionization events is assumed so that impact ionization rates are always highest at the base–collector metallurgical junction[3–5]. However, in transistors with a highly doped collector ($\geqslant 10^{17}$ cm^{-3}), the width of the high field region is comparable to the energy relaxation length λ_w, hence the profile of the electron energy $W(x)$ does not coincide with the distribution of the electric field $F(x)$[2]. Since ionization rates really depend on the electron energy and not on the local electric field, the electron never attains an energy corresponding to the maximum energy of the electric field when the space-charge region is narrow. As a result the electron energy lags the electric field shifting the peak electron impact ionization rate from the collector–base metallurgical junction into the collector. This results in lower than otherwise expected multiplication factors resulting in a higher breakdown voltage (BV_{CEO}). Thus when the collector region is highly doped, it is essential that the nonlocal properties of the avalanche multiplication are taken into account[2].

We have estimated the value of M using numerical simulation[6] under local as well as nonlocal avalanche multiplication conditions. By calculating the above device parameters using nonlocal model, we show that advanced bipolar transistors are expected to have superior performance than otherwise would be predicted by the local avalanche multiplication model.

2. THEORY

In the following analysis, we have assumed that: (i) base–collector junction is one sided and abrupt; (ii) no base width modulation due to collector voltage variations ($0 \leqslant V_{CE} \leqslant \mathrm{BV_{CEO}}$); (iii) collector doping is $\geqslant 10^{17}$ cm^{-3}; and (iv) base push-out due to kirk effect is negligible.

2.1. C_{jc} *due to impact ionization*

The reverse-bias collector–base depletion capacitance can be expressed as[7]:

$$C_d = \sqrt{\frac{qN_BN_C\epsilon_B\epsilon_C}{2(\epsilon_BN_B + \epsilon_CN_C)(V_{bi} + V_{CB})}} \tag{1}$$

where N_B and N_C are the base and collector dopings, ϵ_B and ϵ_C are the base and collector permittivities, V_{bi} is the collector–base junction built-in potential and V_{CB} is the collector–base applied voltage. The peak electric field in the CB space-charge region can be as high as 10^5 V cm^{-1} for transistors having highly doped collector structures ($\geqslant 10^{17}$ cm^{-3}). As the impact ionization due to this high electric field generates a large number of free carriers in the depletion region, the modulation of mobile charge with base–collector voltage becomes significant near avalanche regime and gives rise to a free carrier capacitance given by[8,9]:

$$\begin{aligned} C_F &= q\int|\mathrm{d}(\Delta n \quad \text{or} \quad \Delta p)/\mathrm{d}V|\mathrm{d}x \\ &= |\partial Q_p(\text{or} \quad \partial Q_n)/\partial V_{BC}| \end{aligned} \tag{2}$$

where Δn and Δp are excess electron and hole concentrations, Q_p and Q_n are excess hole and electron mobile charges. In the collector depletion region, the impact ionization induced electrons move towards the collector while holes generated by impact ionization, drift to the base terminal. This results in an incremental base current density ΔJ_B [$= (M - 1)J_C$] due to ionized hole charge generation, given by[9]

$$Q_p = \tau(M-1)J_C = \tau(M-1)\left[\frac{MJ_{CO}}{1-\alpha M}\right] \tag{3}$$

where τ is injection level independent base lifetime, α is common base current gain, J_{CO} is the reverse saturation current density and M is the multiplication factor given by

$$M = \frac{1}{1 - \left(\dfrac{V_{CB}}{BV_{CBO}}\right)^n} \tag{4}$$

where BV_{CBO} is collector–base breakdown voltage with emitter left open and n is the empirical parameter. Using eqns (3) and (4), the free carrier capacitance due to impact ionization can be written as

$$C_F = \left|\frac{\partial}{\partial V_{BC}}\left[\frac{\tau J_{CO} M(M-1)}{1-\alpha M}\right]\right|$$

$$= \frac{\tau J_{CO} n(2M - \alpha M^2 - 1)\left[\left(1-\frac{1}{M}\right)^{(1-1/n)}\right]}{BV_{CBO} M^2 (1-\alpha M)^2} \qquad (5)$$

The collector–base junction capacitance C_{jc} including impact ionization effect is, therefore, a sum of C_d and C_F given by

$$C_{jc} = C_d + C_F \qquad (6)$$

2.2. Output conductance g_0 and early voltage V_A

Assuming that $V_{CE} \approx V_{CB}$, g_0 and V_A can be expressed as

$$g_0 = \frac{\partial I_C}{\partial V_{CE}} \approx \frac{I_C}{V_A + V_{CB}}\bigg|_{V_{CE} \approx V_{CB}}$$

$$= \frac{nI_{CO}\left[\left(1-\frac{1}{M}\right)^{(1-1/n)}\right]}{BV_{CBO} M^2 (1-\alpha M)^2} \qquad (7)$$

$$V_A = \frac{BV_{CBO}\left[M^3(1-\alpha M) - n\left(1-\frac{1}{M}\right)\right]}{n\left[\left(1-\frac{1}{M}\right)^{(1-1/n)}\right]}. \qquad (8)$$

The above analytical expressions for C_{jc}, g_0 and V_A are used to show the effect of multiplication factor M on these device parameters near avalanche breakdown regime.

3. SIMULATION AND DISCUSSION

To evaluate the collector–base junction capacitance [eqn (6)], output conductance [eqn (7)] and early voltage [eqn (8)] we first need to find the multiplication factor M and the empirical parameter n for both local and nonlocal impact ionization conditions. We have estimated the values of M for different reverse bias conditions using BIPOLE3[6] device simulator. In our simulation, we have considered a uniformly doped SiGe heterojunction bipolar transistor with emitter doping $N_E = 5 \times 10^{17}\,\text{cm}^{-3}$, base doping $N_B = 10^{19}\,\text{cm}^{-3}$, collector doping $N_C = 10^{17}\,\text{cm}^{-3}$, emitter thickness $W_E = 0.1\,\mu\text{m}$, base thickness $W_B = 30$ nm and collector thickness $W_C = 0.6\,\mu\text{m}$ as shown in Fig. 1. A uniform Ge mole fraction at $x = 0.3$ is assumed in the base region. We have used the value of the empirical parameter to be $n = 3$ for the local impact ionization and $n = 6$ for the nonlocal model based on the values of n reported by Kumar and Roulston[10].

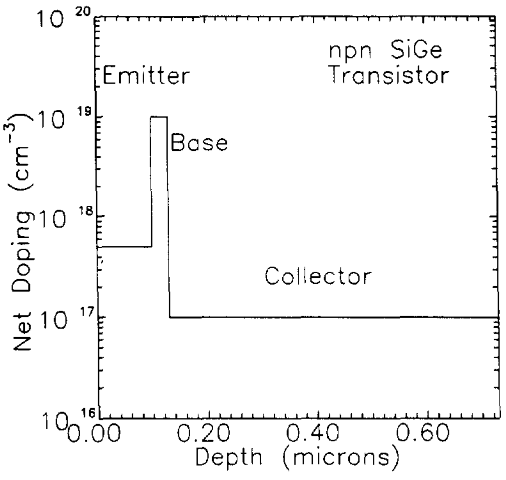

Fig. 1. Schematic diagram of the doping profile used in our study.

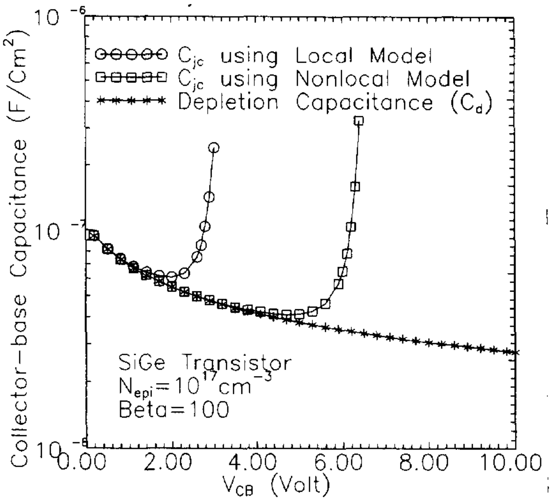

Fig. 2. Collector–base junction capacitance vs collector-base voltage.

Figure 2 shows the collector–base junction capacitance plotted as a function of collector–base voltage. As V_{CB} is increased, due to collector–base depletion region widening, the collector–base junction capacitance decreases. However, as V_{CB} is further increased and approaches BV_{CEO}, the collector-base junction capacitance increases sharply. This is due to the avalanche multiplication which increases free carrier capacitance. It is interesting to note that the total capacitance using nonlocal model is less than that using local model for a given V_{CB} near breakdown regime. As nonlocal model and not the local model is valid for the collector doping $\geqslant 10^{17}\,\text{cm}^{-3}$, nonlocal model predicts lower capacitance for the same V_{CB}.

Figure 3 shows the output conductance plotted as a

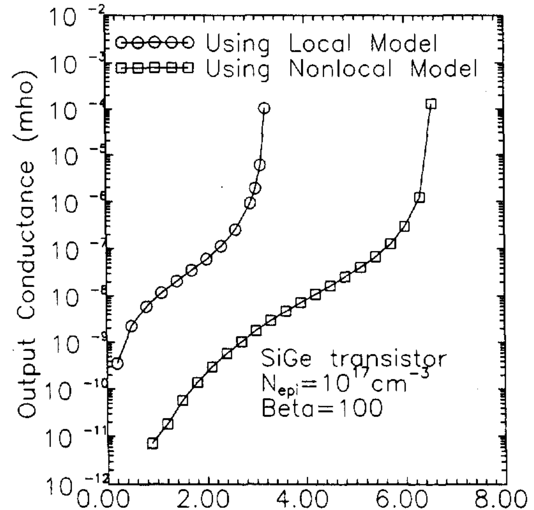

Fig. 3. Output conductance vs collector–base voltage.

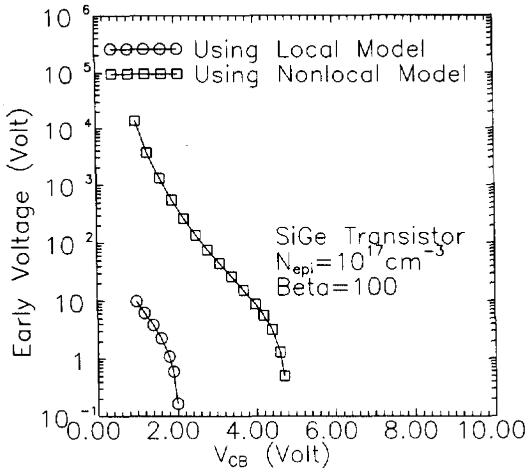

Fig. 4. The early voltage vs the collector–base voltage.

function of CB voltage. The increase in g_0 with increasing V_{CB} stems from the avalanche effect. For a given V_{CB} (say 2 V) the output conductance using nonlocal model is less than that using local model.

Figure 4 shows V_A vs V_{CB} using both local as well as nonlocal impact ionization model. At low V_{CB}, the value of V_A is high. This is due to the assumption that base width modulation effect is assumed to be negligible in our analysis. As V_{CB} increases, V_A decreases due to impact ionization. For a given V_{CB} (say 1 V), the nonlocal impact ionization model predicts considerably higher early voltage as compared to the local model.

4. CONCLUSIONS

In conclusion, we have reported a simple model for the collector–base junction capacitance (C_{jc}), output conductance (g_0) and early voltage (V_A) of advanced bipolar transistors operating near avalanche breakdown conditions. By estimating the multiplication factor M under local and nonlocal impact ionization conditions, we have calculated C_{jc}, g_0 and V_A for different collector voltages V_{CB}. From our results we have demonstrated that when the above device parameters are estimated using nonlocal ionization, advanced bipolar transistors with collector dopings $\geqslant 10^{17}$ cm^{-3} have superior performance than otherwise would be predicted by local avalanche multiplication model.

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