(9A-2)

Physically-Based Collector- and Base-Resistance Model for Sub-Micron Bipolar Transistor

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1 INTRODUCTION As transistor dimensions are scaled down to sub-micron level, the transistor characteristics are strongly influenced by the intricate carrier behavior with parasitic effects. The collector-depletion-layer width extremely changes according to bias condition and affects the collector resistance. Base resistance is modulated by the two-dimensional carrier behavior. However, these phenomena are not included in the SPICE model. The purpose of this work is to clarify the physical phenomena in the base and the collector of sub-micron bipolar transistor and to propose a new collector- and base-resistance modulation model for the SPICE simulation.

2 CONCEPT OF NEW MODEL For the NPN transistor which operates in an active mode, the epi collector can be divided into two regions; high electric field and moderate electric field regions. These two regions are defined as transition and ohmic regions, respectively, as shown in Fig. 1. The internal collector resistance is defined by this ohmic region resistance. At the active bias condition (Ib=10uA, Vce=0.5V), the electron concentration in the transition region is much less than the collector doping concentration, and that in the ohmic region is nearly equal to the collector doping concentration (Fig. 2). When Vce is 3V, the ohmic region vanishes because the epi collector is fully depleted. On the other hand, when Vce is 0.05V, the transistor operates in the saturation mode and collector conductivity is modulated by the increased electron density due to the charge neutrality. Figure 3 shows the calculation results of the collector resistance by using eqs. (1) and (2) in Table 1. When the collector voltage is increased, the collector resistance is reduced by the reduction of the ohmic region. When the transistor operates in the saturation mode, the collector-resistance is reduced by the conductivity modulation. The conductivity modulation for base current 30uA case becomes larger than that for 6uA and 10uA case because of the larger base voltage. Thus, the peak collector resistance becomes small.

The base resistance is modulated by the injection condition. In the high level injection condition, hole concentration in the base is increased, compared with the thermal equilibrium condition. Furthermore, the hole concentration of the emitter corner near the base terminal becomes larger than that of the emitter center by the emitter crowding effect (Fig. 4). From these simulation results, we propose a new base resistance model in which the conductivity modulation effect is added to the Hauser's emitter crowding model[1] as described by eqs. (3) and (4) in Table 1.

3 RESULT AND DISCUSSION The calculated base resistance was in good agreement with the extracted value from measurements for sub-micron transistor as shown in Fig. 5. Vce-Ic characteristics was simulated by SPICE in which the collector- and base- resistance modulation effect was implemented. The quasi-saturation characteristics were represented accurately by using this new model.

4 CONCLUSION The physically-based collector- and base-resistance model for submicron transistor has been proposed and implemented in SPICE. Representative simulations and measurements are presented to demonstrate model utility and necessity.

[1] J. R. Hauser, IEEE Trans. Electron Devices, ED-11, p238 (1964).

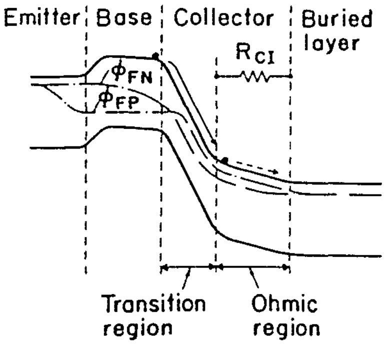

Fig. 1 Band diagram of NPN transistor which operates in the active mode.

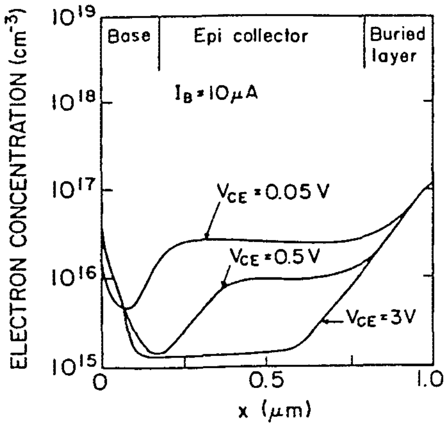

Fig. 2 Electron concentration profile in base and collector. Epi collector doping concentration is $1\times10^{16}\mathrm{cm}^{-3}$.

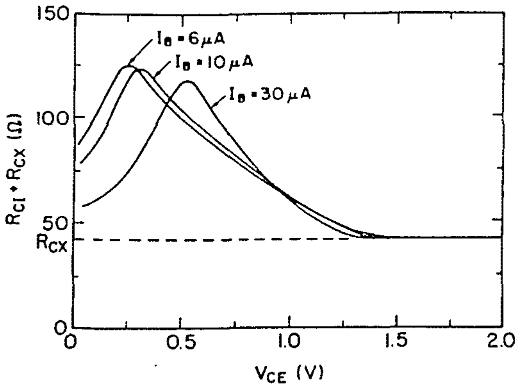

Fig. 3 Calculated collector resistance as a function of Vce. RCI and RCX represent the internal (epi) and the external collector resistance, respectively.

Table 1 Formulation of the new collector-and base-resistance modulation model.

$$\rho_c = \{q\mu_n N_c\ (1+\frac{n_i{}^2}{N_c{}^2}\ [\exp(\frac{qV_{BCI}}{kT})-1])\}^{-1} \quad (1)$$

$$R_{CI}=\frac{\rho_c}{A_E}\ [W_c-(2\varepsilon_{si}v_s\ \frac{A_E\ (-V_{BC}+\Phi_{bi})-I_c\ \rho_c\ W_c}{A_E\ qN_c\ v_s-I_c})^{1/2}] \quad (2)$$

$$Z\tan Z=\frac{q}{2kT}\ \frac{R_{B0}}{Q_B}\ I_B \quad (3)$$

$$R_{BI}=R_{B0}\frac{\tan Z-Z}{Z\tan^2 Z} \quad (4)$$

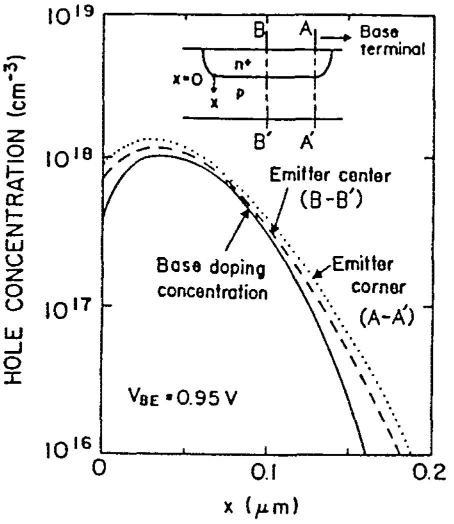

Fig. 4 Hole concentration profile in base in the high injection condition.

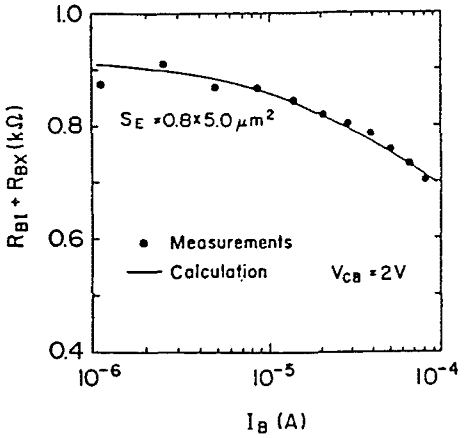

Fig. 5 Base resistance as a function of base current. RBI and RBX represent the intrinsic and the extrinsic base resistance, respectively.

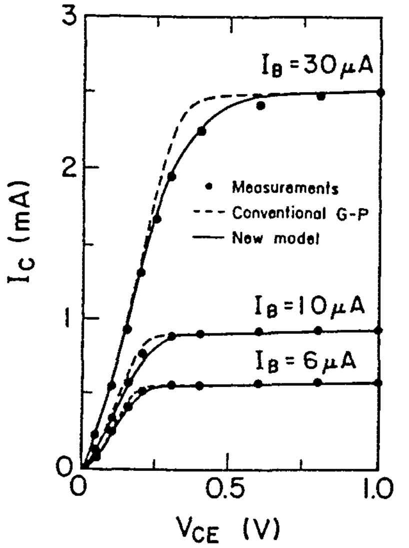

Fig. 6 Vce-Ic characteristics. Simulation results by the new model are in good agreement with measurements, compared with the conventional Gummel-Poon model.