VALIDATION OF BIPOLE

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SUMMARY

Discrete, single-emitter transistors have been made with a 3 GHz process. SIMS dopant profiles have been used as an input to BIPOLE, a bipolar device model, and the net profile produced has been compared with a spreading resistance profile. The input profiles have been adjusted until the net profile and the spreading resistance profiles were identical. This input profile has then been used with the device dimensions, to simulate device parameters.

It is concluded that good, first order approximations to performance can be obtained, and that this is capable of some optimisation if recombination parameters are known.

1. INTRODUCTION

This work forms part of an Alvey project on validation of two- and three-dimensional device simulators. The objectives are to assess currently available device models for accuracy and applicability, and to identify any shortcomings.

The paper will describe part of the work that has been carried out on BIPOLE.

BIPOLE is accessed on-line from the University of Waterloo, Ontario, Canada using an IPSS link.

2. THE BIPOLE MODEL

2.1 Basic Outline

BIPOLE is a model for predicting the electrical characteristics of bipolar devices from mask and profile data. It is based on a one-dimensional (vertical) solution of the transport equations and Poisson's equation, coupled to a one-dimensional (horizontal) solution of the transport equations in the neutral base. Physical effects such as bandgap narrowing, mobility and lifetime dependence upon doping levels, are included, as are electrical effects such as high level injection, the Kirk effect, emitter current crowding, quasi-saturation and narrow base effects [1,2]. A reference version and a regularly updated version are available. The reference version used for the work described here is V15.02.

2.2 BIPOLE Input Parameters

Several different types of bipolar structures can be modelled. Our work so far has been confined to discrete transistors.

The minimum dimensional information required is that of the emitter and base diffusions, the base contact windows, and the distance between the edge of the emitter and the base contact.

By default, Gaussian profiles are assumed and the values of the surface concentration and junction depth for the emitter and base diffusions are required. Also available is an error function complement, and the characteristic length L (from $N_x = N_0$ erfc x/L) is required. L must be calculated separately (not using BIPOLE) from the surface and background concentrations and the junction depth.

A third option is to input a table of values of the emitter and base distribution. This is useful if a process model (e.g. SUPREM) is used to derive the profile, or if profile information is available from measurements. It should be remembered that BIPOLE requires N_A and N_D, but that a spreading resistance profile only provides $N_A - N_D$, which means that several sets of acceptor and donor profiles could produce the same net profile.

In all of the above cases the thickness and doping concentration of the epitaxial layer are required.

The value of the collector-base voltage is also required for the calculation of gain and f_T.

2.3 BIPOLE Output

Information on profiles is generated first. Based on these, emitter-base and collector-base breakdown voltages and the epi reach-through voltage are computed, together with the Kirk current (the current at which current induced base widening starts), the current at which high level injection starts and the current at which internal saturation starts. These values are used by the programme to determine the range of current used in the computations. Sheet resistance and Gummel numbers, and intrinsic and extrinsic base resistances are also calculated. This information is printed out, with an option to choose the actual or net doping profiles.

The next information available results from the integration of Poisson's equation for the two space charge layers and includes depletion widths, capacitance (with or without edge effects) and built-in barrier potentials.

A second table, from the result of one-dimensional integration of the transport equation in the quasi-neutral base and of Poisson's equation in the collector-base space charge layer, gives values of current densities, gains, delay times, widths of space charge layer and neutral base width, etc, as a function of increasing current. Options are available to suppress some or all of the table. The maximum value of β in this table, the Gummel number for the junction voltages actually used, the small signal base resistance (r_{bb}') and an empirical value for the collector-emitter voltage, are then printed.

A third table gives the results of integrating the transport equation in the horizontal (lateral) direction. Base and collector current, β, emitter current crowding, f_T, and terminal base-emitter voltage are all given as a function of current. The output is completed by plots (which can be suppressed) of β and f_T as a function of current.

Parameters for generating CAD models (Gummel-Poon, Ebers-Moll, etc) can be obtained.

3. EXPERIMENTAL COMPARISON

A high performance transistor developed at STL is being used as a test vehicle. It has a single 2 µm wide emitter and is designed to operate at 2 mA. The first devices were made using a 3 GHz f_T process, the emitter junction depth and base width being of the order of 0.25 µm. Gain and f_T have been measured as a function of current. Noise has been measured and r_{bb}' has been derived from this [3]. The junction capacitance has been measured as a function of voltage and the zero bias junction capacitances have been obtained. Collector current has been measured as a function of base-emitter voltage, and the Gummel number for the base region has been calculated [4]. Test wafers processed at the same time as the transistors have been used to obtain SIMS and spreading resistance profiles, sheet resistance, junction depths and epitaxial layer thickness and resistivity.

4. SIMULATIONS USING BIPOLE

4.1 The Doping Profile

Values of doping density at various depths were obtained from the SIMS profiles for the emitter and base region. These were used as an input to BIPOLE to obtain a net impurity profile which was compared with a spreading resistance profile. The input values were then modified until the net profile produced by BIPOLE was identical to the spreading resistance profile (Fig. 1). The resulting input profiles are shown in comparison with the original SIMS profiles in Fig. 2.

Fig 1. Comparison of Spreading Resistance and Net (BIPOLE) Profiles

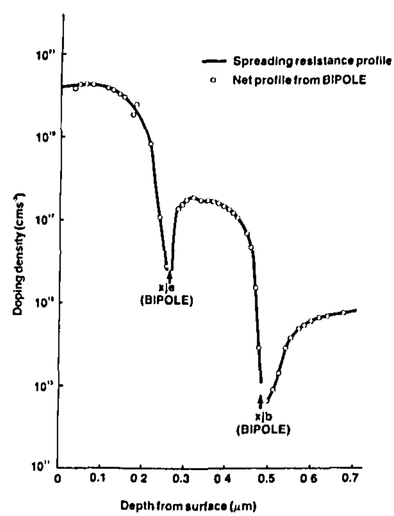
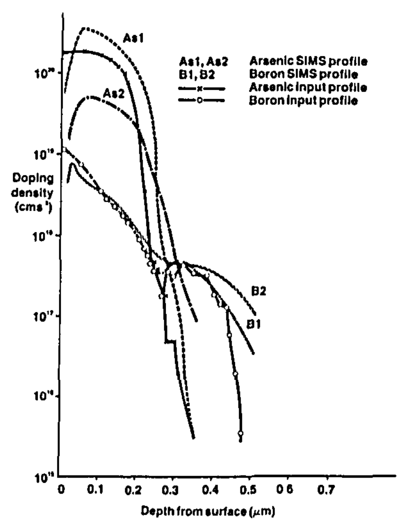


Fig 2. Comparison of SIMS and Input Profiles



The desired base profile follows the SIMS profile fairly accurately up to the emitter-base junction. Within the base region, the desired profile, although close, shows some perturbation about the SIMS profile, and then falls off in the region of the collector-base junction. For a large part of the emitter region, the desired emitter profile is between two SIMS arsenic profiles, and falls off to be about an order lower, as the emitter-base junction is approached. The two SIMS profiles and the spreading resistance profile were carried out on three separate test wafers in different parts of the boat which could possibly explain some of the differences. The different resistivities of the test wafers and the device wafers is taken into account by BIPOLE.

For the simulations, an allowance has been made for undercutting of the narrow windows during processing, and for outdiffusion from the highly doped substrate into the epitaxial layer.

4.2 Comparison of Simulation and Measurement

The variation of simulated gain and f_T with collector current is shown in Fig. 3 compared with measured values. In Fig. 3a the measured gain of two typical devices is shown, together with the simulation using default values of recombination parameters for both the reference (V15.02) and updated version (V15.18). The reference and updated versions show little difference until the rated current (2 mA), and both show very large differences from the measured values. However, if the recombination parameters are adjusted, then good agreement with measured values can be obtained.

Fig 3a. Variation of Gain with Collector Current for Different Recombination Parameters

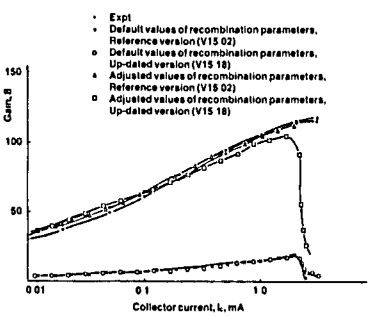
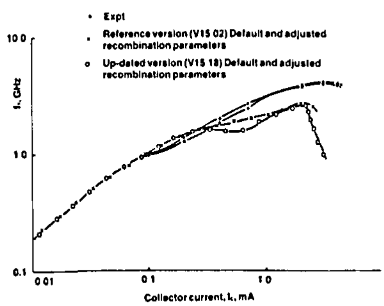


Fig 3b. Variation of f_T with Collector Current for Different Recombination Parameters



The default and adjusted values of emitter time constant, surface recombination velocity and the recombination volume used are shown in Table 1. If a parameter is not included in the table, this indicates that the default value has been used. A discussion of the effects of some of the other parameters is made in a later section.

Table 1

Comparison of Default and Adjusted Recombination Parameters

Parameter	Default Value	Adjusted Value
TAUE	1.0×10^{7}	1.0×10^{-6}
XFS	20×10^{-4}	1.0×10^{5}
SME	1.0×10^{7}	1.0×10^{4}

The variation of f_T is shown in Fig. 3b, with measured values for two typical devices. It is seen that the recombination parameters have no effect on f_T and that there is little difference in f_T at the rated current for the reference and updated versions. There is, however, an anomaly in the shape of the curve using the updated version. This shape often arises due to interpolation errors. The standard version shows reasonable agreement with measured values up to 20% of the rated current, and at the rated current is about 70% of the measured f_T. The simulated values fall off rapidly above the rated current, and the current at which f_T peaks is not correctly predicted.

Using surface concentration and junction depth or characteristic length for the emitter and base regions taken from the input profiles previously described, profiles can be generated within BIPOLE. Simulations using these are compared with measured values in Fig. 4. Using default parameters, both Gaussian and erfc profile device parameters are lower than measured values, and using the adjusted parameters both profiles give considerably higher values than those measured (Fig. 4a). It would be possible, of course, to re-adjust the recombination parameters to obtain a better fit, but this has not been done. Again, recombination parameters do not affect f_T and the error function compliment profile gives excellent agreement over the range rated current $\pm$50%. Fall-off above this value is faster than for the measured values (Fig. 4b).

Fig 4a. Variation of Gain with Collector Current for Different Profiles

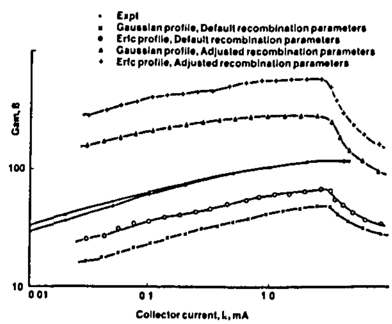
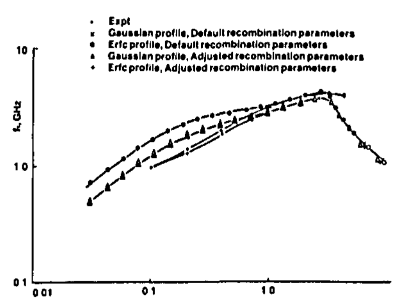


Fig 4b. Variation of f_T with Collector Current for Different Profiles



Various other parameters calculated by BIPOLE are shown in Table 2, where they are compared with measured values. The measured values of voltages are not breakdown voltages, but voltages at a particular reverse current, and for the 10 μA case are median voltages for about 20 transistors. For the 5 mA case, measurements were for two devices only. $r_{bb'}$, and f_T are also for the same set of 20 transistors.

Table 2
Comparison of Measured and Simulated Device Parameters

	Measured		Bipole					
			Tabulated		Gaussian		ERFC	
			D	A	D	A	D	A
V_{ebo}	4.6 5.3	1) 2)	6.7	6.7	7.3	7.3	9 7	9.7
V_{cbo}	44 62	1) 2)	46	46	46	46	46	46
V_{ceo}	30 33	1) 2)	12.0	9.31	8.79	6.78	7.3	5.29
h_{FE}	115	3)	19.5	113	38	290	66	'590
r_{bb}'	44		42.6	42.6	148	148	23 6	23 6
f_T	3.88	3)	2.75	2.75	3 6	3.6	3.95	3 95
ρ_B	839		689	689	498	498	673	673
ρ_E	30.5		24.9	24.9	28.5	28.5	43.6	43.6
Base Gummel No	0.65 E12		0 388 E13	0.388 E13	0.587 E12	0.587 E12	0 127 E12	0.127 E12
C_{jeo}	0.182 E-12		0.158 E-12	0.158 E-12	0 146 E-12	0 146 E-12	0 875 E-13	0 875 E-13

Notes: 1) at 10 μA
2) at 5 mA
3) at 7 V 2 mA

D) using default recombination parameters
A) using adjusted recombination parameters

There are considerable differences between the parameters from simulations for the three types of profile (except for V_{cbo}), although surface concentration and junction depth are the same for all. The collector-base breakdown voltage, BV_{cbo}, is calculated as 46, and whereas this is in good agreement with the measured value of V_{cbo} (10 μA) it is considerably less than the value at 5 mA. Measured values of emitter-base voltages at both 10 μA and 5 mA are considerably less than any of the calculated values. The collector-emitter voltage (V_{ceo}) is very much greater than any of the calculated values. The emitter-base and collector-base voltages calculated by BIPOLE could be considered as a reasonable first approximation, but if any reliance were placed on the collector-emitter voltage value, then designs would be very pessimistic, and if profiles were adjusted to obtain a good value of BV_{ceo}, this could compromise f_T and gain.

The base resistance, r_{bb}', calculated using the tabulated profile, gives very good agreement. That from the Gaussian profile is too high, being three times the measured value, and that from the erfc profile is about one-half.

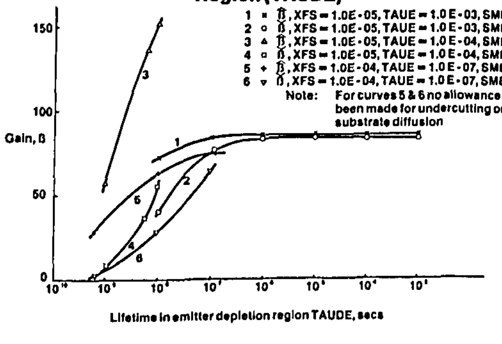
A possible reason for the disagreement can be found from the sheet resistance values, zero voltage capacitance and base Gummel number, where in some cases fair agreement is obtained and in others there are large discrepancies. This indicates that although the profiles used give an exact fit to the spreading resistance profile, they are not in good agreement. (It should be recalled that a number of different acceptor and donor profiles could lead to the same net profile.) The base sheet resistance is 20% higher than that calculated for the tabulated case and is up to almost 70% higher for the other profiles. The calculated emitter sheet resistance for the Gaussian profile compares well with measured values, but the value for the tabulated profile is about 20% lower while that for the erfc profile is 40% higher. The calculated base Gummel number varies from five-times to one-fifth of the measured value, depending upon the profile used, with the Gaussian profile being only 10% out. The zero voltage emitter capacitance is 15% greater than the calculated value for the tabulated profile. The values for the other profiles range from 25% to 50% lower than measured values.

The recombination parameters are seen to affect gain and collector-emitter voltage only.

4.3 The Effect of Recombination Parameters

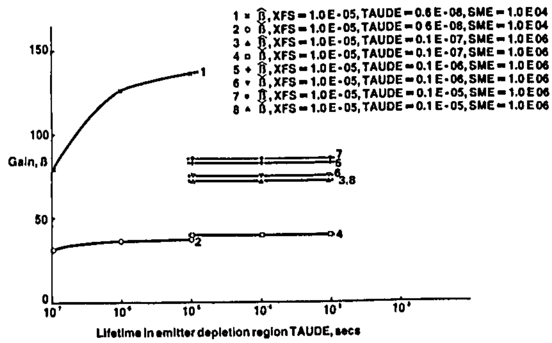
It has already been shown that in general the recombination parameters affect only the calculation of gain. Some of the parameters have more effect than others, and the effect of a particular parameter may well depend on values of the other parameters. This last part is true for the lifetime in the emitter depletion region (TAUDE), the lifetime in the emitter region (TAUE) and an emitter surface recombination factor (XFS). This factor is a notional space above the emitter, in which recombination can take place [5]. This has been calculated to be nearer to 0.1 μm than the 20 μm of the default value. The effects on the maximum gain ($\hat{\beta}$) and on the gain ($\check{\beta}$) at the first value of current (between 10 and 13 μA, depending upon the parameters) of these parameters are shown in Figs. 5 to 7 inclusive.

Fig 5. Gain (β) vs Lifetime within the Emitter Depletion Region (TAUDE)



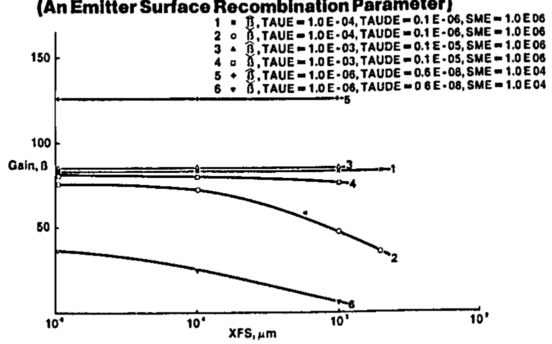
As TAUDE is increased, gain is increased until saturation occurs. If TAUE and surface recombination velocity (SME) are reduced, then increases in TAUDE have a much larger affect on gain (Fig. 5). TAUE has no effect on gain for some conditions of TAUDE and SEM, but for another set of conditions $\hat{\beta}$ increases at a much faster rate than does $\check{\beta}$ with increased TAUE (Fig. 6).

Fig 6. Gain, ß vs Emitter Region Lifetime (TAUE)



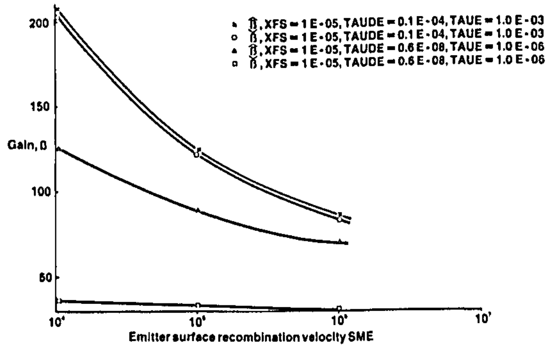
As XFS is increased, $\hat{\beta}$ does not change but $\check{\beta}$ falls off at a rate determined by other parameters (Fig. 7).

Fig 7. Gain vs XFS
(An Emitter Surface Recombination Parameter)



Reductions in the emitter surface recombination velocity cause an increase in gain, the amount of which is also affected by the parameters (Fig. 8). Changes in SME are normally caused by contacts other than metal ohmic contacts.

Fig 8. Gain vs Emitter Surface Recombination Velocity



The above four parameters appear to be very interdependent and to obtain a comprehensive representation of their variation would be very time consuming. However, a set of values for them has been found, which accurately reproduces the measured gain versus current curve (see 4.2). It is, however, possible that a different set of parameters could give the same good result.

A number of other recombination factors have been found to have little effect on gain. These are, lifetime in the base region (TAUB), lifetime in the collector region (TAUC), lifetime in the collector depletion region (TAUDC), and the collector surface recombination factor (XFSC). Table 3 shows the effect on the gain when the lifetimes are changed by a factor of 100 and XFSC changed by 20. In all cases, for the set of other recombination parameters used, changes were negligible.

Table 3
Effects of Some Recombination Parameters

Parameter	Value		Conditions	$\hat{\beta}$	$\check{\beta}$
XFSC	20.0E-04	D	a	75.0	21.9
	1.0E-04		a	75.0	21.9
	20.0E-04	D	b	85.5	84.1
	1.0E-04		b	85.5	84.1
TAUB	1.0E-06	D	b	85.5	84.1
	1.0E-04		b	85.6	84.2
TAUC	1.0E-06	D	b	85.5	84.1
	1.0E-04		b	85.5	84.1
TAUDC	1.0E-07	D	b	85.5	84.1
	1.0E-05		b	85.5	84.1

Notes:
D Indicates default value
a Indicates XFS = 1.0E-05, TAUE = 1.0E-06, TAUDE = 0.1E-07, SME = 1.0E07 with no allowance for undercutting or diffusion into epitaxial layer from substrate
b Indicates XFS = 1.0E-05, TAUE = 1.0E-03, TAUDE = 0.1E-04, SME = 1.0E07 with allowance for undercutting and diffusion into epitaxial layer from substrate

For low current space-charge recombination, the current dependence is modelled as exp(qV/mkT) where m = PEE for the emitter space-charge region, and m = PCE for the corresponding collector region. The effect of these parameters on gain and f_T is shown in Fig. 9. Reducing PEE from the default value of 2.0 to 1.0, considerably increases the low current gain, without affecting the peak gain. Additionally reducing PCE from 2.0 (default) to 1.0 made no further change (Fig. 9a). Slight increases in f_T are found in the medium-current range as PEE is reduced to 1.0 and f_T is reduced slightly at its peak, and at high currents. Again reducing PCE has no further effect (Fig. 9b).

Fig 9a. Variation of Gain with Collector Current, Showing Effect of Space Charge Layer Parameters

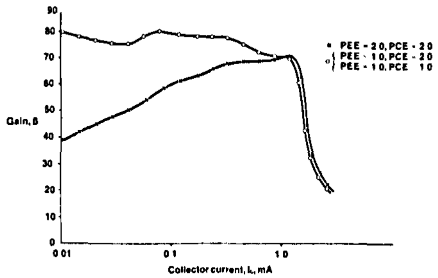
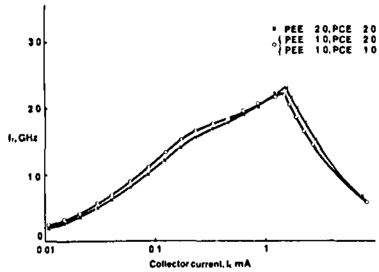


Fig 9b. Variation of f_T with Collector Current Showing the Effect of Space Charge Layer Recombination Parameters



4.4 Effect of Numerical Analysis Parameters

A number of parameters are available which can increase (reduce) precision, with a corresponding increase (reduction) in execution time. Two parameters which have been found to affect the simulation are RA and CREJ.

RA is the ratio of two adjacent values of concentration in the impurity profiles. The default value is 1.2. For many of the simulations a warning to reduce RA has been given. The effect on the gain and f_T versus I_c is shown in Fig. 10, where it is seen that odd changes occur in the mid-current range.

Fig 10a. Variation of Gain with Collector Current Showing Effect of the Ratio Parameter, RA

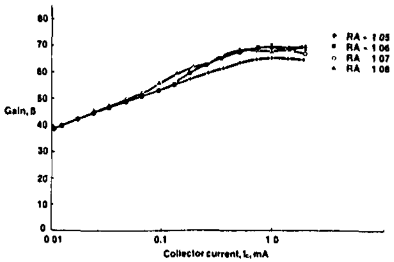
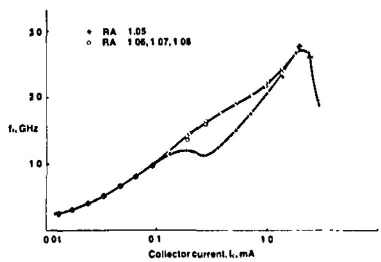
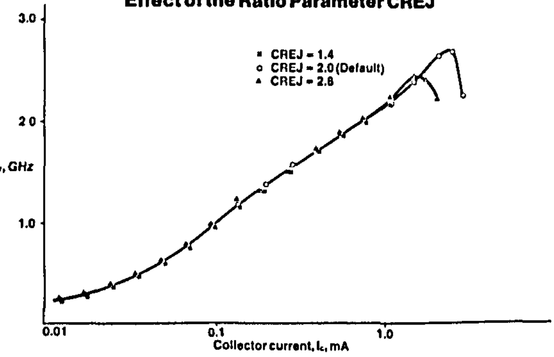


Fig 10b. Variation of f_T with Collector Current Showing the Effect of the Ratio Parameter, RA



CREJ is the ratio of two successive current density values selected in the vertical analysis for the solution of the base-collector region. Gain-versus-current was found to show only minor perturbations as CREJ was changed, but f_T showed a considerable reduction in the region of rated current as the ratio was increased from 2.0 to 2.8. For a value of 1.4 the calculation stopped short at about 1/3 rated current and another parameter (NTOT) needs to be increased to extend the current range (Fig. 11).

Fig 11. Variation of f_T with Collector Current Showing the Effect of the Ratio Parameter CREJ



It is thought that the effects of these two parameters are not 'real' effects, but due to interpolation errors.

5. CONCLUSIONS

The usefulness of a device model depends upon it being able to predict accurately device performance if correct input data is supplied. With the impurity profile data available simulations on a discrete transistor have shown that reasonable agreement with measured f_T near the rated current can be obtained using a Gaussian or error function compliment profile, but that the value given using a tabulated input (from which surface concentration and junction depth were used for the Gaussian and erfc profiles) gave a value approximately 30% low. Using default values of recombination parameters, no agreement on gain was found for any profile, although the values calculated for the Gaussian profile were about 60% of the measured values, and so some indication of the gain could be obtained. The recombination parameters can be adjusted to give good agreement with an existing device, but this could not be used to predict device performance unless the parameters were known from other tests.

Although the tabulated profiles gave a net profile identical to that of a spreading resistance profile, measured profile parameters (e.g. sheet resistance, base Gummel number, zero voltage capacitance), did not agree with simulated values, which no doubt contributed to the lack of agreement of the device parameters.

For the discrete transistor simulated, BIPOLE gave a good first-order approximation, which was capable of optimization.

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