

COMPUTER CALCULATION OF BIPOLAR TRANSISTOR CURRENT GAIN USING THE TRANSISTOR IMPURITY DOPING PROFILE

By

5th Year Microelectronic Engineer
Rochester Institute of Technology
James Hermanowski

ABSTRACT

A new program, BETA, will calculate a one-dimensional vertical transistor current gain using a modified Gummel approach [1], which incorporates heavy doping effects in the emitter such as band gap narrowing [2]. It is assumed that the base transport factor is equal to one, that the transistor is operating at intermediate current levels, and that the minority carrier lifetime in the emitter is greater than 10 nanoseconds. The gain will be calculated using information from the impurity doping profile generated by SUPREM II. Preliminary results indicate that this approach will give results with less than 25% error.

INTRODUCTION

The common emitter forward current gain is a bipolar transistor parameter which is necessary in order to accurately simulate many linear and digital circuit designs. It also necessary to understand the effects that processing variations have on the current gain in order to obtain better control of its value.

The common emitter current gain of planar transistors, operating at intermediate current levels, is directly related to two terms. These are the emitter injection efficiency and the base transport factor, both of which are very close to unity. The limiting term for modern transistors, whose base width is very narrow, is the emitter injection efficiency. The gain of the transistor is

$$\text{BETA} = \text{GAMMA} / (1 - \text{GAMMA}) \quad (1)$$

where BETA is the common emitter transistor current gain, and GAMMA is the emitter injection efficiency. This assumes the base transport factor, ALPHA, is 1.0.

It has been demonstrated [1], that the calculation of the emitter injection efficiency must take into account the effect of bandgap narrowing. Bandgap narrowing is caused by heavy doping, and is given by

$$\Delta E_G = 22.5 (N/10^{18})^{(1/2)} \text{ meV} \quad (N < 10^{18}) \quad (2)$$

$$\Delta E_G = 162.0 (N/10^{20})^{(1/6)} \text{ meV} \quad (10^{18} < N < 1.2 \times 10^{20}) \quad (3)$$

where ΔE_G is the bandgap narrowing. It should be noted that equation 2 is valid only at 300 Kelvin, [2]. Heavy doping reduces the energy required to produce an electron-hole pair. This causes an increase in the intrinsic carrier concentration [3].

$$n_{ie}^2 = n_i^2 e^{(E_G/(KT/q))} \quad (4)$$

where n_{ie} is the effective intrinsic carrier concentration, and n_i is the intrinsic carrier concentration.

It has been shown, [1] that for a normal transistor the gain is independent of the minority carrier lifetime in the emitter if this lifetime is higher than 10 nanoseconds. This criteria is normally met for silicon with a deep level impurity concentration less than $10^{15}/\text{cm}^3$. Under this condition the current transport equations in the semiconductor may be directly integrated yielding

$$\text{BETA} = \frac{\int_0^{X_{eb}} (((ND(x)-NA(x))/DP(x))(n_i/n_{ie})^2) dx}{\int_{X_{eb}}^{X_{bc}} ((NA(x)-ND(x))/DN(x)) dx} \quad (5)$$

where $ND(x)$ is the donor concentration (assuming NPN transistor), $NA(x)$ is the acceptor concentration, $DP(x)$ is the diffusion constant for holes, $DN(x)$ is the diffusion constant for electrons, x is the distance into the wafer, where X equals 0.0 at the silicon surface, n_i is the intrinsic carrier concentration, n_{ie} is the effective intrinsic carrier concentration, X_{eb} is the emitter-base junction depth, and X_{bc} is the base-collector junction depth. The numerator is the emitter Gummel number modified by the term $(n_i/n_{ie})^2$, and the denominator is the base Gummel number [1]. A similar equation is used for PNP transistors.

$$\text{BETA} = \frac{\int_{x_{eb}}^{x_{eb}} (((NA(x)-ND(x))/DN(x))(ni/nie)^2) dx}{\int_{x_{eb}}^{x_{bc}} ((ND(x)-NA(x))/DP(x)) dx} \quad (6)$$

The result of the above equations is that a one-dimensional BETA may be calculated from the transistor impurity profiles because DN, DP, ni, and nie depend only on temperature and the transistor impurity profile. Equations 5 and 6 assume that the base transport factor is unity, that the device is operating at intermediate current levels, and that the minority carrier lifetime in the emitter is greater than 10 nanoseconds.

EXPERIMENTAL:

BISIM, [5] is an RIT introductory educational computer program which models the the doping and performance characteristics of NPN transistors and calculates among other things the common emitter current gain. However, the simplified models used in BISIM, such as Gaussian impurity profiles, and an ideal bandgap throughout the device, tend to result in an inaccurate calculation of the common emitter current gain.

The authors of reference 1 have calculated the common emitter current gain using equation 5. The values for $(ni/nie)^2$ used in their calculations are from [4], and the transistor impurity profiles used are assumed to be Gaussian. It is believed that these two approximations lead to the 2.7% to 26.6% variation between the calculated and the measured values of the current gain.

A new program, BETA, has been written to numerically integrate equation 5 or 6 to obtain a one dimensional approximation to the common emitter current gain. Program BETA uses an impurity profile generated by the process simulation program SUPREM II, [6] to replace the Gaussian distribution approximation. Equations 2, 3, and 4 are also used to calculate the effects of heavy doping on the emitter profile.

RESULTS/DISCUSSION

Programs BETA and BISIM were used to calculate the common emitter current gain of a bipolar transistor with the impurity profile shown in Figure 1.

The gain of the transistor calculated by BETA is 154. The gain of the same transistor calculated by BISIM using an emitter Gummel number of 1.1×10^{13} , is 12. The actual transistor has not yet been fabricated and tested but it is believed that the measured gain would be close to 154.

Although program BETA is useful in calculating a bipolar transistor current gain from the transistor doping profile, there are limitations to its performance. Program BETA does not at this time calculate the depletion widths at the emitter-base, and base-collector junctions. The boundary between the emitter neutral region and the emitter space charge region, X_{eb}^* , could then be used to replace X_{eb} in the numerator of equations 5 and 6. The same is true for the boundary between the base space charge region and the base neutral region, X_{b}^* , which could be used to replace X_{eb} in the denominator of equations 5 and 6.

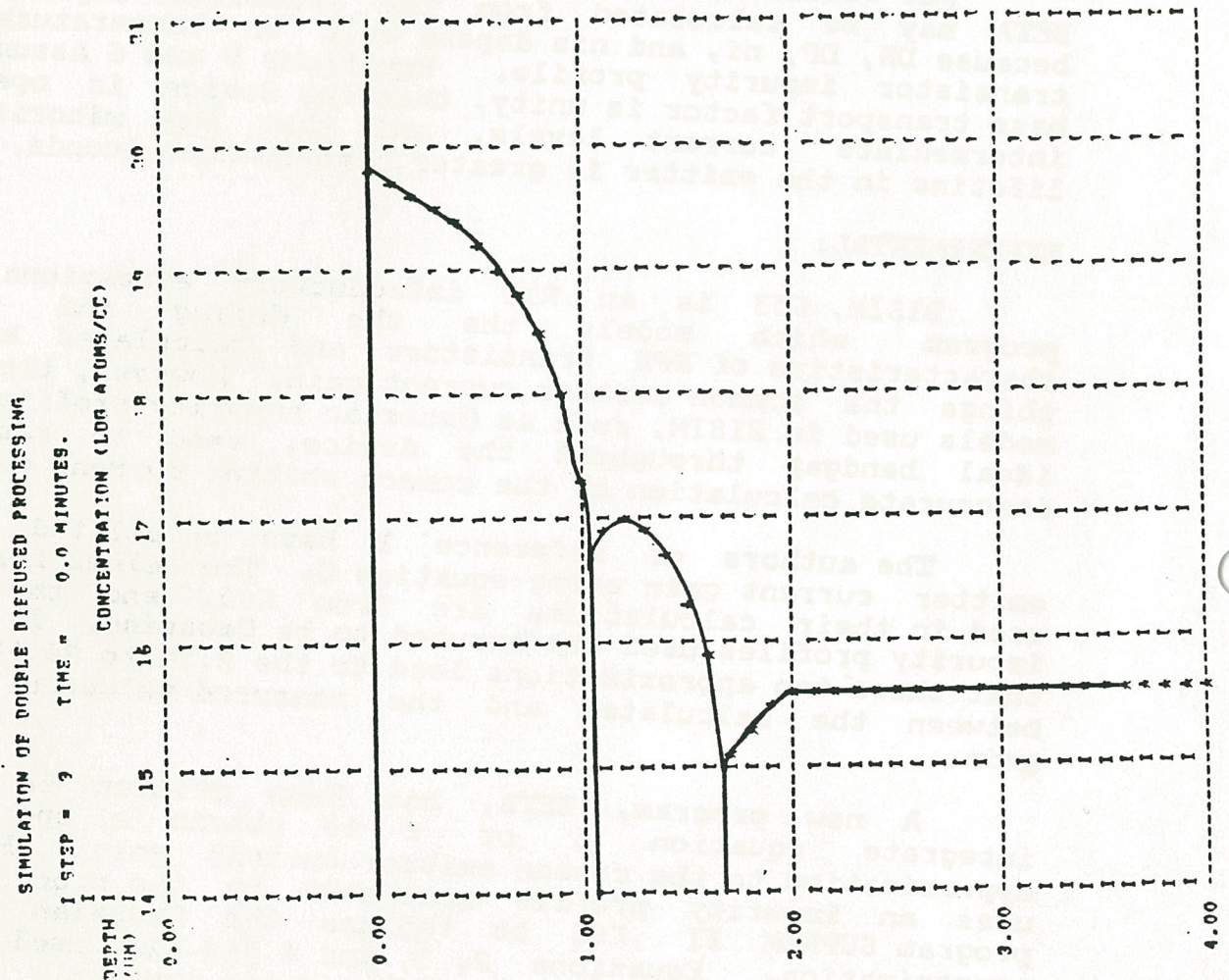


Figure # 1

CONCLUSION

A working program, BETA, has been written which will calculate a common emitter current gain from a transistors impurity profile distribution.

REFERENCES

- [1] Robert P. Merthens, Hugo J. DeMan, and Roger J. Van Overstraeten, "Calculation of the Emitter Efficiency of Bipolar Transistors," IEEE, Vol. ED-20, pp. 772-778, Sept. 1973.
- [2] H.P.D. Lanyon, "Bandgap Narrowing in Moderately to Heavily Doped Silicon," IEEE, Vol ED-26, pp. 1014-1018, July 1979.
- [3] Robert F. Pierret, Modular Series on Solid State Devices, Vol.1 (Mass.:Addison-Wesley, 1983),p.43.
- [4] R.J. Van Overstraeten, H.J. DeMan, and R.P. Mertens, "Transport equations in heavy doped silicon," IEEE, Vol. ED-20, pp. 290-298, March 1973.
- [5] Bipolar Integrated Circuit Process Simulation; BISIM, manual.
- [6] SUPREM II users manual.