FACTA UNIVERSITATIS (NIŠ)
SERIES: ELECTRONICS AND ENERGETICS VOL. 9, NO. 2 (1996), 247–254

NEW INVESTIGATION ON SILICON BIPOLAR TRANSISTOR AT LOW TEMPERATURES

Xiao Zhixiong and Wei Tongli

Abstract. The intrinsic carrier concentration is calculated with the non-parabolic energy bands at low temperatures. Besides, the current gain of a silicon bipolar transistor is quantitatively modeled at $77K$ and $300K$, and the temperature dependence of the mean nonideal coefficient of the base current is also analyzed. The obtained results are in agreement with experimental data.

1. Introduction

The intrinsic carrier concentrtation, the current gain and the non-ideal coefficient are fundamental parameters in silicon bipolar transistors. Their detailed investigation is useful for the undestanding of the low temperature device physics.

2. Calculation of the intrinsic carrier concentration

On the basis of Chakravarti et al.'s work [1], the intrinsic carrier concentration n_{in} with the non-parabolic energy bands could be deduced as

$$n_{inD(A)} = n_i \times \left[\frac{2F_{1/2}(\eta_{nC(V)}}{\sqrt{\pi}\exp(\eta_{nC(V)})} + \frac{5KT\alpha_{D(A)}F_{3/2}(\eta_{nC(V)})}{\sqrt{\pi}\exp(\eta_{nC(V)})} \right]^{1/2} \tag{1}$$

where n_i is the intrinsic carrier concentration with the non-degenerate approximation. $\alpha_D = 1/E_{gD}, \alpha_A = 1/E_{gA}$. $F_{1/2(\eta)}$ and $F_{3/2(\eta)}$ are Fermi integrals with orders of 1/2 and 3/2 respectively. T is the absolute temperature and K is the Boltzmann constant. E_{gD} and E_{gA} are silicon bandgaps with

---

Manuscript received February 21, 1995.

The authors are with Microelectronics Center, Southeast University, Nanjing 210018, P.R. China.

doping of donor (N_D) and acceptor (N_A), respectively. With the degenerate approximation, the intrinsic carrier concentration n_{id} could be expressed as

$$n_{idD(A)} = n_i \times \left[\frac{F_{1/2}(\eta_{C(V)})}{\exp(\eta_{C(V)})} \right]^{1/2} \tag{2}$$

Figures 1 and 2 show curves of $n_{idD(A)}/n_{inD(A)}$ as a function of $N_D(N_A)$. It is clear that n_{id} deviates from n_{in} at high concentrations.

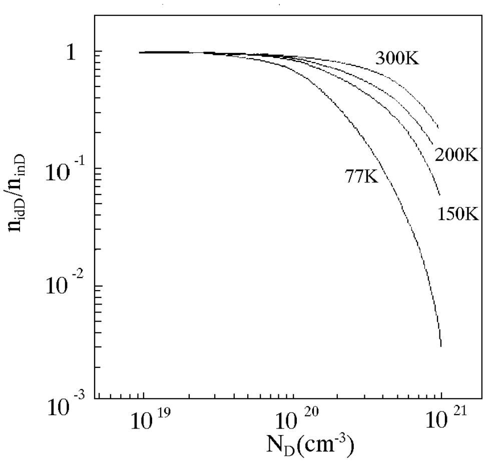

Figure 1. $n_{idD}/ninD$ versus N_D at different T.

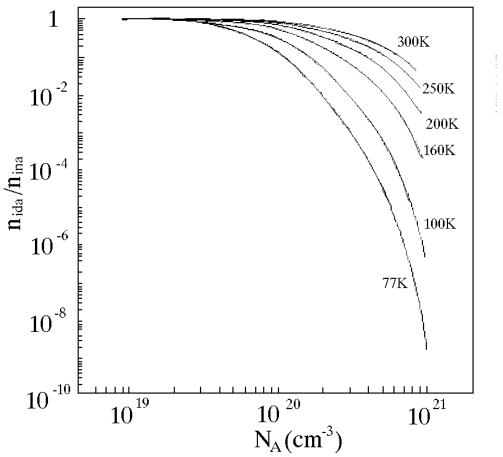

Figure 2. $n_{idA}/ninA$ versus N_A at different T.

3. Modeling of the current gain

For a common n^+pn silicon bipolar transistor, minority–carrier concentrations in the base and in the emitter could be approximately written, respectively, as

$$\begin{aligned} n_B(x) &= n_B(0)(1-\frac{x}{W_B}) \\ p_E(x) &= p_E(0)(1-\frac{x}{W_E}) \end{aligned} \tag{3}$$

where W_E and W_B are widths of the emitter and the base, respectively. $n_B(0)$ and $p_E(0)$ are minority–carrier concentratiions at edges of the emitter–base junction.

The collector current I_C may be written as

$$I_C = \frac{qA_E n_i^2 \exp(\frac{qV_{BE}}{KT})}{\int\limits_0^{W_B} \frac{C_B(x)+n_B(x)}{D_{nB}(x)} \times \frac{n_i^2}{n_{ib}^2(x)} dx} \tag{4}$$

where A_E is the emitter area. V_{BE} is a voltage on the emitter–base junction. $C_B(x)$, $D_nB(x)$ and $n_{ib}(x)$ are the effective majority–carrier concentration, the electron diffusion coefficient and the effective intrinsic carrier concentration in the base, respectively. q is the electronic charge.

The ideal base current I_{BI} could be written as.

$$I_{BI} = \frac{qA_E n_i^2 \exp(\frac{qV_{BE}}{KT})}{\int\limits_0^{W_E} \frac{C_E(x)+P_E(x)}{D_{pE}(x)} \times \frac{n_i^2}{n_{ie}^2(x)} dx} \tag{5}$$

where $C_E(x)$, $D_{pE}(x)$ and $n_{ie}(x)$ are the effective majority–carrier concentration, the hole diffusion coefficient and the effective intrinsic carrier concentration in the emitter, respectively.

The non–ideal base current could be written as [2]

$$I_R = qA_E W^* \frac{n_i \exp(\frac{qV_{BE}}{2KT}) \exp(\frac{q\sqrt{\beta E}}{2KT})}{2\sqrt{\tau_p \tau_n}} \tag{6}$$

where W^* is the width of the emitter-base space charge region. τ_p and τ_n are minority-carrier lifetimes in the emmiter and in the base, respectively. E is the electric field intensity in the space charge region. ε is the silicon dielectric constant. $\beta = q/\pi\varepsilon$

The base recombination current I_{RB} could be written as

$$I_{RB} = \frac{qA_B n_i^2 W_B^2 \exp(\dfrac{qV_{BE}}{KT})}{2\int\limits_0^{W_B} [C_B + n_B(x)]\, \tau_n dx} \tag{7}$$

where A_B is the base area.

At a medium collector electric intensity, the base widening W_B' may be written as [3]

$$W_B' = W_C(1 - \frac{J_{C0}}{J_C}) \tag{8}$$

where W_C is the collector width. J_C is the collector current density and J_{C0} is the collector current density corresponding to the beginning of the effective base widening effect [4].

The contribution of the Erly effect may be expressed by C_{early} [5].

$$C_{early} = 1 + \frac{d_c}{2(W_B + W_B')} \tag{9}$$

where d_c is the width of the base-collector space charge region.

The current gain H_{FE} could be expressed as

$$H_{FE} = \frac{I_E}{I_{BI} + I_R + I_{RB}} \times C_{early} \times \frac{W_B}{W_B + W_B'} \tag{10}$$

With the current crowding effect, $n_B(0)$ and $p_E(0)$ may be written as

$$\begin{aligned} n_{Bcr}(0) &= n_B(0)\frac{S_e}{S_{eff1}} \\ p_{Ecr}(0) &= p_E(0)\frac{S_e}{S_{eff2}} \end{aligned} \tag{11}$$

where S_e is the half emitter width. S_{eff1} and S_{eff2} are effective emitter half widths for the forward and the inverse injections [6], respectively. By $n_B(0)$ and $p_E(0)$, the emitter current crowding effect makes the conductivity modulation effect easily happen.

Figure 3 shows curves of $n_B(0)$ and $p_E(0)$ as a function of V_{BE} at $77K$. When the emitter current crowding effect is not considered, they exponentially increase with V_{BE}, but when it is considered, $n_B(0)$ and $p_E(0)$ increase much faster than the exponential function at high injection levels. Figure 4 showes H_{FE} as a function of I_C with $V_{CE} = 1V$ at $77K$.

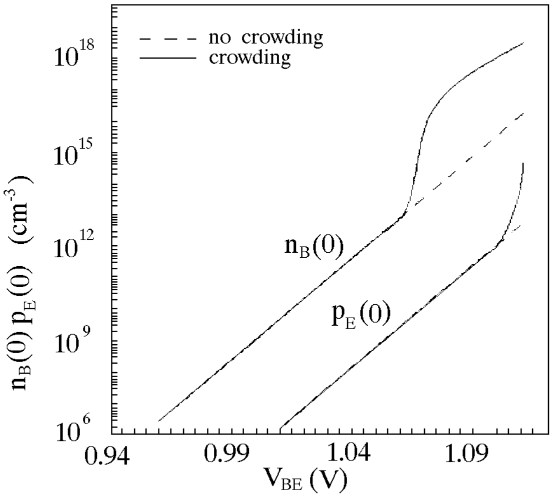

Figure 3. $n_B(0)$, $p_E(0)$ versus V_{BE} at $77K$.

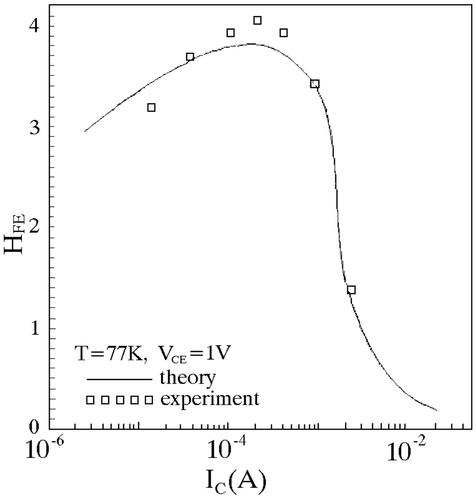

Figure 4. H_{FE} versus I_C at $77K$ with $V_{CE} = 1V$.

The modeled result is in agreement with experimental data. When $V_{CE} = 1V$, $J_{C0} \cong 1540A/cm^{-2}$, the related $I_C \cong 3.08 times 10^{-2} A$. In comparison with this value with that of I_C corresponding to the decrease of H_{FE} in Figure 3, it is clear that the effective base widening effect is not the main reason for the decrease of H_{FE}. At $77K$, the conductivity modulation effect and the emitter crowding effect are main factors for the decrease of H_{FE}.

At $300K$, the conductivity modulation effect and the emitter current crowding effect have little influence on $n_B(0)$ and $p_E(0)$. Figure 5 showes $W_{B'}$ as a function of I_C with $V_{CE} = 1V$. $W_{B'}$ rapidly increases with I_C. Figure 6 showes the curve of H_{FE} with $V_{CE} = 1V$ at $300K$.

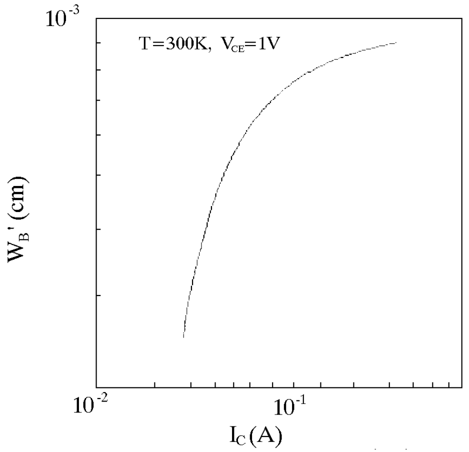

Figure 5. W_B' versus I_C at $300K$ with $V_{CE} = 1V$.

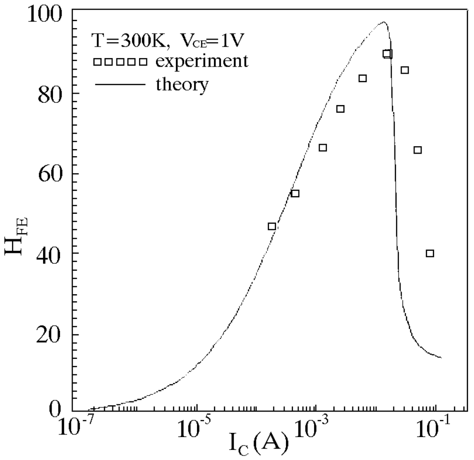

Figure 6. H_{FE} versus I_C at $300K$ with $V_{CE} = 1V$.

When $V_{CE} = 1V, J_{C0} \cong 1044A/cm^{-2}$, the related $I_C \cong 2.09 \times 10^{-2}A$. This value is in agreement with its experimental value. At $300K$, the effective base widening effect is the main reason for the decrease of H_{FE}.

4. Temperature dependance of the mean non–ideal coefficient

Figures 7 and 8 show calculate curves of the mean non-ideal coefficient n_{mean} of the total base current I_B at low injection level as a function of temperature at different N_B and N_E. It is clear that its temperature dependance relies on N_B and N_E. When N_B is high and N_E is low, it has a negative temperature coefficient, otherwise it has a positive temperature coefficient.

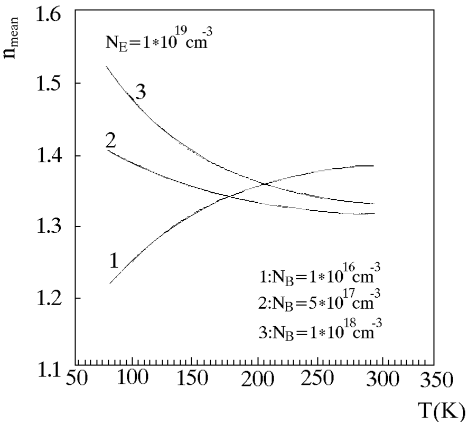

Figure 7. n_{mean} versus T at different N_B.

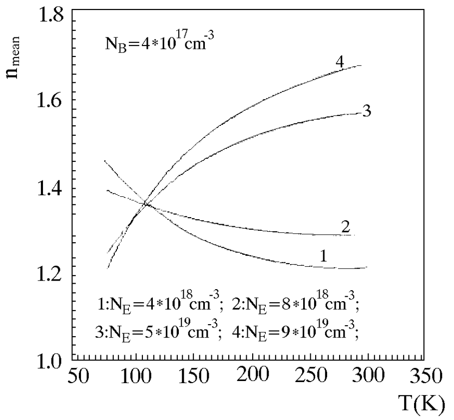

Figure 8. n_{mean} versus T at different N_E.

Stock et al.'s data [7] show that $n_{mean}(83K) = 1.29, n_{mean}(296K) = 1.33$ with $N_B = 8 \times 10^{17} cm^{-3}; n_{mean}(296K) = 1.40, n_{mean}(83K) > 2.74$ with $N_B = 8 \times 10^{18} cm^{-3}$. Woo et al.'s data [8] show that $n_{mean}(79K) = 1.10, n_{mean}(300K) = 1.39$ with $W_B = 0.7 \mu m, G_B = 1.63 \times 10^{12} cm^{-2}$ and $N_E = 4 \times 10^{18} cm^{-3}$ for a metal contacted transistor.

5. Conclusion

It is appropriate to adopt the non–parabolic energy bands at high concetrations. The current gain is determined by the conductivity modulation effect and the emitter current crowding effect at $77K$, but at $300K$, it is mainly determined by the effective base widening effect. The temperature dependance of the mean non-ideal coefficient of the base current relies on the emitter and the base concetrations at low injection levels.

REFERENCES

1. A. N. Chakravarti and B. R. Nag: *Generalized Einstein relation for degeneratesemiconductors having non–parabolic energy bands.* Int. J. Electronics, vol.37, No.2, 1974, pp. 281–284.
2. J. C. S. Woo, J. D. Plummer and J. M. C. Stork: *Non–ideal base curent in bipolar transistors at low temperatures.* IEEE Trans. Electron Devices, ED-34, No.1, 1987), pp. 130–138.
3. A. Blicher: *Field–Effect and Bipolar Power Transistor Physics.* Academic press, ch.7, 1981.
4. G. Rey, F. Dupuy and J. P. Bailbe: *A unified approach to the base widening mechanisms in bipolar transistors.* Solid–State Electronics, vol.18, 1975, pp. 863.
5. J. M. Early: *Effect of space–charge layer widening in junction transistors.* Proc. IRE, vol.40, 1952, pp. 1401.
6. S. K. Ghandhi: *Semiconductor Power Devices Physics of Operation and Fabrication Technology.* John Wiley & Sons.Inc. 1977.
7. J. M. C. Stork, D. L. Harame, B. S. Meyerson and T. N. Nguyen: *Base profile design for high–performance operation of bipolar transistors at liquid–nitrogen temperature.* IEEE Trans. on Elect. Devices, ED–36, No.8, 1989, pp. 1503–1509.
8. J. C. S. Woo and J. D. Plummer: *Optimization of silicon bipolar transistors for high current gain at low temperatures.* IEEE Trans. on Elect. Devices, ED–35, 1988), pp. 1311–1321.