1-1-1990

Effects Of Using The More Accurate Intrinsic Concentration On Bipolar-Transistor Modeling

J. J. Liou
University of Central Florida

J. S. Yuan
University of Central Florida

W. W. Wong
University of Central Florida

Effects of using the more accurate intrinsic concentration on bipolar transistor modeling

Cite as: Journal of Applied Physics **68**, 5911 (1990); https://doi.org/10.1063/1.346942
Submitted: 09 April 1990 . Accepted: 20 August 1990 . Published Online: 04 June 1998

J. J. Liou, J. S. Yuan, and W. W. Wong

Effects of using the more accurate intrinsic concentration on bipolar transistor modeling

J. J. Liou, J. S. Yuan, and W. W. Wong
Electrical Engineering Department, University of Central Florida, Orlando, Florida 32816

(Received 9 April 1990; accepted for publication 20 August 1990)

A more accurate intrinsic concentration was suggested recently. Discrepancies between using the conventional and the more accurate intrinsic concentrations on bipolar transistor modeling are assessed in this study. Our calculations show that the conventional intrinsic concentration overestimates the collector and base currents by a factor of 1.5 to 2 but affects less severely the steady-state current gain.

The intrinsic carrier concentration is an important parameter for semiconductor device modeling.[1,2] The values of intrinsic concentration, effective densities of states, and effective mass in silicon have recently been reassessed theoretically as well as experimentally.[3] It is found that the commonly used values are inconsistent. For example, for the silicon intrinsic concentration at room temperature, the critical evaluation results in a value of 1.08×10^{10} cm^{-3},[3] instead of 1.45×10^{10} cm^{-3} as conventionally used.

This study examines the effects of using the more accurate intrinsic concentration, as compared to using the conventional value, on modeling bipolar junction transistors (BJTs).

Consider an $n/p/n$ BJT (Fig. 1) at room temperature under forward-active operation. Using the assumptions that the charge transport in the base is predominantly due to diffusion and that the transistor has a thin base, the collector current density J_c can be expressed as

$$J_c \approx qD_n[\Delta n(X_2)-\Delta n(X_3)]/(X_3-X_2) \approx qD_n\Delta n(X_2)/(X_3-X_2), \quad (1)$$

where D_n is the electron diffusion coefficient, Δn is the excess electron concentration, and X_2 and X_3 are the edges of the space-charge layers defined in Fig. 1. Because the doping densities are highly asymmetrical in the emitter, base, and collector, we can assume one-sided junctions:

$$X_3-X_2 \approx X_{jc}-X_{jE}-[(2\epsilon/q)(V_{\mathrm{biBE}}-V_{\mathrm{BE}})/N_B]^{0.5}, \quad (2)$$

where X_{jc} and X_{jE} are the metallurgical junctions (Fig. 1), ϵ is the dielectric permittivity, V_{BE} is the base-emitter applied voltage, N_B is the average base doping density and V_{biBE} is the emitter-base junction builtin potential. $\Delta n(X_2)$ in Eq. (1) for all injection levels is[4]

$$\Delta n(X_2) = -0.5N_B + 0.5N_B\{1+[4n_i^2\exp(V_{\mathrm{BE}}/V_T)/N_B^2]\}^{0.5}, \quad (3)$$

where n_i is the intrinsic concentration and V_T is the thermal voltage.

We next proceed to find the base current density J_B. For a thin-base bipolar transistor, J_B is the sum of the recombination current density J_{SCR} in the emitter-base space-charge layer and the hole current density J_{RE} injected from the base to emitter. Thus[5,6]

$$J_B = J_{\mathrm{SCR}} + J_{\mathrm{RE}} = 1.25(qV_T n_i/\tau)\{(qN_E/\epsilon)\times[2V_T\ln(N_E/n_i)-V_{\mathrm{BE}}]\}^{-0.5}\times\exp(V_{\mathrm{BE}}/2V_T)+qD_p\Delta p(X_1)/X_{jE}. \quad (4)$$

τ is the lifetime associated with the space-charge layer recombination, N_E is the average emitter doping concentration, D_p is the hole diffusion coefficient, and Δp is the excess hole density. For all injection levels,

$$\Delta p(X_1) = -0.5N_E + 0.5N_E\{1+[4n_i^2\exp(V_{\mathrm{BE}}/V_T)/N_E^2]\}^{0.5}. \quad (5)$$

Note that J_{SCR} is described based on the simplest and widely used Shockley–Read–Hall model[7] which assumes that there is only one type of trap that dominates the recombination process and that the traps are uniformly distributed in the middle of band gap.

The common-emitter dc current gain β of the transistor is

$$\beta = J_c/J_B. \quad (6)$$

It is apparent from the foregoing analysis that the value of n_i plays an important role in the BJT modeling. We first discuss qualitatively and intuitively the effect of using the

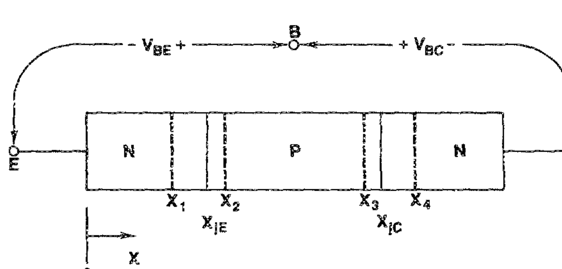

FIG. 1. One-dimensional bipolar transistor structure, where X_1 and X_2 are the edges of the emitter-base space-charge layer and X_3 and X_4 are the edges of the base-collector space-charge layer.

 0021-8979/90/235911-02$03.00

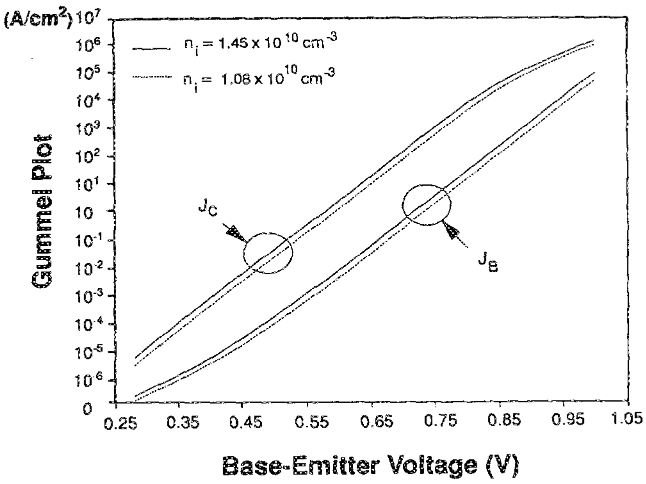

FIG. 2. Base and collector current densities calculated using the conventional intrinsic concentration and using the more accurate intrinsic concentration.

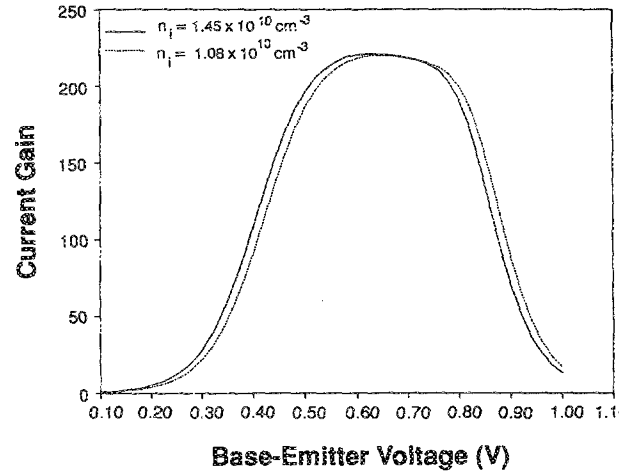

FIG. 3. Common-emitter current gain calculated using the conventional intrinsic concentration and using the more accurate concentration.

more accurate n_i on J_c, J_B, and β. An exact number example will be given latter.

The current-voltage characteristics of a BJT can in general be divided into the following three regions: low-bias region, medium-bias region, and high-bias region. From a fundamental viewpoint, the collector current is proportional to $\Delta n(X_2)$ which is a function of n_i^2 for low- and medium-bias conditions (low injection) and is a function of n_i for high voltage (high injection). On the other hand, because $J_{\rm SCR} \propto \exp(V_{\rm BE}/2V_T)$ and $J_{\rm RE} \propto \exp(V_{\rm BE}/V_T)$, the base current is dominated by $J_{\rm SCR}$ (depends on n_i) at a low-bias condition and is dominated by $J_{\rm RE}$ (depends on n_i^2 if low injection prevails) at medium- and high-bias conditions. It should be pointed out that a low-injection condition can be assumed in the emitter because of the high doping concentration. Thus, $J_C \propto n_i^2$, $J_B \propto n_i$, and $\beta \propto n_i$ for a low-bias region, $J_C \propto n_i^2$, $J_B \propto n_i^2$, and β becomes constant with respect to n_i for a medium-bias region, and $J_c \propto n_i$, $J_B \propto n_i^2$, and $\beta \propto n_i^{-1}$ for a high-bias region. As a consequence, if the more accurate n_i proposed by Green[3] (1.08×10^{10} cm^{-3}) instead of the conventional n_i (1.45×10^{10} cm^{-3}) is used, J_C will decrease by a factor of 0.55 in low- and medium-bias regions and decrease by a factor of 0.74 in a high-bias region, J_B will decrease by a factor of 0.74 in a low-bias region and decrease by a factor of 0.55 otherwise, and β will decrease by a factor of 0.74 in a low-bias region, remain the same in a medium-bias condition, and increase by a factor of 0.74 in a high-bias region.

To verify the above physical intuitions, we now calculate J_C, J_B, and β using the conventional n_i and the more accurate n_i for a typical advanced BJT having $N_E = 10^{19}$ cm^{-3}, $N_B = 2\times 10^{17}$ cm^{-3}, $N_C = 10^{16}$ cm^{-3}, $X_{jE} = 0.15$ μm, and $X_{jC} = 0.35$ μm. Values for D_n and D_p used for calculations are the same as that suggested in Ref. 3 ($D_n = 36.8$ cm^2/s and $D_p = 12.2$ cm^2/s). Shown in Fig. 2 are the base and collector current densities versus the base-emitter applied voltage (Gummel plot) using the more accurate n_i and the conventional n_i. Current gain versus voltage characteristics are given in Fig. 3. The results in Fig. 2 confirm our earlier discussions and the postulate by Green that the use of the conventional n_i value overestimates the current flow in silicon devices.[3] Specifically, the conventional n_i overestimates the collector current and the base current by a factor of 1.5 to 2 depending on the bias condition. However, as shown in Fig. 3, the errors in modeling the current gain originated from the conventional n_i is less severe (by a factor of 1.3 or less) because the two current overestimations counterbalance each other. Note that the trend in Fig. 3 agrees well with our qualitative prediction; using the more accurate n_i results in a smaller β in a low-bias region, about the same β in a medium-bias region, and a larger β in a high-bias region.

In conclusion, the intrinsic concentration was recently reassessed experimentally and theoretically. We have examined the effects of using this more accurate intrinsic concentration on the bipolar transistor modeling at room temperature. It is found that the use of the conventional intrinsic concentration results in overestimating both the collector and base currents by a factor of 1.5 to 2. On the other hand, the dc current gain, which is a critical parameter for the bipolar transistor performance, is less sensitive to the difference between the two intrinsic concentrations.

[1]S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981).
[2]E. S. Yang, *Microelectronics Devices* (McGraw-Hill, New York, 1988).
[3]M. A. Green, J. Appl. Phys. **67**, 2944 (1990).
[4]R. S. Muller and T. I. Kamins, *Device Electronics for Integrated Circuits* 2nd ed. (Wiley, New York, 1986).
[5]M. Shur, *Physics of Semiconductor Devices* (Prentice Hall, Englewood Cliffs, NJ, 1990).
[6]M. Shur, IEEE Trans. Electron Devices **35**, 1564 (1988).
[7]W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).