A NUMERICAL DIODE MODEL FOR INVESTIGATION OF THERMAL SECOND BREAKDOWN

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by

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ABSTRACT

A comprehensive numerical diode model for simulation of thermal second breakdown is developed. The model features one-dimensional electrical effects and simplified two-dimensional thermal conduction along with thermally dependent semiconductor parameters. Four, coupled, nonlinear, partial differential equations which consist of the hole and electron continuity equations, the Poisson equation and the energy balance equation characterize the model. These equations are solved simultaneously for mobile hole and electron concentrations, electric field, and temperature as functions of time and position. A contact-to-contact transient simulation with realistic terminal boundary conditions and a constant temperature substrate is performed.

Investigations with the numerical model have lead to several conclusions with respect to thermal second breakdown. First, it is observed that junction inhomogeneities, current constrictions and variable perturbations, through various mechanisms, are not required to initiate and support thermal second breakdown. Second, the simulation results support the theory that thermal second breakdown is primarily a consequence of the diode leakage current temperature dependence. Third, under appropriate conditions the thermal second breakdown transition results in all but a total collapse of the junction voltage without the benefit of a melt filament.

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TABLE OF CONTENTS

		Page
ABSTRACT		ii
ACKNOWLEDGEMENTS		iii
LIST OF TABLES		vi
LIST OF FIGURES		vii
CHAPTER 1	INTRODUCTION	1
CHAPTER 2	DESCRIPTION OF THE THERMAL SECOND BREAKDOWN PHENOMENON	4
	2.1 THERMAL SECOND BREAKDOWN IN THIN FILM SILICON-ON-SAPPHIRE DIODES	4
	2.1.1 Avalanche Breakdown Transition	5
	2.1.2 Junction Hot Spot Nucleation	6
	2.1.3 Current Filament Development	8
	2.1.4 Melt Filament Transition	9
	2.2 ONE-DIMENSIONAL ANALYSIS OF THERMAL SECOND BREAKDOWN	10
CHAPTER 3	DIODE MODEL	12
	3.1 MATHEMATICAL MODEL	12
	3.1.1 Two-Dimensional Thermal Conduction	13
	3.1.2 System of Equations for Mathematical Model	16
	3.1.3 Boundary Conditions	18
	3.1.4 Carrier Generation-Recombination Expressions	22
	3.1.5 Mobility Coefficients Formulation	23
	3.1.6 Semiconductor Resistivity	25
	3.1.7 Normalization of Mathematical Model	30
	3.2 NUMERICAL MODEL	35
	3.2.1 Designation of Spacial Grid and Model Geometry	35

Page

3.2.2 Finite Difference Formulation of the Mathematical Model 37
3.2.3 Generalized Crank-Nicolson Formulation 40
3.2.4 Linearization of the Mathematical Model 42
3.2.5 Current Approximations 44
3.2.6 Finite Difference Formulation of Boundary Conditions 47
3.2.7 Solution Procedure 50

CHAPTER 4 RESULTS AND CONCLUSIONS 52

4.1 SIMULATION OF THERMAL SECOND BREAKDOWN 52

4.2 CONCLUSIONS 69

4.3 RECOMMENDATIONS FOR FURTHER STUDY 71

APPENDIX A COEFFICIENT FORMULATION 72

APPENDIX B COMPUTER DIODE MODEL 88

B.1 PROGRAM DS 94

B.2 PROGRAM COMP 116

B.3 PROGRAM GDG 165

B.4 PROGRAM GRAPH 165

LIST OF REFERENCES 192

LIST OF TABLES

Table		Page
3.1	BOUNDARY CONDITION SYSTEMS	20
3.2	LIST OF NORMALIZATION FACTORS FOR DIODE MODEL PARAMETERS AND VARIABLES	33
4.1	DIODE DESIGN AND SIMULATION PARAMETERS FOR THE THERMAL SECOND BREAKDOWN SIMULATION	53
B.1	SIMULATION STATE DATA FORMAT AND VARIABLE DEFINITIONS	90
B.2	SYMBOL DEFINITIONS FOR SIMULATION SUMMARY	126
B.3	GRAPH CODES FOR PROGRAM GRAPH	173

LIST OF FIGURES

Figure		Page
3.1	(a) Electrical Analog of Thermal Model and (b) Diode Model Physical Design	14
3.2	Hole and Electron Ionization Coefficient Versus Electric Field	24
3.3	Electron Mobility Versus Electric Field for Different Impurity Levels	26
3.4	Hole Mobility Versus Electric Field for Different Impurity Levels	27
3.5	Hole Mobility Versus Temperature for Different Impurity Levels	28
3.6	Electron Mobility Versus Temperature for Different Impurity Levels	29
3.7	Semiconductor Resistivity Versus Temperature for Different Impurity Levels	31
3.8	(a) Numerical Diode Model Spacial Grid, (b) Physical Design and (c) External Circuit Configuration	36
3.9	Coefficient Matrix for Equation (3.70)	45
3.10	Solution Procedure Flow Chart	51
4.1	Terminal Voltage as a Function of Time with Transient Reference Points at t_1 through t_{11} (t_1=0.0, t_2=1.0x10^{-8}, t_3=2.0x10^{-8}, t_4=5.06x10^{-8}, t_5=3.0x10^{-6}, t_6=4.0x10^{-5}, t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_9=1.35x10^{-4}, t_{10}=1.78x10^{-4}, t_{11}=1.11x10^{-3} - sec)	54
4.2	Terminal Voltage as a Function of Time (t_9=1.35x10^{-4} sec)	55

Figure Page

4.3 Maximum Temperature as a Function of Time 56

4.4 Maximum Temperature as a Function of Time (t_9=1.35x10^{-4} sec) 57

4.5 Mobile Hole Density as a Function of Position at Various Instants of Time Prior to the Onset of Thermal Second Breakdown (t_1=0.0, t_2=1.0x10^{-8}, t_3=2.0x10^{-8}, t_4=5.06x10^{-8}, t_7=7.82x10^{-5} - sec) 58

4.6 Mobile Hole Density as a Function of Position at Various Instants of Time After the Onset of Thermal Second Breakdown (t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec) 59

4.7 Mobile Electron Density as a Function of Position at Various Instants of Time Prior to the Onset of Thermal Second Breakdown (t_1=0.0, t_2=1.0x10^{-8}, t_3=2.0x10^{-8}, t_4=5.06x10^{-8}, t_7=7.82x10^{-5} - sec) 60

4.8 Mobile Electron Density as a Function of Position at Various Instants of Time After the Onset of Thermal Second Breakdown (t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec) 61

4.9 Electric Field as a Function of Position at Various Instants of Time (t_1=0.0, t_3=2.0x10^{-8}, t_7=7.82x10^{-5}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec) 62

4.10 Temperature as a Function of Position at Various Instants of Time (t_5=3.0x10^{-6}, t_6=4.0x10^{-5}, t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_{10}=1.78x10^{-4}, t_{11}=1.11x10^{-3} - sec) 63

Figure		Page
4.11	Hole and Electron Current Densities as Functions of Position at Various Instants of Time (t_1=0.0, t_4=5.06x10^{-8}, t_7=7.82x10^{-5}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec)	64
4.12	Voltage as a Function of Position at Various Instants of Time (t_1=0.0, t_3=2.0x10^{-8}, t_7=7.82x10^{-5}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec)	65
B.1	Flow Chart for Program DS	97
B.2	Listing for Program DS	99
B.3	Listing for FORTRAN Procedure Collection WRLF	106
B.4	Listing for Subroutines DTMUL, CST and NTAB$	112
B.5	Listing for Subroutine ISTG	113
B.6	Listing for Subroutines THEQCA and INTRI	117
B.7	Listing for Subroutine DEPL	118
B.8	Simulation Summary Example	121
B.9	Flow Chart for Program COMP	129
B.10	Listing for Program COMP	131
B.11	Subroutine Hierarchy for Program COMP	142
B.12	Listing for Subroutine NOR2	143
B.13	Listing for Subroutine HOLION	145
B.14	Listing for Subroutine ELEION	147
B.15	Listing for Subroutine HMOB	148
B.16	Listing for Subroutine EMOB	149
B.17	Listing for Subroutine TNDAOP	150
B.18	Listing for Subroutine CSOP	152

Figure Page

B.19 Listing for Subroutine CICONC 155

B.20 Listing for Subroutine CUR 156

B.21 Listing for Subroutine GION 159

B.22 Listing for Subroutine GSHR 161

B.23 Listing for Subroutine BANDA3 162

B.24 Listing for Subroutines CHECKC and AXR$ 164

B.25 Flow Chart for Program GDG 166

B.26 Listing for Program GDG 167

B.27 Flow Chart for Program GRAPH 175

B.28 Listing for Program GRAPH 176

B.29 Listing for Subroutine GENCUR 180

B.30 Listing for Subroutine LILOY 183

B.31 Listing for Subroutines SELCS and SMIMA 185

B.32 Listing for Subroutine HEADER 188

B.33 Listing for Subroutines LOAD and INMIMA 189

B.34 Listing for Subroutines SPMIMA and SKIP 190

B.35 Listing for Subroutines NEGY and SMIMAY 191

CHAPTER 1

INTRODUCTION

As a consequence of the complexity of the thermal second breakdown problem, past theoretical efforts have been limited to treating only portions of the overall problem. Solutions of this nature involve numerous restrictive assumptions to reduce the state equations describing semiconductor physics to a simplified form to facilitate a particular solution procedure. Solution comprehensiveness is lost under these conditions since the various mechanisms composing thermal second breakdown are decoupled and considered on an individual basis.

This study presents the development of a comprehensive numerical diode model which is used to simulate thermal second breakdown. The electrical characteristics of the model are predicted through the charge transport equations which yield the mobile hole and electron concentrations, and the electric field profile as functions of position and time throughout the diode structure.

The primary difference between this model and previously developed models is with respect to the addition of temperature as a dependent variable. This model expansion is necessitated by the temperature dependence of the thermal second breakdown phenomenon and is accomplished through the inclusion of the energy continuity equation. Hence, a theoretical diode model sufficient for thermal second breakdown

simulation is formulated at the expense of additional model complexity. The resulting model yields a unified simulation of the thermal second breakdown transition by including both one-dimensional electrical effects and simplified two-dimensional thermal effects. The model features a contact-to-contact transient simulation with realistic terminal boundary conditions and a constant temperature substrate.

To demonstrate the numerical diode model a thermal second breakdown simulation for a typical diode design is presented. For this simulation the diode is initially in a low-level, reverse bias state. Upon being pulsed with a high amplitude constant current pulse, the diode undergoes a dynamic transient which terminates in a stable post-second breakdown state. During this transient the diode model exhibits electrical and thermal behavior that closely approximates experimental characterizations of this phenomenon.

Preliminary investigations with the numerical model have lead to several conclusions with respect to thermal second breakdown. First, it is observed that junction inhomogeneities, current constrictions and variable perturbations, through various mechanisms, are not required to initiate and support thermal second breakdown. This implies that thermal second breakdown is a fundamental aspect of semiconductor physics and thus is a property of the semiconductor state equations. Various junction inhomogeneities, etc., simply serve to enhance or prematurely initiate this phenomenon. Second, the simulation results support the theory that thermal second breakdown is primarily a consequence of thermal quenching of avalanche breakdown by the diode

leakage current. Third, it is observed that the thermal second breakdown transition results in all but a total collapse of the junction voltage without the benefit of a melt filament.

The remainder of this study consists of three additional chapters and an appendix. Chapter 2 presents a description of thermal second breakdown in thin film silicon-on-sapphire diodes. The development of the numerical model is presented in Chapter 3. Chapter 4 gives an example second breakdown simulation along with recommendations for further study. Appendix A contains a summary of equations pertinent to the numerical model and Appendix B presents a description of the computer program version of the numerical model.

CHAPTER 2

DESCRIPTION OF THE THERMAL SECOND BREAKDOWN PHENOMENON

Comprehensive experimental investigations have provided detailed insight into the physics of thermal second breakdown. The resulting description of the second breakdown mechanism is presented in this chapter along with consideration of the applicability of a one-dimensional numerical analysis of this phenomenon.

2.1. THERMAL SECOND BREAKDOWN IN THIN FILM SILICON-ON-SAPPHIRE DIODES

Experimental investigations into the thermal second breakdown phenomenon were restricted primarily to electrical measurements and physically destructive autopsies until the advent of a new experimental technique developed by Sunshine and Lampert [1] and further refined by Budenstein et.al. [2]. This technique employs thin film silicon-on-sapphire (SOS) diodes in conjunction with a temperature monitoring system which yields a spacial resolution of down to one micron and a temperature resolution of a few degrees Celsius. Furthermore, when this technique is used stroboscoptically time resolutions on the order of nanoseconds were obtained. The system developed for these studies also allowed enhanced observation of light emission by the specially designed specimens. The subsequent experiments yielded a thermal and temporal picture of the second breakdown mechanism.

Experiments performed by this new technique revealed a four phase transition into the post-second breakdown mode of operation for reverse biased SOS diodes. The test diodes were reverse biased by constant current pulses and the subsequent voltage and thermal characteristics were monitored as a function of time with the current pulse amplitude serving as a variable parameter. First, the diodes were observed to undergo a transition from a non-uniform avalanche breakdown to a uniform avalanche breakdown. Second, one or more hot spots formed within the junction. Third, the hot spots elongated into the high resistivity side of the junction forming thermal filaments. Fourth, coincident with bridging of the high resistivity region by a thermal filament rapid growth of a melt filament interior to the thermal filament occurred. The remainder of this section is devoted to a detailed description of each of these four phases of second breakdown development as reported by the above researchers.

2.1.1 Avalanche Breakdown Transition

Avalanche breakdown is accompanied by light emission which is proportional to the avalanche generated current; therefore, the uniformity of the avalanche breakdown along a junction can be investigated through the subsequent emission pattern. Upon pulsing a SOS diode with a constant current pulse, the initial avalanche emission pattern is non-uniform indicating avalanche breakdown at discrete locations along the junction. However, the emission pattern uniformity along the junction increased with increasing junction temperature and current. This relationship is attributed to the negative temperature dependence of the avalanche coefficients and space-charge induced depletion region widing.

The tendency toward avalanche breakdown uniformity for increasing temperature implies a thermally stable mechanism which is contrary to the thermal second breakdown mechanism.

2.1.2 Junction Hot Spot Nucleation

The second phase, and perhaps the most crucial, begins with the appearance of one or more hot spots within the junction. These hot spots are discrete regions along the junction which manifest a temperature considerably higher than that of the surrounding semiconductor region. Temperature measurements for these regions yield temperatures in excess of the resistivity turn-over temperature for the impurity concentration on the high resistivity side of the junction. The resistivity turn-over temperature corresponds to that temperature for which the resistivity versus temperature characteristics for silicon passes through a maximum. Temperatures in excess of the turn-over temperature result in an unstable condition which supports the formation of current constrictions. A local increase in current produces a higher temperature, which produces a corresponding decrease in resistivity, which causes a further increase in current, etc. Although this condition most certainly enhances second breakdown through current filamentation, it does not account for the large decrease in diode voltage which occurs during the second breakdown transition for a constant current pulse. This aspect of second breakdown is attributed to a thermally motivated quenching of avalanche breakdown. It was noted that the junction saturation current, or leakage current increased rapidly with increasing junction temperature. Upon pulsing a junction with a constant current pulse the leakage current component corresponds to the initial junction

temperature. The difference between the current pulse amplitude and the initial leakage current is compensated for through avalanche breakdown. The large voltage associated with avalanche breakdown, in conjunction with the increased current level, raises the junction temperature through joule heating. This in turn leads to an increase in leakage current and an equal decrease in avalanche generated current.

The junction voltage does not reflect this change in the current generation mechanism until the leakage current becomes virtually equal to the total diode current since avalanche breakdown voltage is essentially independent of the avalanche breakdown current. However, once the leakage current takes on values comparable to the total current, the junction voltage becomes increasingly sensitive to further increases in leakage current, as avalanche breakdown is quenched. Accordingly, junction hot spots are associated with a thermally motivated change in the diode current generation mechanism. The extent to which this mechanism reduces the diode voltage is dependent upon the spacial and thermal characteristics of the subsequent junction hot spots. This topic receives further consideration in Section 2.1.3. Moreover, this explanation for junction hot spot physics is further supported by the observation that avalanche light emission is extinguished within and to either side of the junction hot spot regions. A large amount of current is funneled through this region ballasted by spreading resistance in the bulk region. This spreading resistance is accompanied by a voltage gradient in the bulk regions and along the junction. At some distance along the junction and away from the hot spot region, avalanche breakdown voltage is obtained as a consequence of the lateral

current flow and thus accounting for avalanche light emission in regions of the junction away from the various junction hot spots.

For low amplitude current pulses a single hot spot almost invariably forms in the center of the junction as would be expected from purely thermal considerations. On the other hand, for increasing current pulse amplitude multiple junction hot spots begin to occur. This dynamic process begins with the initiation of a high amplitude current pulse. Several hot spot regions quickly develop across the junction without any apparent relation to the device geometry or neighboring junction hot spot regions. This seemingly randomn behavior is possibly a consequence of some type of junction inhomogeneity. With increasing time additional hot spot regions continue to form until a nearly uniform distribution is obtained. Spreading resistance readily accounts for this uniformity trend. The number of junction hot spot regions which form tends to a limiting number with increasing current pulse amplitude.

2.1.3 Current Filament Development

There is no decisive division between the second and third phases of second breakdown development; although, under certain conditions the second phase can be readily produced without initiating the third phase. The third phase is simply an elongation of a junction hot spot into the high resistivity side of the junction such as to form a thermal filament extending into this region. The junction hot spot elongates into the high resistivity side of the junction because joule heating is most significant on this side of the junction. Since the resulting thermal filament is intimately associated with a high current density, it is often referred to as a current filament. Growth of the

current filament across the high resistivity region produces a continuous decrease in device voltage.

As with the junction hot spot regions, temperature measurements have shown the thermal filament temperatures to be in excess of the corresponding resistivity turn-over temperature, but less than the molten temperature for silicon. Thus, a potentially unstable situation exists. To maintain the current filament at a particular stage requires a very delicate balance between electrical and thermal conditions. More often than not, thermal filament formation is a highly dynamic process resulting in a rapidly growing filament which leads directly to the fourth and final stage of second breakdown development. It may be well to mention that these filaments were, on occasion, observed to exhibit a rather irregular path in translating the high resistivity region.

2.1.4 Melt Filament Transition

The fourth phase of second breakdown development is of course the climatic phase and it is this phase which is generally associated with irreversible device damage. Although the growth of the thermal filament across the high resistivity region is in most cases quite dynamic, the portion of this region not covered by the filament tends to exert a governing influence on the advancement of the thermal filament. Once the filament has penetrated this region, however, all significant resistive ballasting within the device is eliminated creating an extremely unstable condition. As a consequence of the high positive thermal feedback associated with these circumstances, the current filament undergoes a rapid transition to a molten filament with an immediate thirty-fold,

or so increase in conductivity. This rapid increase in conductivity results in an equally rapid decrease in device voltage with the final device current and voltage levels being determined primarily by the test circuitry. These events usually produce irreversible, catastrophic damage and thus completing the four phase development of second breakdown.

2.2 ONE-DIMENSIONAL ANALYSIS OF THERMAL SECOND BREAKDOWN

The previous description of thermal second breakdown was derived primarily through interpretation of experimental results. The second breakdown phenomenon is too complex to analyze through conventional analytic techniques. The general mathematical model for semiconductor behavior, which is presented in Chapter 3, consists of four, nonlinear, coupled, partial differential equations. Under second breakdown conditions, the only reasonable solution approach for this system of equations is through numerical techniques. Even for numerical techniques a comprehensive three-dimensional solution, or even a two-dimensional solution, presents a formidable problem. A compromise between model sophistication and solution complexity is required. To this end, a one-dimensional diode model is selected. The major disadvantage of this choice pertains to the elimination of the current constriction capability. On the other hand, it presents an opportunity to investigate second breakdown in the absence of this mechanism. Furthermore, the absence of the current constriction mechanism may be compensated for, to the extent desired, by simply increasing the diode current. A diode current comparable to an actual constriction current effectively

simulates the respective current constriction. In this manner, the semiconductor resistivity turn-over temperature and the leakage current thermal dependence with respect to second breakdown can be further investigated. Moreover, the numerical model affords the ability to monitor directly the physics of second breakdown.

CHAPTER 3

DIODE MODEL

In this chapter a one-dimensional numerical diode model for investigation of thermal second breakdown is developed. The numerical technique employed was essentially developed at Bell laboratories for the analysis of the IMPATT diode [1,2]. This procedure has also been used to investigate transient and permanent radiation effects in both diode and transistor structures [3], as well as for small signal analysis [4]. These models, however, are thermally independent; and consequently, insufficient for simulation of thermal second breakdown. Accordingly the basic model is expanded to include temperature as a dependent variable to produce a numerical diode model capable of simulating thermal second breakdown.

3.1 MATHEMATICAL MODEL

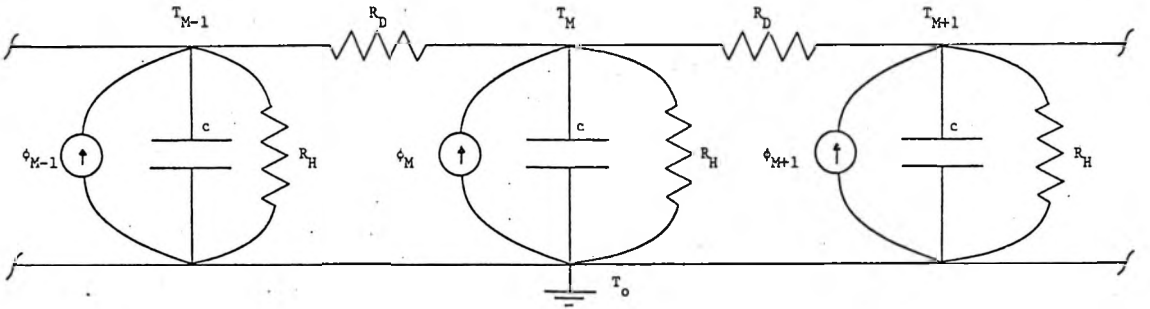
A comprehensive mathematical diode model capable of simulating thermal second breakdown is developed. The model features simplified two-dimensional thermal conduction along with thermally dependent semiconductor parameters and is characterized by four coupled nonlinear partial differential equations which are to be solved simultaneously for hole and electron concentrations, electric field and temperature as functions of time and position.

3.1.1 Two-dimensional Thermal Conduction

Since in practice semiconductor devices are generally mounted on some form of substrate for heat sinking and for physical support, the validity of a one-dimensional thermal conduction model is questionable. On the other hand comprehensive two-dimensional thermal conduction is overly complex and would destroy the important banded matrix form of the system of linear equations which characterize the numerical model being expanded. A compromise solution which allows for simplified two-dimensional thermal conduction without altering the banded form of the system of equations for the overall numerical model is depicted in Fig. 3.1. This model exhibits heat flow along the axis of the one-dimensional diode structure and perpendicular to this axis through the substrate into a constant temperature heat sink. Heat storage and generation is restricted to the diode structure; the substrate material simply acts as a thermal resistance between the diode structure and the constant temperature heat sink. Since this thermal model requires only a one-dimensional temperature profile it can be modeled by the one-dimensional version of the energy continuity equation.

$$\rho c \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} \left[K_D(x,t) \frac{\partial T(x,t)}{\partial x} \right] + \Phi(x,t) \qquad (3.1)$$

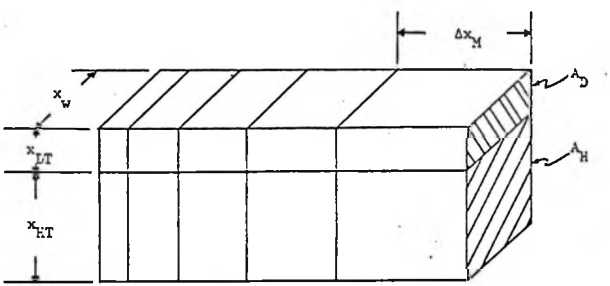
For this case the heat sink effect enters equation (3.1) through the power density term, $\Phi(x,t)$. This term is defined as a net power density factor which accounts for both heat generation and heat lost by mechanisms other than conduction along the axis of the model.



(a)

Symbols:

- ϕ - Heat generation
- T - Temperature
- T_* - Heat sink temperature
- ρ - Diode density
- c - Diode specific heat
- K_D - Diode thermal conductivity
- R_D - Diode thermal resistance
- K_H - Substrate thermal conductivity
- R_H - Substrate thermal resistance
- x - Position
- x_w - Diode and substrate width
- x_{DT} - Diode thickness
- x_{HT} - Substrate thickness
- Δx_M - Distance between adjacent M-nodes
- A_D - Diode cross sectional area
- A_H - Substrate cross sectional area



(b)

Fig. 3.1 (a) Electrical Analog of Thermal Model and (b) Diode Model Physical Design

From basic thermal conduction principles [5] and the model design shown in Fig. 3.1, the net power density factor for the case at hand can be derived and is given as

$$\Phi(x,t) = |E(x,t)| \; [|J_p(x,t)| + |J_n(x,t)|] - \frac{K_H(x,t)}{x_{DT} x_{HT}} \; [T(x,t) - T_o] \tag{3.2}$$

For some aspects of second breakdown theory it is important to monitor the distribution of thermal energy between that stored in the diode structure and that lost to the substrate through thermal conduction. For this purpose the ratio of the total amount of thermal energy stored in the active semiconductor layer to the total amount of thermal energy generated, on a per time step basis, is evaluated as

$$QSGR \equiv \frac{\Delta Q \text{ stored}}{\Delta Q \text{ generated}} = \frac{\rho \; c \; A_D \int_0^{\Delta t} \int_0^{X_L} \frac{\partial T(x,t)}{\partial t} \, dx \, dt}{A_D \int_0^{\Delta t} \int_0^{X_L} |E(x,t)| \; [|J_p(x,t)| + |J_n(x,t)|] \, dx \, dt} \tag{3.3}$$

And, in discrete form QSGR (heat-storage-generation-ratio) becomes

$$QSGR = \frac{\rho \; c \; \sum_M \Delta T(M) \; \Delta x(M)}{\Delta t \; \sum_M |E(M)| \; [|J_p(M)| + |J_n(M)|] \; \Delta x(M)} \tag{3.4}$$

3.1.2 System of Equations for Mathematical Model

The transient and static behavior of a one-dimensional semiconductor device is accurately modeled by a system composed of the carrier transport equations and the energy continuity equation as follows: hole continuity equation, electron continuity equation, Poisson equation, and the energy continuity equation (3.1), or

$$q \frac{\partial p(x,t)}{\partial t} = G_{gr}(x,t) - \frac{\partial J_p(x,t)}{\partial x} \qquad (3.5)$$

$$q \frac{\partial n(x,t)}{\partial t} = G_{gr}(x,t) + \frac{\partial J_n(x,t)}{\partial x} \qquad (3.6)$$

$$\frac{\partial E(x,t)}{\partial x} = \frac{q}{\varepsilon} [p(x,t) - n(x,t) + N_D(x) - N_A(x)], \qquad (3.7)$$

and

$$\rho c \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} [K_D(x,t) \frac{\partial T(x,t)}{\partial x}] + \Phi(x,t) \qquad (3.8)$$

where

$$J_p(x,t) = q \mu_p(x,t) p(x,t) E(x,t) - D_p(x,t) \frac{\partial p(x,t)}{\partial x}, \qquad (3.9)$$

$$J_n(x,t) = q \mu_n(x,t) n(x,t) E(x,t) + D_n(x,t) \frac{\partial n(x,t)}{\partial x}. \qquad (3.10)$$

$$G_{gr}(x,t) = q\,\frac{n_i(x,t)^2 - p(x,t)n(x,t)}{[p(x,t)+n_i(x,t)]\tau_n + [n(x,t)+n_i(x,t)]\tau_p} + q\,\alpha_p(x,t)|J_p(x,t)|$$

$$+ q\,\alpha_n(x,t)|J_n(x,t)| \quad , \tag{3.11}$$

and

$$\Phi(x,t) = |E(x,t)|\,[|J_p(x,t)| + |J_n(x,t)|] - \frac{K_H(x,t)}{x_{DT}x_{HT}}[T(x,t) - T_o] \quad . \tag{3.12}$$

Additional subsidiary relations are: Einstein relation for holes, Einstein relation for electrons, intrinsic carrier concentration, displacement current equation, and electrostatic potential relation:

$$D_p(x,t) = \frac{K}{q}\,\mu_p(x,t)\,T(x,t) \quad , \tag{3.13}$$

$$D_n(x,t) = \frac{K}{q}\,\mu_n(x,t)\,T(x,t) \quad , \tag{3.14}$$

$$n_i(x,t) = \sqrt{N_v N_c}\,T(x,t)^{3/2}\,e^{-q\,E_g/[2K\,T(x,t)]} \quad , \tag{3.15}$$

$$J_T(t) = J_p(x,t) + J_n(x,t) + \varepsilon\,\frac{\partial E}{\partial t} \quad , \tag{3.16}$$

and

$$E(x,t) = -\frac{\partial V(x,t)}{\partial x} \quad . \tag{3.17}$$

This system of equations consists of four independent nonlinear coupled partial differential equations with variable coefficients. The system variables include hole and electron concentrations, electric field and temperature as dependent variables with time and position as independent variables and features simplified two-dimensional thermal conduction. The system is derived assuming that magnetic effects are negligible and that the hole and electron current components are adequately approximated through the Van Roosbroeck equations [6]. In practice both of these assumptions have been found to be valid. It is also assumed that the impurity dopant is completely ionized and that non-degenerate doping levels are maintained for the validity of the Boltzmann statistics used in calculating hole-electron concentrations.

3.1.3 Boundary Conditions

Formulation of the mathematical model is not complete without appropriate boundary conditions. The two continuity equations (3.5) and (3.6) and the energy continuity equation (3.8) exhibit one first order time derivative each implying that three boundary conditions in time, or three initial conditions, are required. It may be suspected that the first order time derivative which appears in the displacement current equation (3.16) should also be considered since the system has four dependent variables. This would add another initial condition. However, as a consequence of coupling between the hole, electron, and electric field values through the Poisson equation this additional initial condition can be omitted. For, given the hole and electric field profiles, or the electron and electric field profiles, the third profile can be evaluated directly through the Poisson equation (3.7). Then the required initial conditions can be written as

$$p(x,0),\ E(x,0),\ T(x,0)\ , \tag{3.18}$$

or

$$n(x,0),\ E(x,0),\ T(x,0) \tag{3.19}$$

These initial conditions are usually available through an approximate analytic solution or from a previous simulation.

Considerably more latitude exist with the spacial boundary conditions than with the initial conditions. Examining the system of equations for the mathematical model, (3.5) through (3.8), with respect to the highest order spacial derivative in each variable, seven boundary conditions are indicated. In this case, system coupling does not provide for a further reduction. The two continuity equations yield one second order derivative for each carrier type implying that two boundary conditions are required on each of the respective carrier concentrations. The Poisson equation has one first order spacial derivative of the electric field requiring one boundary condition on the electric field and the energy continuity equation requires two boundary conditions on temperature due to a second order spacial derivative of temperature.

The above seven boundary conditions are defined in conjunction with the particular application of the mathematical model. Table 3.1 presents four possible boundary condition systems which are considered most relevant to this study. In particular, for a second breakdown simulation it is desirable to drive the diode under study with a current source. This condition most accurately simulates the optimal experimental configuration [7] for investigating this phenomenon, and readily facilitates the

TABLE 3.1

BOUNDARY CONDITION SYSTEMS

Boundary Condition Systems		Type Boundary Condition	Technique for Incorporating Driving Function	
p-side contact	n-side contact		Current $J_T(t)$	Voltage $V_D(t)$
1) $J_p = J_T(t)$	$J_p = 0$	Current	Direct	Iterative
$J_n = 0$	$J_n = J_T(t)$			
$E = 0$	(or, $E = 0$)			
$T = T_o$	$T = T_o$			
2) $p = p_{po}$	$p = p_{no}$	Ohmic	Indirect	Iterative
$n = n_{po}$	$n = n_{no}$			
$E = E(t)$	(or, $E = E(t)$			
$T = T_o$	$T = T_o$			
3) $J_p = J_T(t)$	$p = p_{no}$	Hybrid	Direct	Iterative
$J_n = 0$	$n = n_{no}$			
$E = 0$	-----			
$T = T_o$	$T = T_o$			
4) $p = p_{po}$	$J_p = 0$	Hybrid	Direct	Iterative
$n = n_{po}$	$J_n = J_T(t)$			
-----	$E = 0$			
$T = T_o$	$T = T_o$			

comparison of the numerical simulation with experimental data. For a current source driving function the boundary conditions are defined by:

$$p(0,t) = f_{p0}[J_p(0,t),\ J_n(0,t)]\ , \tag{3.20}$$

$$n(0,t) = f_{n0}[J_p(0,t),\ J_n(0,t)]\ , \tag{3.21}$$

$$p(x_L,t) = f_{pL}[J_p(x_L,t),\ J_n(x_L,t)]\ , \tag{3.22}$$

$$n(x_L,t) = f_{nL}[J_p(x_L,t),\ J_n(x_L,t)]\ , \tag{3.23}$$

and either

$$E(0,t) = f_{E0}[J_p(0,t),\ J_n(0,t)]\ , \tag{3.24}$$

or

$$E(x_L,t) = f_{EL}[J_p(x_L,t),\ J_n(x_L,t)]\ . \tag{3.25}$$

The four boundary system cases presented in Table 3.1 along with equations (3.9) and (3.10) permit evaluation of the above relations.

Note that the mathematical model developed here does not readily facilitate the specification of a voltage source driving function. To implement this case with the present formulation would require an iterative procedure on the electric field boundary value at each time step

and would be quite inefficient with respect to computation time. This situation could be circumvented by reformulating the mathematical model in terms of voltage rather than electric field as a dependent variable.

3.1.4 Carrier Generation-Recombination Expressions

Carrier generation and recombination consist of thermal generation and recombination through defect centers and impact or avalanche ionization.

Thermal generation and recombination through defect centers are represented by the Shockley-Read-Hall single-level model, equation (3.11). This model characterizes defects with neutral and single-charge states.

Hole and electron generation through avalanche ionization is also included in equation (3.11). The ionization coefficients in this relation are strongly dependent upon the electric field and to a lesser extent temperature. This behavior is given by

$$\alpha_p(E,T) = a_p[1 - \beta(T-T_o)]\, e^{-b_p/E}, \qquad (3.26)$$

and

$$\alpha_n(E,T) = a_n[1 - \beta(T-T_o)]\, e^{-b_n/E} \qquad (3.27)$$

where for silicon

$$a_p = 3.8 \times 10^6 \text{ cm}^{-1},\ b_p = 1.75 \times 10^6 \text{ V cm}^{-1},\ a_n = 2.25 \times 10^7 \text{ cm}^{-1},$$

$$b_n = 3.26 \times 10^6 \text{ V cm}^{-1}. \qquad (3.28)$$

The above description of the ionization coefficients was derived from Sze's [8] characterization of these coefficients and represents an empirical approximation of their thermal dependence. The ionization thermal coefficient β has units of $(1/K^{\circ})$ and specifies a linear dependence on temperature. β is assigned a value of 10^{-4} and may be increased slightly to enhance the thermal dependence of the ionization coefficients. It should be emphasized that although this formulation for the thermal dependence of the ionization coefficients is not completely accurate, it does exhibit a reasonably good description of the thermal behavior of the coefficients. Moreover, this formulation is concise and readily implemented numerically. The electric field dependence of the hole and electron ionization coefficients as predicted by equations (3.26) and (3.27) is shown in Fig. 3.2.

3.1.5 Mobility Coefficient Formulation

The second breakdown phenomenon is generally characterized by large abrupt changes in electric field and temperature. Furthermore, most diode structures of interest in this area feature asymmetric impurity profiles. Since mobility is a rather sensitive function of impurity concentration, electric field and temperature it is necessary that the mobility coefficients be formulated in terms of these quantities. A thermally independent approximation of theoretical mobility [2] as a function of net impurity density N_I and electric field is given by

$$\mu(N_I,E) = \mu_o \left[1 + \frac{N_I}{N_I/S+N} + \frac{(E/A)^2}{E/A+F} + \left(\frac{E}{B}\right)^2\right] \qquad (3.29)$$

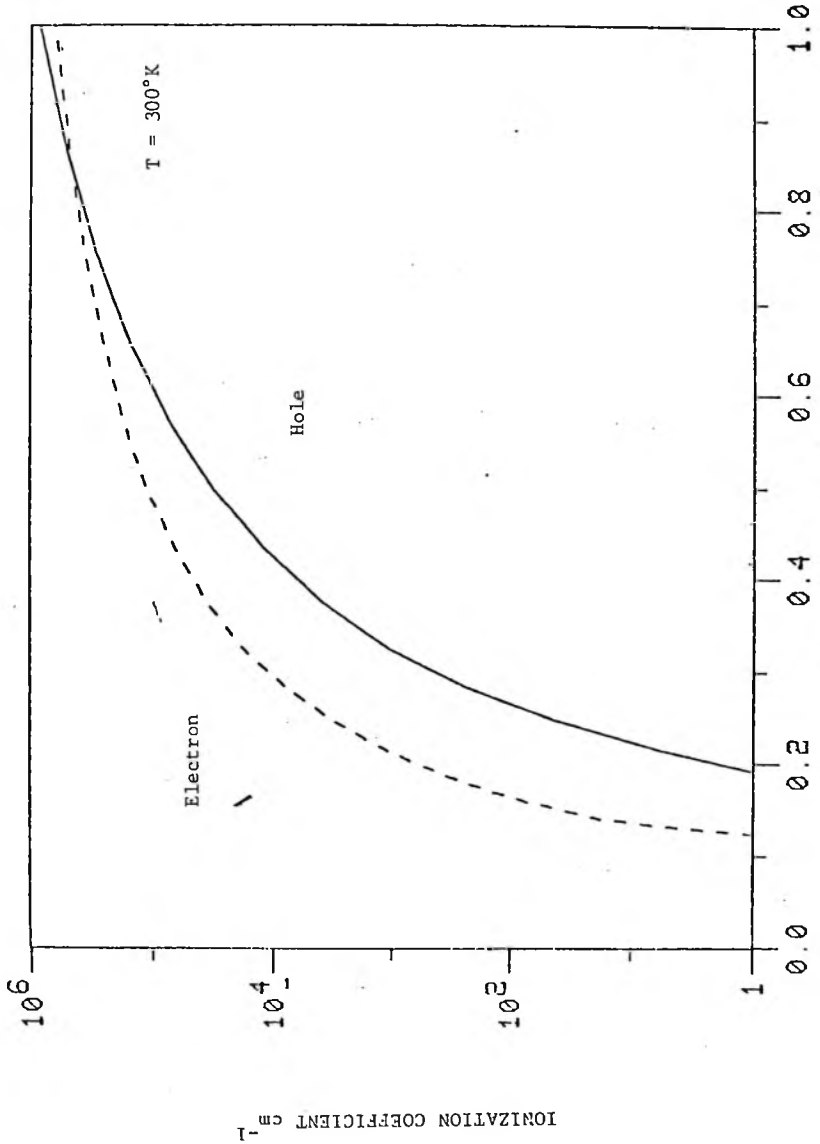


Fig. 3.2. Hole and Electron Ionization Coefficient Versus Electric Field

where

	μ_o	N	S	A	F	B
Holes	480	$4x10^{16}$	81	$6.1x10^{3}$	1.6	$2.5x10^{4}$
Electrons	1400	$3x10^{16}$	350	$3.5x10^{3}$	8.8	$7.4x10^{3}$

(3.30)

In actual practice the temperature variation of mobilities can usually be described by a power law [9], such as

$$\mu \propto T^{-\gamma} \tag{3.31}$$

where for silicon γ has been determined experimentally to be approximately equal to 5/2 for both holes and electrons. Then with this result mobility thermal dependence can be conveniently added to equation (3.29) to yield

$$\mu(N_I,E,T) = T^{-5/2}\, \mu(N_I,E). \tag{3.32}$$

The mobility behavior predicted by (3.32) is presented in Figs. 3.3 through 3.6.

3.1.6 Semiconductor Resistivity

The thermal behavior of semiconductor resistivity is critical to some aspects of thermal second breakdown theory. For this reason the thermal dependence of resistivity for the diode model is characterized.

Assuming thermal equilibrium conditions and fully ionizationed impurities, semiconductor resistivity as a function of net impurity concentration, electric field, and temperature is given by

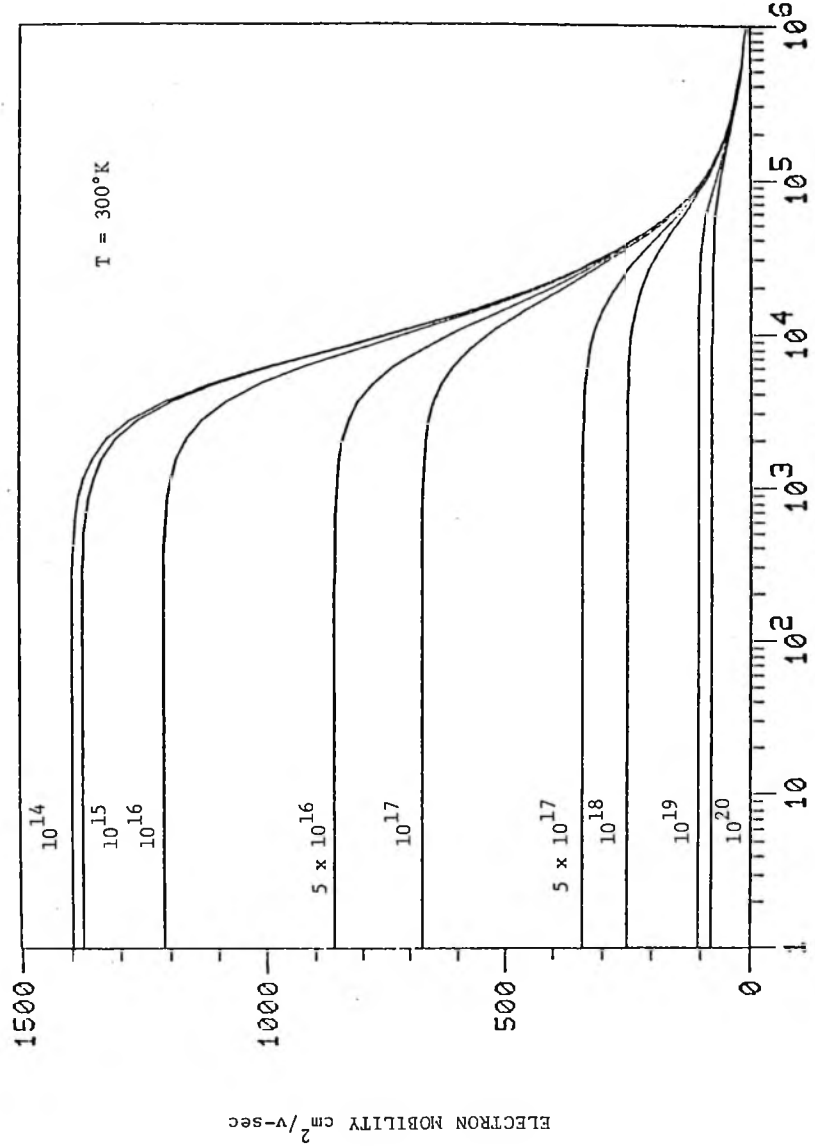


Fig. 3.3 Electron Mobility Versus Electric Field for Different Impurity Levels

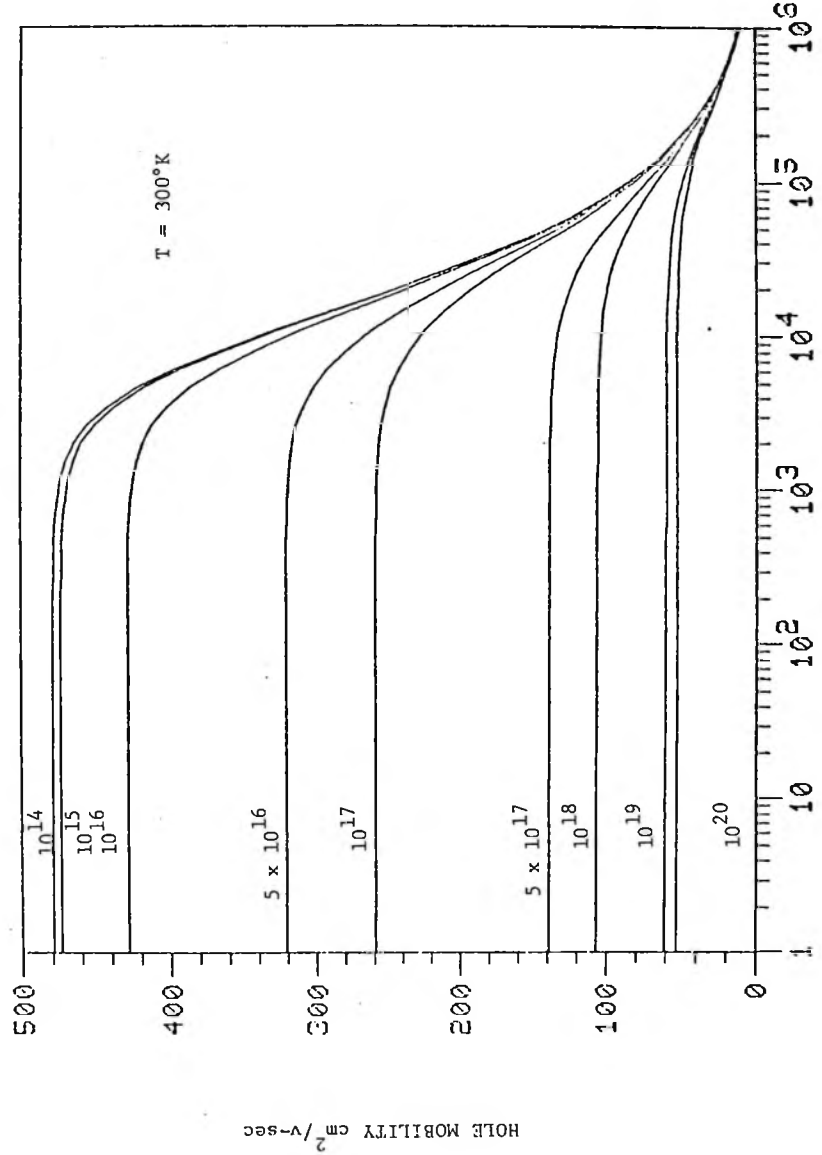


Fig. 3.4. Hole Mobility Versus Electric Field for Different Impurity Levels

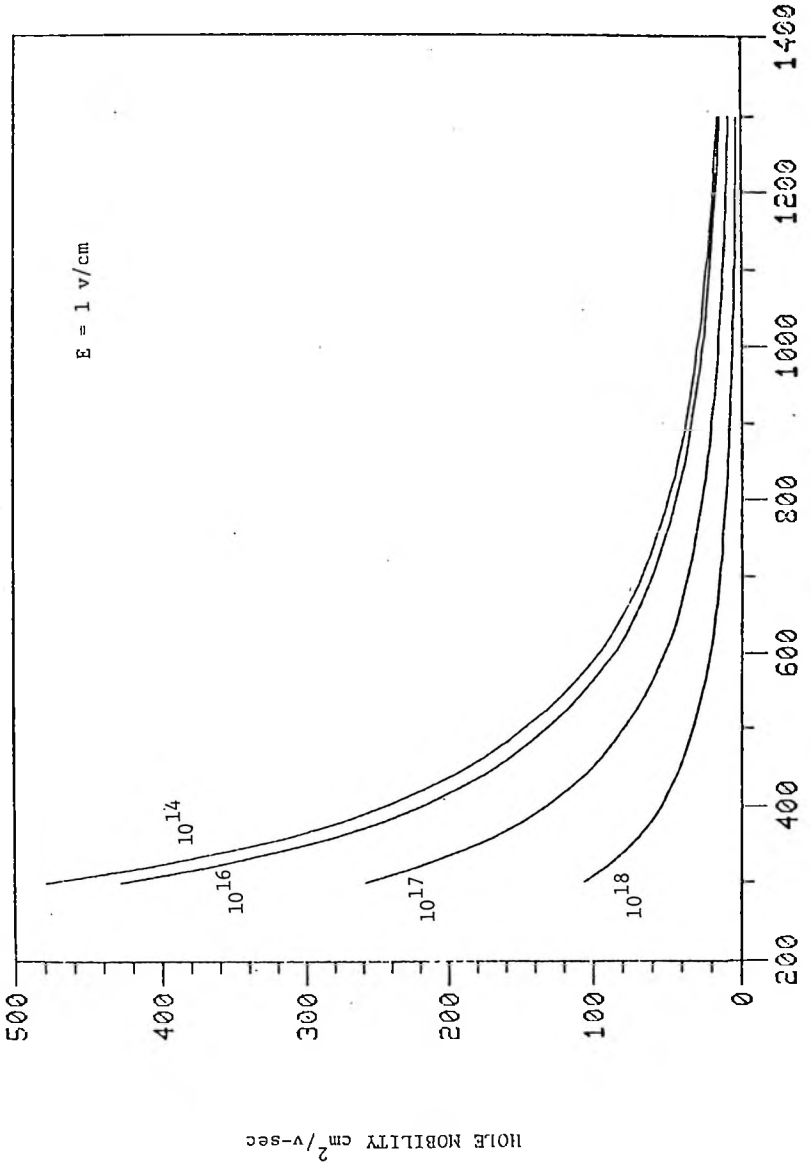


Fig. 3.5. Hole Mobility Versus Temperature for Different Impurity Levels

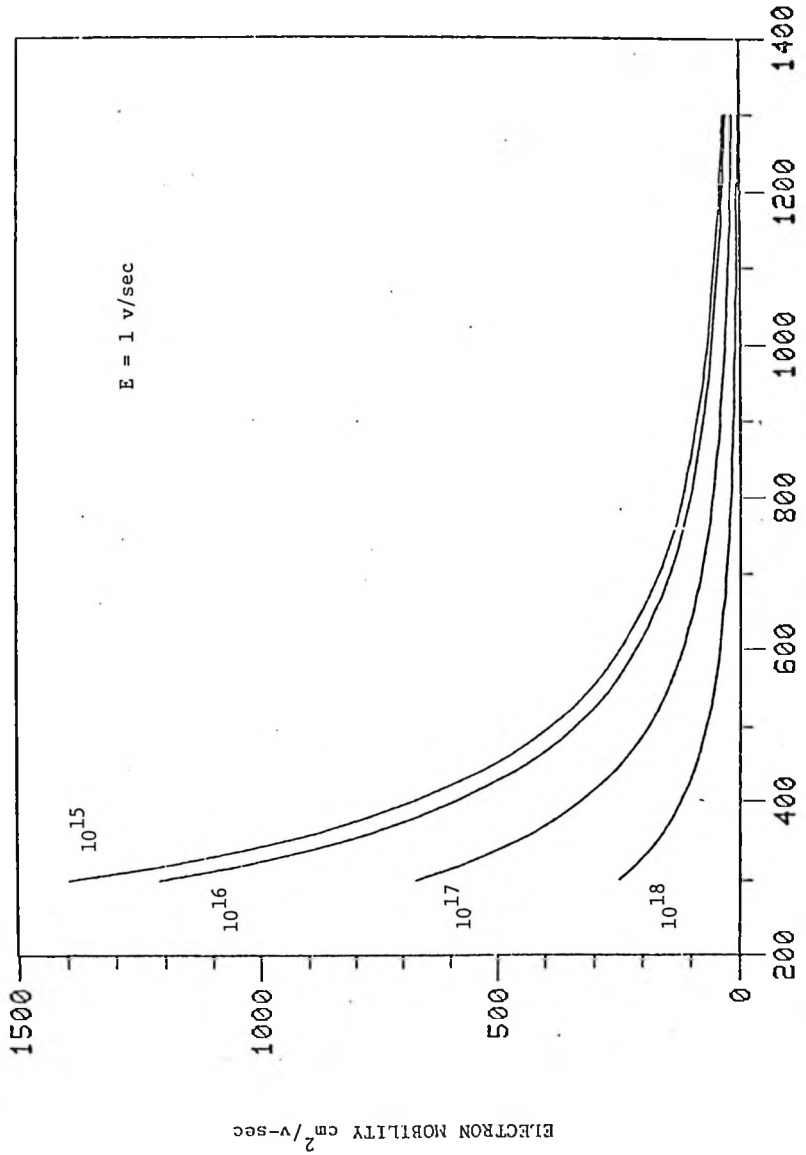


Fig. 3.6. Electron Mobility Versus Temperature for Different Impurity Levels

$$\rho_S(N_I,T,E) = \frac{1}{q[\mu_p(\frac{N_I}{2} + \surd) + \mu_n(-\frac{N_I}{2} + \surd)]} \qquad (3.33)$$

where

$$\surd = \sqrt{(\frac{N_I}{2})^2 + n_i^2} \; .$$

The mobilities are defined through equation (3.32) and the intrinsic carrier concentration by equation (3.15). The resistivity predicted by equation (3.33) is shown in Fig. 3.7 as a function of temperature for several different impurity levels.

Failure of these curves to converge smoothly for high temperature values is attributed to the approximate and equal values assigned to γ in the power law description, equation (3.31), of the hole and electron mobility thermal dependence. Better estimates, and not necessarily equal estimates, of γ should yield a corresponding improvement in the resistivity thermal behavior. However, for the purposes of this work the previously formulated mobility relations are employed.

3.1.7 Normalization of Mathematical Model

It is most convenient to normalize the system of equations composing the mathematical model for the purpose of simplicity during further mathematical manipulations and to reduce the number of algebraic operations required by the subsequent numerical solution procedure. Development of the normalization factors follows De Mari [10] except for the sign associated with the current normalization factor and the addition of several normalization factors pertaining to the energy continuity equation and the ionization relation for carrier generation.

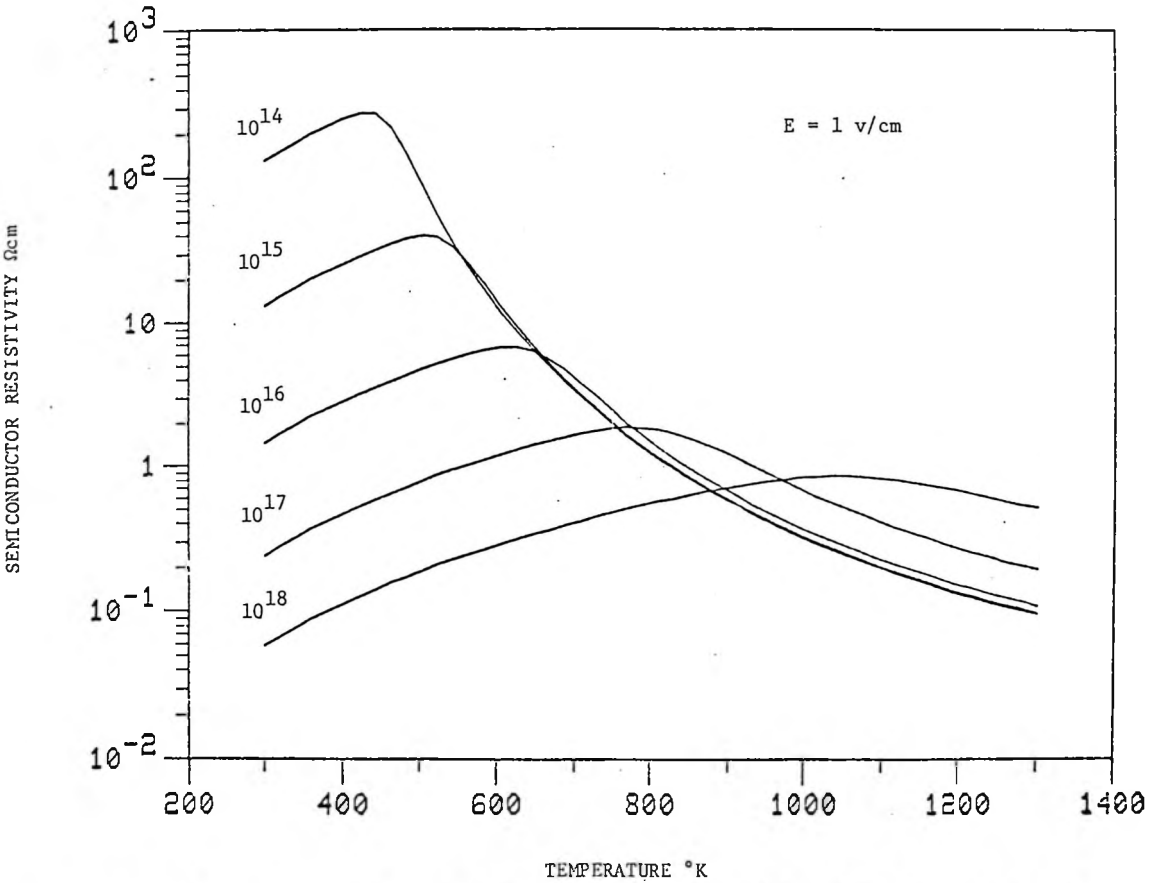


Fig. 3.7. Semiconductor Resistivity Versus Temperature for Different Impurity Levels

De Mari elected to negate the current normalization factor such as to yield a positive current under forward bias for his model configuration. In this work the current normalization factors are maintained positive, thereby, allowing the signs associated with the current components to be determined in the conventional manner.

A temperature normalization constant is added to account for the addition of temperature as a dependent variable. In addition, normalization factors are defined for the semiconductor thermal conductivity, specific heat, density, the substrate thermal conductivity, and the ionization coefficients. The subsequent normalization factors are listed in Table 3.2. The same symbols previously used for unnormalized variables will also be used for the normalized ones. For the remainder of this work all symbols will consistently represent normalized values unless stated otherwise.

Using the normalization constants in Table 3.2, the normalized, or dimensionless form of the mathematical model becomes:

$$\frac{\partial p(x,t)}{\partial t} = G_{gr}(x,t) - \frac{\partial J_p(x,t)}{\partial x} , \qquad (3.34)$$

$$\frac{\partial n(x,t)}{\partial t} = G_{gr}(x,t) + \frac{\partial J_n(x,t)}{\partial x} , \qquad (3.35)$$

$$\frac{\partial E(x,t)}{\partial x} = p(x,t) - n(x,t) + N_D(x) - N_A(x) , \qquad (3.36)$$

and

$$\frac{\partial T(x,t)}{\partial t} = \frac{1}{\rho c} \frac{\partial}{\partial x} [K_D(x,t) \frac{\partial T(x,t)}{\partial x}] + \frac{1}{\rho c} \Phi(x,t) \qquad (3.37)$$

TABLE 3.2

LIST OF NORMALIZATION FACTORS FOR DIODE MODEL PARAMETERS AND VARIABLES

Description	Normalized Quantity	Formulation	Computer Name	Value for Si
Position coordinate	x	$L_D = \sqrt{\epsilon V_t / qn_i}$	XN	3.41×10^{-3} cm
Time coordinate	t	L_D^2/D_o	TN	1.16×10^{-5} sec
Charge concentration	p, n, N_A, N_D	n_i	CARN	1.43×10^{10} cm^{-3}
Electric field intensity	E	V_t/L_D	EN	7.59 V cm^{-1}
Temperature	T	T_o	TEMPN	300° K
Current density	J_p, J_n, J_D	$qD_o n_i/L_D$	CURN	6.75×10^{-7} amp cm^{-2}
Voltage	V	$V_t = KT_o/q$	VN	2.59×10^{-2} V
Net generation-recombination	G	$D_o n_i/L_D^2$	RECN	1.24×10^{15} sec^{-1} cm^{-3}
Mobility coefficient	μ_p, μ_n	D_o/V_t	RMOBN	38.6 cm^2 sec^{-1} V^{-1}
Diffusion coefficient	D_p, D_n	D_o	DIFN	1.0 cm^2 sec^{-1}
Ionization coefficient	α_p, α_n	$1/L_D$	GIONN	2.93×10^2 cm^{-1}
Density coefficient	ρ	ρ_o	DENN	1.0 gm cm^{-3}
Specific heat	c	$qn_i V_t/T_o \rho_o$	SPHN	4.20×10^3 J/gm-K°
Thermal conductivity	K_D, K_H	$qn_i V_t D_o/T_o$	TCONN	4.20×10^3 W/cm-K°

where

$$J_p(x,t) = \mu_p(x,t)\ [p(x,t)\ E(x,t) - T(x,t)\ \frac{\partial p(x,t)}{\partial x}], \tag{3.38}$$

$$J_n(x,t) = \mu_n(x,t)\ [n(x,t)\ E(x,t) + T(x,t)\ \frac{\partial n(x,t)}{\partial x}], \tag{3.39}$$

$$G_{gr}(x,t) = \frac{n_i(x,t)^2 - p(x,t)n(x,t)}{[p(x,t)+n_i(x,t)]\tau_n + [n(x,t)+n_i(x,t)]\tau_p} + \alpha_p(x,t)|J_p(x,t)| + \alpha_n(x,t)|J_n(x,t)|, \tag{3.40}$$

$$\Phi(x,t) = |E(x,t)|\ [|J_p(x,t)| + |J_n(x,t)|] - \frac{K_H(x,t)}{\chi_{DT}\chi_{DH}}[T(x,t) - T_o], \tag{3.41}$$

$$J_T(t) = J_p(x,t) + J_n(x,t) + \frac{\partial E(x,t)}{\partial t}, \tag{3.42}$$

$$E(x,t) = -\frac{\partial V(x,t)}{\partial x}, \tag{3.43}$$

$$n_i(x,t) = \sqrt{N_v N_c}\ T(x,t)^{3/2}\ e^{-q\ E_g/[2KT(x,t)]}, \tag{3.44}$$

$$D_p(x,t) = \mu_p(x,t)\ T(x,t), \tag{3.45}$$

and

$$D_n(x,t) = \mu_n(x,t)\ T(x,t). \tag{3.46}$$

3.2 NUMERICAL MODEL

In this section a numerical solution for the mathematical diode model developed in the previous section is formulated. Finite difference techniques are used to discretize the system of equations and the generalized Crank-Nicolson implicit formulation is employed to improve numerical stability and accuracy. A further improvement in numerical stability is achieved through the use of current approximations, according to Scharfetter and Gummel [2], which facilitates a coarse spacial grid. The resulting model is characterized by a banded system of linear simultaneous equations which are solved for each incremental advancement in time during a simulation. The model is equally applicable to steady state generation through accelerated pseudo transients.

3.2.1 Designation of Spacial Grid and Model Geometry

Before casting the four fundamental equations of the mathematical model, (3.34) through (3.37), in terms of standard finite difference techniques a spacial grid must first be designated. Fig. 3.8 shows the grid structure to be used and one which has demonstrated utility for similar mathematical models through numerious applications [2,3,10]. The continuity equations and the Poisson equation are formulated about the N-nodes and thus associate the concentration variables with these nodes and the electric field with the M-nodes. The current terms are assigned to the M-nodes to facilitate the current derivative formulation in the continuity equations. Since the energy continuity equation requires values for the hole and electron currents, and the electric field, this equation is written about the M-node and assigns temperature to these nodes.

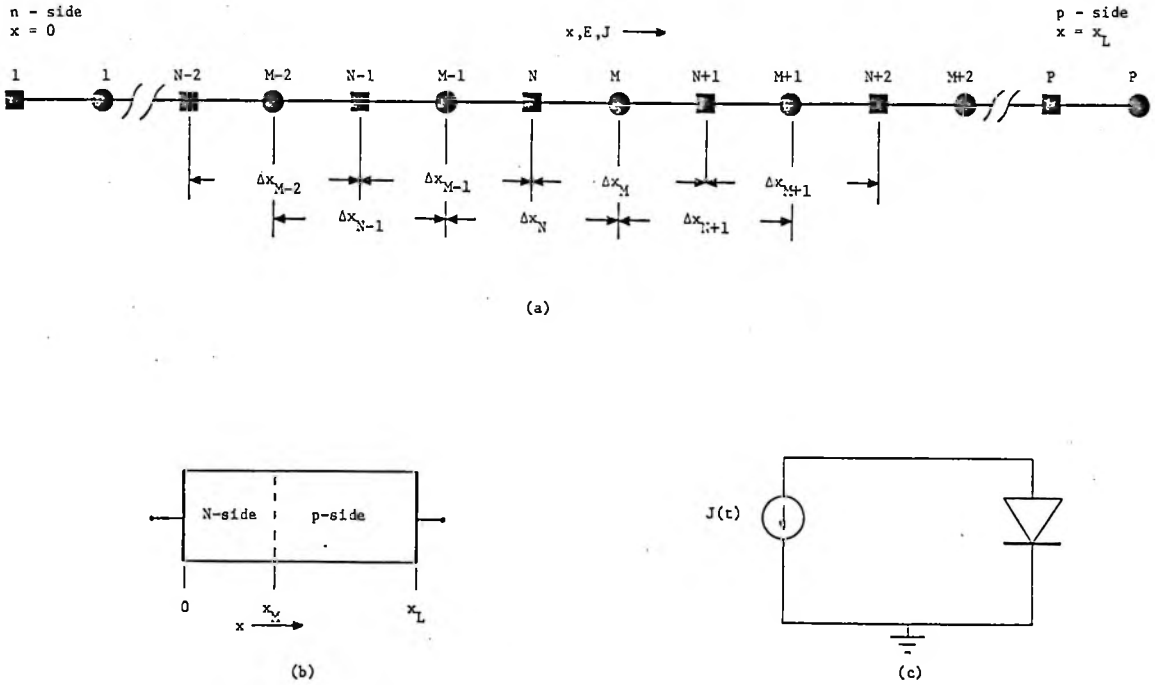


Fig. 3.8. (a) Numerical Diode Model Spacial Grid, (b) Physical Design and (c) External Circuit Configuration

The physical design of the diode model and the orientation of pertinent axes are superimposed on the spacial grid in Fig. 3.8. These conventions will be used throughout the remainder of this work. The np spacial configuration shown was adapted for the diode model, in lieu of an optional junction orientation, to minimize the model complexity. Model generality is maintained through symmetric current boundary conditions.

3.2.2 Finite Difference Formulation of the Mathematical Model

The four fundamental equations which compose the diode model are discretized through finite difference techniques [11] in conjunction with the spacial grid defined in the previous section. The unknowns in this formulation are the incremental changes in the dependent variables values Δp, Δn, ΔE, and ΔT over the respective time step. First consider the two continuity equations (3.34) and (3.35) which can be written directly in a finite difference form as

$$\frac{\Delta p(N)}{\Delta t} = G_{gr}(N,t) - \frac{J_p(M,t) - J_p(M-1,t)}{\Delta x(N)} , \qquad (3.47)$$

and

$$\frac{\Delta n(N)}{\Delta t} = G_{gr}(N,t) + \frac{J_n(M,t) - J_n(M-1,t)}{\Delta x(N)} . \qquad (3.48)$$

Next the Poisson equation is discretized and written in terms of the unknown variable values at the next point in time as

$$\frac{[E(M,t) + \Delta E(M,t)] - [E(M-1,t) + \Delta E(M-1,t)]}{\Delta x(N)} = [p(N,t) + \Delta p(N,t)]$$

$$- [n(N,t) + \Delta n(N,t)] + N_I(N) \ . \qquad (3.49)$$

Discretization of the energy continuity equation (3.37) through finite difference techniques is hampered by the nonlinear form of the second-order spacial derivative in this equation. However, this difficulty is overcome if rather than attempting to discretize equation (3.37) directly, the energy continuity equation is rederived in the finite difference form [12]. Consider first the definition of the energy continuity equation which may be written as

$$\begin{bmatrix}\text{Rate of energy}\\ \text{storage in V}\end{bmatrix} = \begin{bmatrix}\text{Rate of heat entering}\\ \text{V through its boundary}\\ \text{surfaces}\end{bmatrix} + \begin{bmatrix}\text{Rate of heat}\\ \text{generation in}\\ \text{V}\end{bmatrix} \qquad (3.50)$$

Employing similar procedure as was used to derive the net power density factor, equation (3.2), the energy continuity equation, in finite difference form becomes

$$\frac{\Delta T(M)}{\Delta t} = \frac{-K_D(M,t)}{\rho c \Delta x(M)} \ \frac{T(M,t) - T(M-1,t)}{\Delta x(N)}$$

$$+ \frac{K_D(M,t)}{\rho c \Delta x(M)} \ \frac{T(M+1,t)-T(M,t)}{\Delta x(N+1)} \ - \frac{K_H(M,t)}{x_{DT}\rho c} \ \frac{T(M,t)-T_o}{x_{HT}}$$

$$+ \frac{1}{\rho c} \ |E(M,t)| \ [|J_p(M,t)| + |J_n(M,t)|] \ . \qquad (3.51)$$

By comparing equation (3.51) with equation (3.37) it is apparent that the above discretization procedure changed only the equivalent finite difference form of the nonlinear second-order spacial derivative term in equation (3.37). This alternate discretization procedure also maintains the generality of the spacial grid in that it does not restrict the model to a uniform spacial grid. The nonuniform spacial grid feature for a reverse bias diode simulation is quite desirable in view of the potentially dynamic spacial behavior for this type simulation.

For the formulation of the numerical model the thermal conductivity for the semiconductor material and the thermal conductivity for the substrate material are assumed constant. This assumption is made to simplify the implementation of the numerical model and not as a consequence of any limitations associated with the numerical technique employed. The computer program version of the numerical model will accept modifications to restore these coefficients to a variable status dependent upon both position and time.

The resulting discretized version of the four fundamental equations are summarized in functional form as:

$$\frac{\nabla p(N,t)}{\nabla t} = F_p[p(N-1,t),n(N-1,t),E(M-1,t),T(M-1,t),p(N,t),n(N,t),E(M,t),$$
$$T(M,t),p(N+1,t),n(N+1,t)] , \qquad (3.52)$$

$$\frac{\nabla n(N,t)}{\nabla t} = F_n[p(N-1,t),n(N-1,t),E(M-1,t),T(M-1,t),p(N,t),n(N,t),E(M,t),$$
$$T(M,t),p(N+1,t)n(N+1,t)] , \qquad (3.53)$$

$$- \Delta E(M-1,t) - \Delta x(N)\,\Delta p(N,t) + \Delta x(N)\,\Delta n(N,t) + \Delta E(M,t) =$$

$$F_E[E(M-1,t),p(N,t),n(N,t),E(M,t)] \ , \qquad (3.54)$$

and

$$\frac{\Delta T(M,t)}{\Delta t} = F_T[T(M-1,t),p(N,t),n(N,t),E(M,t),T(M,t),p(N+1,t),$$

$$n(N+1,t),T(M+1,t)] \qquad (3.55)$$

where the unknown variable values at the next point in time are given by

$$p(N,t + \Delta t) = p(N,t) + \Delta p(N,t) \ , \qquad (3.56)$$

$$n(N,t + \Delta t) = n(N,t) + \Delta n(N,t) \ , \qquad (3.57)$$

$$E(M,t + \Delta t) = E(M,t) + \Delta E(M,t) \ , \qquad (3.58)$$

and

$$T(M,t + \Delta t) = T(M,t) + \Delta T(M,t) \ . \qquad (3.59)$$

3.2.3 Generalized Crank-Nicolson Formulation

The discretized equations (3.47) through (3.51) represent an explicit formulation of the diode model. This type of finite difference formulation is characterized by stability limitations [13] which restrict

the size of time step Δt for a given value of Δx, i.e., if the space step Δx is to be chosen small to improve accuracy and the simulation performed over a large period of time, the computational load becomes prohibitive. Fortunately, an alternative formulation, the generalized Crank-Nicolson implicit technique [14], alleviates this problem at the expense of a modest increase in the computational load. Unlike the explicit formulation which features a straight forward evaluation of the variable values for the next point in time, the implicit technique requires a simultaneous solution for all variable values. However, this increased complexity is more than compensated for through improved stability which allows for greatly increased time step increments and a reduced truncation error.

The Generalized Crank-Nicolson technique employs a weighted average between the respective values, at times t and $t+\Delta t$, for the functional terms in equations (3.52) through (3.55). Upon applying this technique, the finite difference form for the diode model becomes

$$\frac{\Delta p(N,t)}{\Delta t} = (1 - \theta)\, F_p(N,t) + \theta\, F_p(N,t + \Delta t)\ , \qquad (3.60)$$

$$\frac{\Delta n(N,t)}{\Delta t} = (1 - \theta)\, F_n(N,t) + \theta\, F_n(N,t + \Delta t)\ , \qquad (3.61)$$

$$- \Delta E(M-1,t) - \Delta x(N)\Delta p(N,t) + \Delta x(N)\Delta n(N,t) + \Delta E(M,t) = F_E(M,t)\ , \qquad (3.62)$$

and

$$\frac{\Delta T(M,t)}{\Delta t} = (1 - \theta)\ F_T(M,t) + \theta\ F_T(M,t + \Delta t) \qquad (3.63)$$

where $0 \leq \theta \leq 1$. For $\theta = 0$, the above equations revert to the explicit form with inherent instability, and for $\theta = 1$, a purely implicit formulation results which exhibits a considerably improved stability. A balance between optimum stability and a low truncation error is usually achieved by $\theta = 0.5$.

Note that the Poisson equation (3.62), having been previously written in terms of the unknown variable values at the next point in time, is omitted from the above transition and retains the same form as equation (3.54).

3.2.4 Linearization of the Numerical Model

The functional terms evaluated at $t+\Delta t$ in the implicit diode model, equations (3.60) through (3.63), contain unknown dependent variable values that in some cases appear in nonlinear form. The linear occurrances of these values are written directly in terms of the system unknowns, or incremental changes in the dependent variables across the respective time step, by equations (3.56) through (3.59). On the other hand, the nonlinearities are resolved through first order Taylor series expansions in the respective dependent variable values.

Applying this procedure to the hole continuity equation (3.60) yields the following linear version

$$\frac{\Delta p(N,t)}{\Delta t} = (1 - 0)\, F_p(N,t) + \theta \left\{ F_p(N,t) + \Delta p(N-1,t) \frac{\partial F_p(N,t)}{\partial p(N-1,t)} \Big|_t + \right.$$

$$\left. \Delta E(M-1,t) \frac{\partial F_p(N,t)}{\partial E(M-1,t)} \Big|_t + \text{-----} \right\} , \qquad (3.64)$$

which can be reduced directly to the simplier form

$$\frac{\Delta p(N,t)}{\theta\, \Delta t} = \frac{1}{\theta} F_p(N,t) + \Delta p(N-1,t) \frac{\partial F_p(N,t)}{\partial p(N-1,t)} \Big|_t +$$

$$\Delta E(M-1,t) \frac{\partial F_p(N,t)}{\partial E(M-1,t)} \Big|_t + \text{-----} . \qquad (3.65)$$

Using this procedure to linearize the two additional equations (3.61) and (3.63), the final form of the system of equations for the numerical diode model can be summarized as:

$$\frac{1}{\theta \Delta t} \Delta p(N,t) = \frac{1}{\theta} F_p(N,t) + \Delta p(N-1,t) \frac{\partial F_p(N,t)}{\partial p(N-1,t)} \Big|_t + \text{-----} ,$$

(3.66)

$$\frac{1}{\theta \Delta t} \Delta n(N,t) = \frac{1}{\theta} F_n(N,t) + \Delta n(N-1,t) \frac{\partial F_n(N,t)}{\partial n(N-1,t)} \Big|_t + \text{-----} ,$$

(3.67)

$$- \Delta E(M-1,t) - \Delta x(N) \Delta p(N,t) + \Delta x(N) \Delta n(N,t) + \Delta E(M,t) = F_E(M,t) ,$$

(3.68)

and

$$\frac{1}{\theta\Delta t}\,\Delta T(M,t) = \frac{1}{\theta}\,F_T(M,t) + \Delta T(M-1,t)\,\frac{\partial\, F_T(M,t)}{\partial\, T(M-1,t)}\Bigg|_t + \text{-----}\ . \tag{3.69}$$

Or, in matrix form as:

$$\left\{\left[\frac{1}{\theta\Delta t}\right]\left[I\right] - \left[\frac{\partial F_{ij}}{\partial Y_j}\right]\right\}\left[\Delta Y_j\right] = \frac{1}{\theta}\left[F_i\right]\ . \tag{3.70}$$

Fig. 3.9 shows the detailed structure of the above coefficient matrix and demonstrates the banded form of this system of linear equations. Formulation for the required coefficients is presented in Appendix A.

3.2.5 Current Approximations

Normally the hole and electron current density components would be evaluated from finite difference forms of the current density equations (3.38) and (3.39). These relations, however, exhibit instability under low current conditions when the voltage drop between adjacent nodes is equal to or in excess of 2KT/q [4]. For most simulations, and especially reverse bias, an excessive number of grid points are required to overcome this instability.

An improved finite difference approximation [2] can be obtained by considering the current density expressions as differential equations in p(x) and n(x) and integrating them between adjacent node points. This is achieved for the hole current density equation (3.38) by assuming the

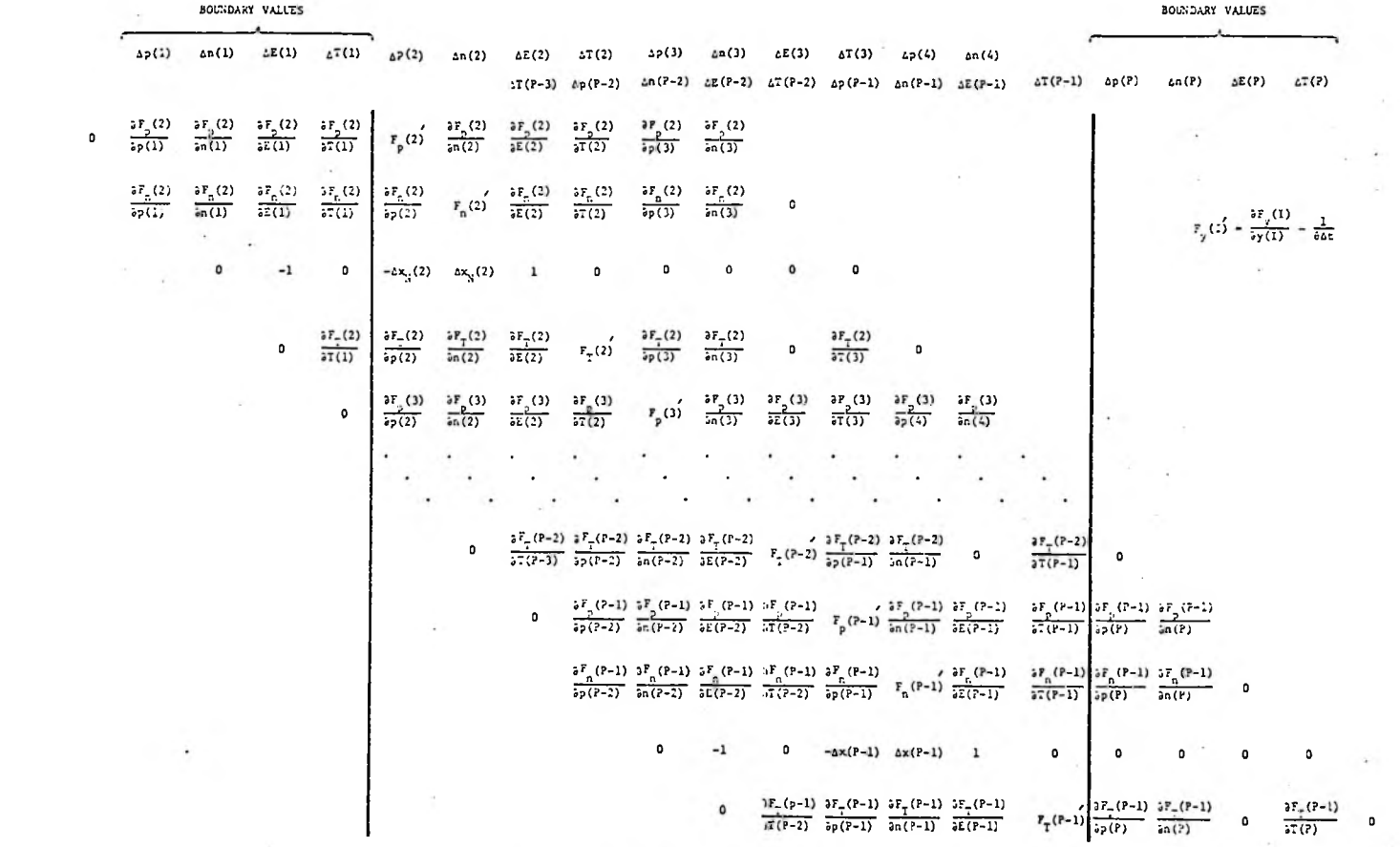


Fig. 3.9. Coefficient Matrix for Equation (3.70)

mobility, current densities, temperature, and electric field between the N-node points constant and rewriting equation (3.38) as

$$\frac{\partial p(x,t)}{\partial x} - \frac{E(M,t)p(x,t)}{T(M,t)} = -\frac{J_p(M,t)}{\mu_p(M,t)T(M,t)} , \qquad (3.71)$$

and integrating between consecutive N-nodes to yield

$$\int_N^{N+1} \frac{\partial}{\partial x}\left[p(x,t)\, e^{-\frac{E(M,t)}{T(M,t)}x}\right] dx = -\int_N^{N+1} \frac{J_p(M,t)}{\mu_p(M,t)T(M,t)}\, e^{-\frac{E(M,t)}{T(M,t)}x}\, dx , \qquad (3.72)$$

where

$$J_p(M,t) = \mu_p(M,t)E(M,t)\left[\frac{p(N+1,t)}{\left[1 - e^{-\frac{\Delta x(M)E(M,t)}{T(M,t)}}\right]} + \frac{p(N,t)}{\left[1 - e^{\frac{\Delta x(M)E(M,t)}{T(M,t)}}\right]}\right] . \qquad (3.73)$$

Through a similar procedure the electron current becomes:

$$J_n(M,t) = \mu_n(M,t)E(M,t)\left[\frac{n(n+1,t)}{\left[1 - e^{\frac{\Delta x(M)E(M,t)}{T(M,t)}}\right]} + \frac{n(N,t)}{\left[1 - e^{-\frac{\Delta x(M)E(M,t)}{T(M,t)}}\right]}\right] . \qquad (3.74)$$

These equations provide numerically stable estimates of current density under all conditions. If the term $\Delta x(M)E(M,t)/T(M,t)$ is small, these equations approach the standard difference form of the diffusion

current, whereas, when it is large, they approach the drift current density. Numerically, however, these expressions are difficult to evaluate for very low electric field values. Under these conditions the respective Taylor series expansions of these relations are used and are as follows:

$$J_p(M,t) = \frac{\mu_p(M,t)T(M,t)}{\Delta x(M)} [g\ p(N+1,t) + h\ p(N,t)], \quad (3.75)$$

and

$$J_n(M,t) = \frac{\mu_n(M,t)T(M,t)}{\Delta x(M)} [h\ n(N+1,t) + g\ n(N,t)] \quad (3.76)$$

where

$$\lambda = \Delta x(M)E(M,t)/T(M,t) , \quad (3.77)$$

$$g = -1 + \frac{\lambda}{2} - \frac{\lambda^2}{12} , \quad (3.78)$$

and

$$h = 1 + \frac{\lambda}{2} + \frac{\lambda^2}{12} . \quad (3.79)$$

3.2.6 Finite Difference Formulation of Boundary Conditions

Of the four boundary condition systems shown in Table 3.1 only the two hybrid cases can be implemented directly for a current driving function. For these cases the carrier concentration values at one contact are set equal to their thermal equilibrium values; thus simulating

an ohmic contact. At the opposite contact a current boundary condition is specified and the electric field is set equal to zero, i.e., the currents at this contact are restricted to diffusion currents. Then since the minority carrier current is assigned a value of zero at this contact, the minority carrier concentration gradient must be equal to zero. The current driving function is incorporated by specifying the contact majority carrier concentration through the finite difference relation for the majority carrier diffusion current which is equal to the total current.

The current boundary condition system, which features current boundary conditions at both contacts, is formulated similarly to the single current boundary condition for the hybrid system described above. In this case, however, electric fields at both contacts are assumed zero. Since only one boundary condition is allowed for the electric field, one contact features an implicit specification of the electric field. The validity of this condition is most easily assessed by monitoring the electric field value at this contact during simulations; large deviations from zero would indicate difficulties.

The ohmic boundary condition system is the most difficult of the three systems to implement for a current driving function. For this system the carrier concentrations at both contacts are assigned their thermal equilibrium values. The difficulty arises in calculating the electric field boundary condition which will yield the specified total current. This procedure requires the solving of a transendental equation at each time step, since the current approximations are nonlinear functions of electric field.

As a consequence of the additional complexity associated with the formulation of the ohmic boundary condition system, it is not included in the computer program implementation of the numerical model. The hybrid and current boundary condition systems are incorporated directly in the program on an optional and default bases respectively. Furthermore, since the numerical model is formulated in terms of incremental changes in the dependent variables, the boundary conditions must also be formulated in this manner according to equations (3.56) through (3.59). Then a constant boundary value for a dependent variable translates to a zero incremental value for the corresponding system unknown and the specification of a zero gradient boundary condition requires the appropriate change in the respective boundary value to perpetuate this condition. Moreover, a time dependent boundary value, such as required to implement a driving function, must be formulated in terms of a time dependent incremental boundary value.

The expressions required for evaluation of the contact incremental carrier concentrations values for the above described current boundary conditions and for the np junction configuration adopted for the mumerical model are as follows:

$x = 0$:

$$\nabla p(1,t) = \nabla p(2,t) + p(2,t) - p(1,t) \ , \tag{3.80}$$

$$\nabla n(1,t) = \nabla n(2,t) + [n(2,t) - n(1,t) - \frac{\nabla x_M(1)}{\mu_n(1,t)T(1,t)} J_T(t)] \tag{3.81}$$

$x = x_L$:

$$\Delta p(P,t) = \Delta p(P-1,t) + [p(P-1,t) - p(P,t) - \frac{\Delta x_M(P-1)}{\mu_p(P-1,t)T(P-1,t)} J_T(t)] \ , \tag{3.82}$$

and

$$\Delta n(P,t) = \Delta n(P-1,t) + n(P-1,t) - n(P,t) \ . \tag{3.83}$$

3.2.7 Solution Procedure

A flow chart for the general solution procedure of the numerical diode model developed in this chapter is shown in Fig. 3.10. Initially the diode design parameters and the simulation control parameters must be specified to define the simulation. From this data dependent variable profiles are then generated for initial conditions; unless, appropriate profiles are available from a previous run. With the initial conditions established, the time-step loop is entered wherein each cycle moves the simulation through time by one time increment. These discrete advancements in time are made by solving the matrix equation (3.70) which completely describes the diode behavior over each time step. Once the time step loop has been cycled through a sufficient number of times to complete the simulation, the resulting diode state is stored for potential use as an initial state for a subsequent simulation.

Appendix B presents a detailed account of the computer programs used to implement the numerical diode model formulated.

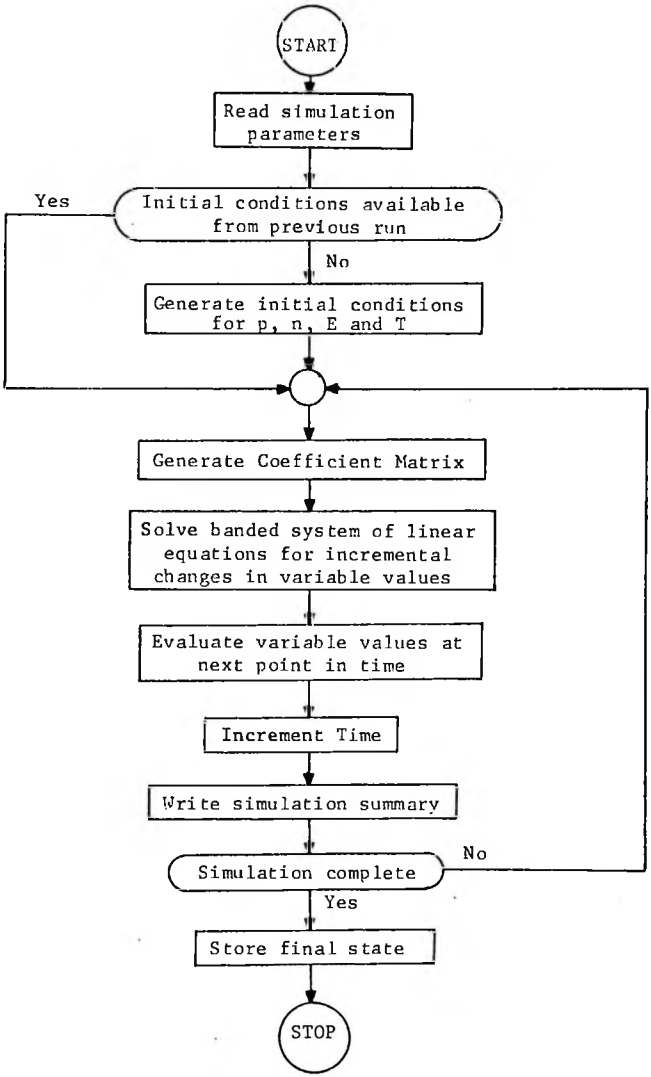


Fig. 3.10. Solution Procedure Flow Chart

CHAPTER 4

RESULTS AND CONCLUSIONS

Thermal second breakdown is simulated using the previously developed numerical diode model. The subsequent diode behavior is described and conclusions are drawn with respect to the physics of thermal second breakdown. Finally, recommendations for further study are presented.

4.1 SIMULATION OF THERMAL SECOND BREAKDOWN

The computer program version of the numerical diode model developed in Chapter 3 is used to simulate thermal second breakdown. The simulation parameters and diode design for this simulation are summarized in Table 4.1. An abrupt impurity profile is specified with a donor concentration of 10^{17} and an acceptor concentration of 10^{16}. The junction is located 3 μm from the n-side contact and the diode length is 10 μm. Although a more asymmetric impurity profile and a longer diode structure are desirable, the above values are chosen as a consequence of the uniform spacial grid restriction for the present version of the computer model. Under this restriction increases in diode length are accompanied by a uniform decrease in the spacial grid resolution since the number of gird points is limited to 101 or less. The 10 μm diode length is chosen to insure that several grid points fall within the depletion

TABLE 4.1

DIODE DESIGN AND SIMULATION PARAMETERS FOR
THE THERMAL SECOND BREAKDOWN SIMULATION

Material	Silicon
Number of Spacial Grid Points	101
Substrate Temperature	300° K
Type Junction	Abrupt
Dimensions	Total length - 10 μm Junction depth - 3.0 μm Semiconductor width - 0.1 μm Semiconductor thickness - 0.1 μm Substrate thickness - 1.0 μm
Doping Profile	Donor concentration - 10^{17} cm^{-3} Acceptor concentration - 10^{16} cm^{-3}
Lifetime	$\tau_p = \tau_n = 1.0 \times 10^{-9}$
Ionization Temperature Coefficient	2.5×10^{-3} 1/K°
Thermal Conductivity	Semiconductor - 5×10^{-7} watt/cm-K° Substrate - 5×10^{-7} watt/cm-K°
Semiconductor Specific Heat	0.7 J/gm-K°
Semiconductor Density	2.3 gm/cm^3
Constant Current Source Amplitude	10 $amps/cm^2$

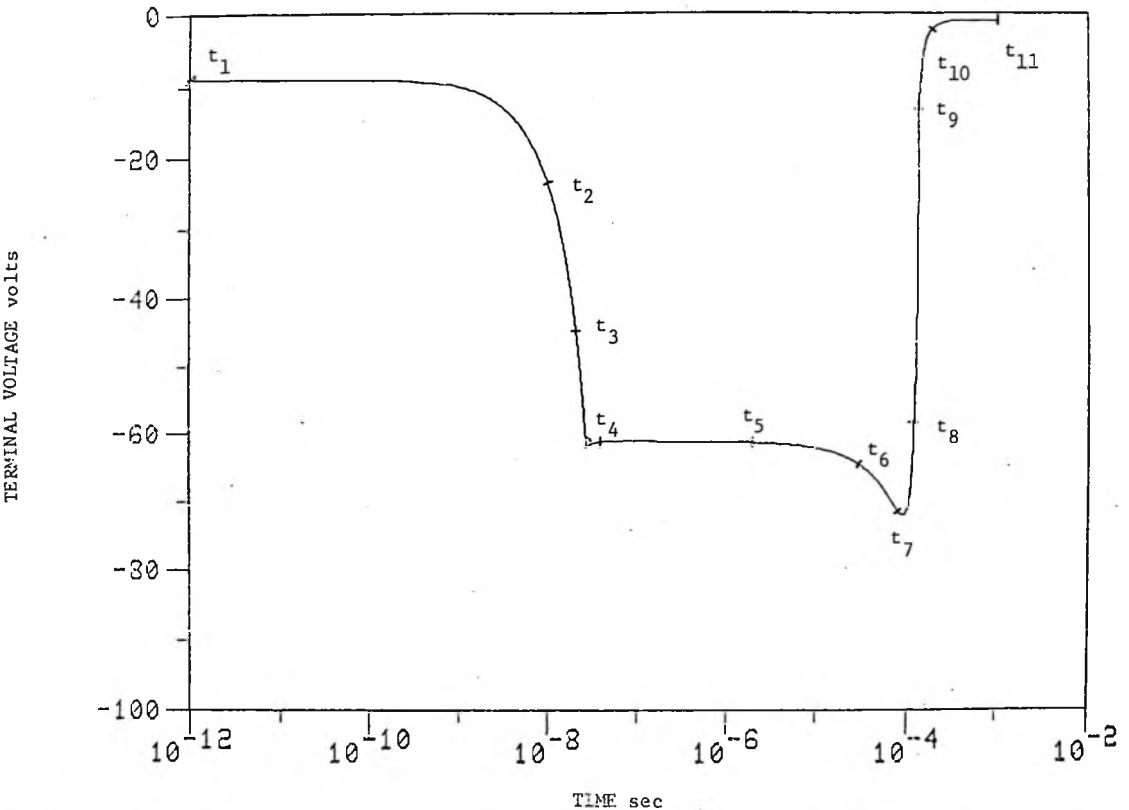


Fig. 4.1. Terminal Voltage as a Function of Time with Transient Reference Points at t_1 through t_{11} (t_1=0.0, t_2=1.0x10^{-8}, t_3=2.0x10^{-8}, t_4=5.06x10^{-8}, t_5=3.0x10^{-6}, t_6=4.0x10^{-5}, t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_9=1.35x10^{-4}, t_{10}=1.78x10^{-4}, t_{11}=1.11x10^{-3} - sec).

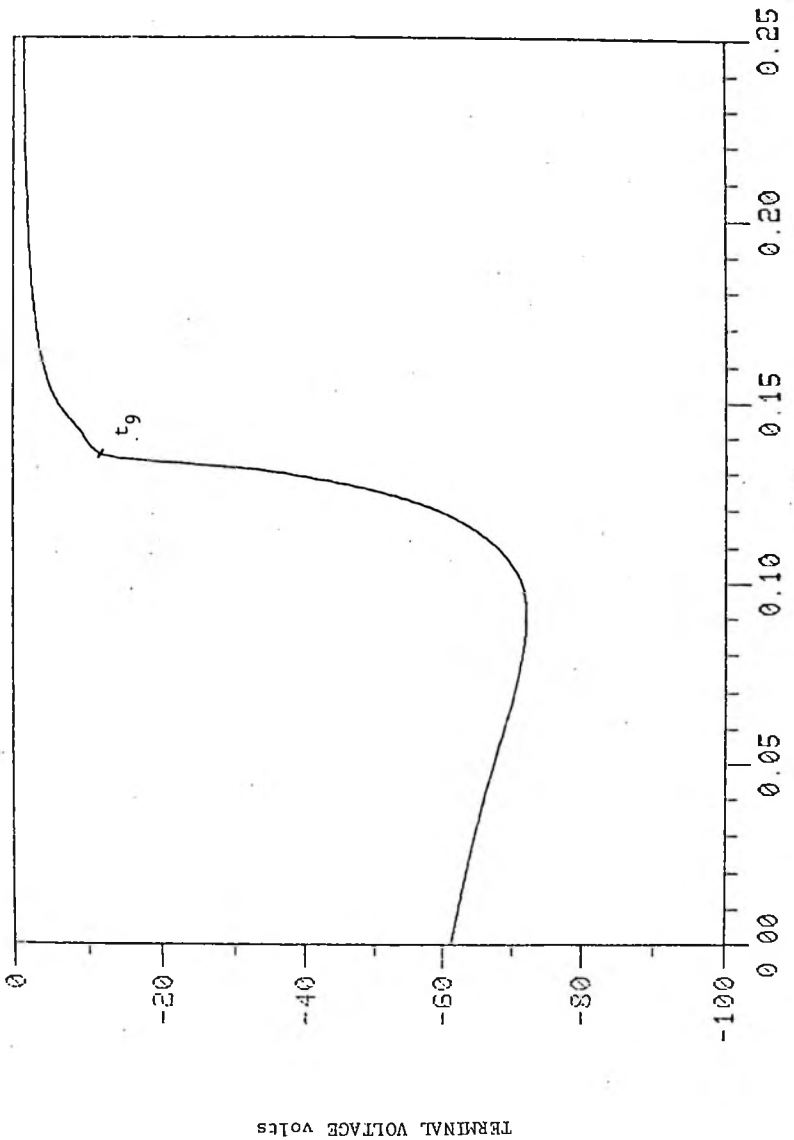


Fig. 4.2. Terminal Voltage as a Function of Time (t_9=1.35x10^{-4} sec).

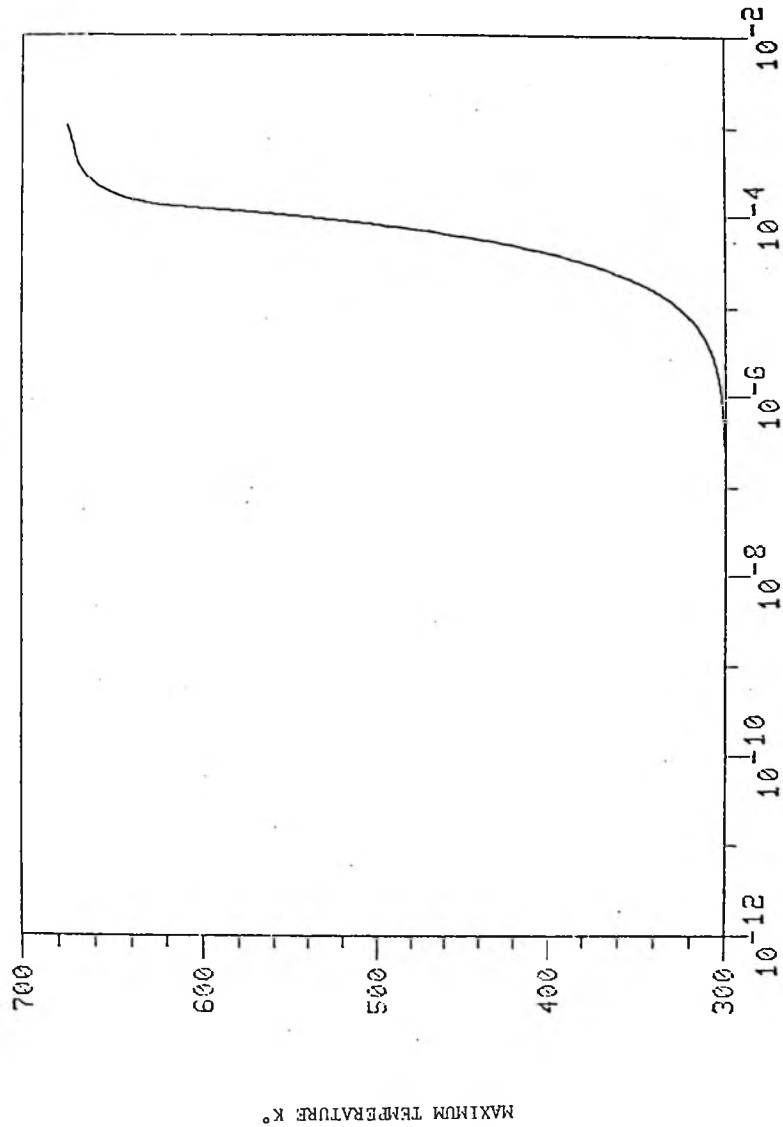


Fig. 4.3. Maximum Temperature as a Function of Time.

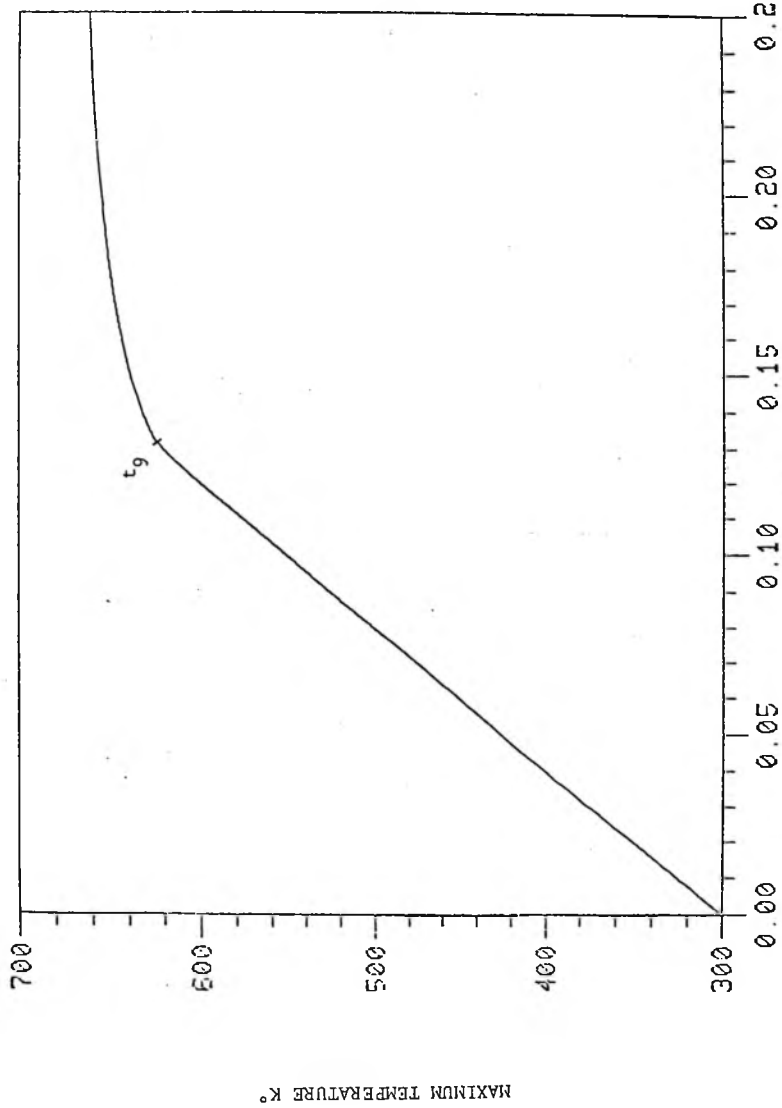


Fig. 4.4. Maximum Temperature as a Function of Time (t_g=1.35x10^{-4} sec).

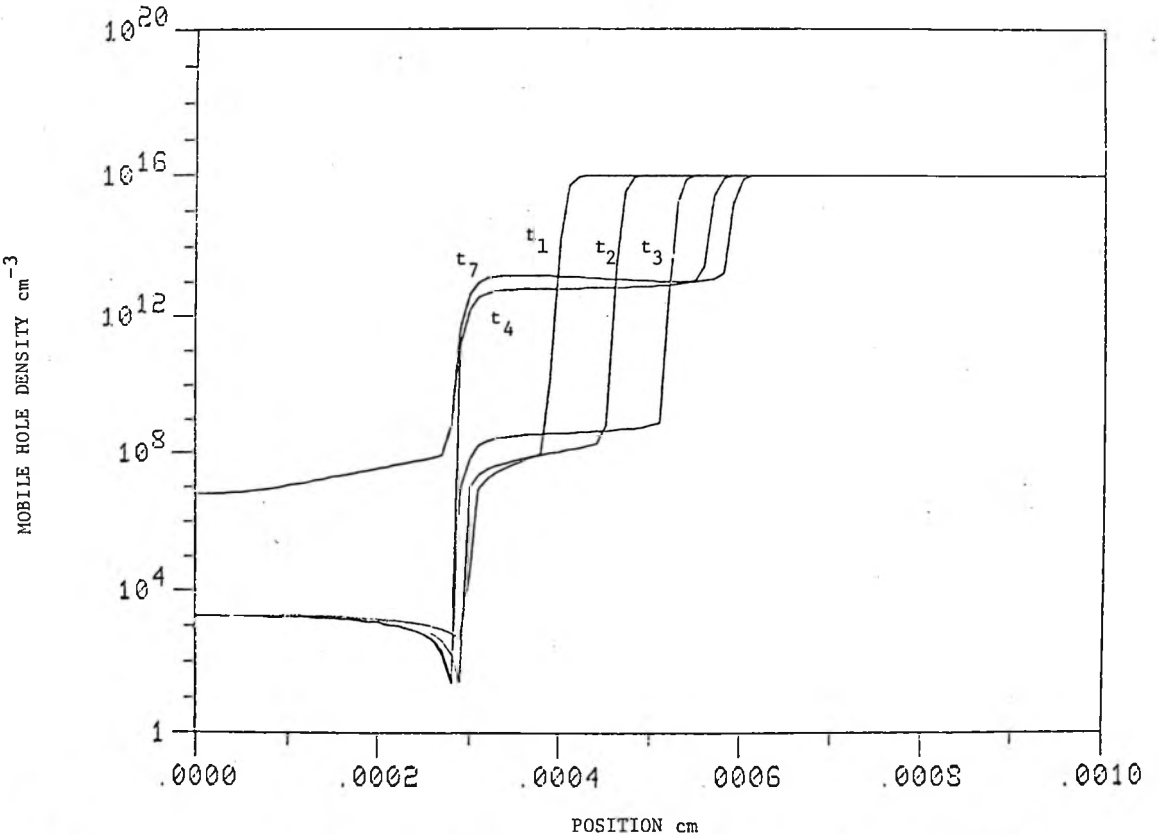


Fig. 4.5. Mobile Hole Density as a Function of Position at Various Instants of Time Prior to the Onset of Thermal Second Breakdown (t_1=0.0, t_2=1.0x10^{-8}, t_3=2.0x10^{-8}, t_4=5.06x10^{-8}, t_7=7.82x10^{-5} - sec).

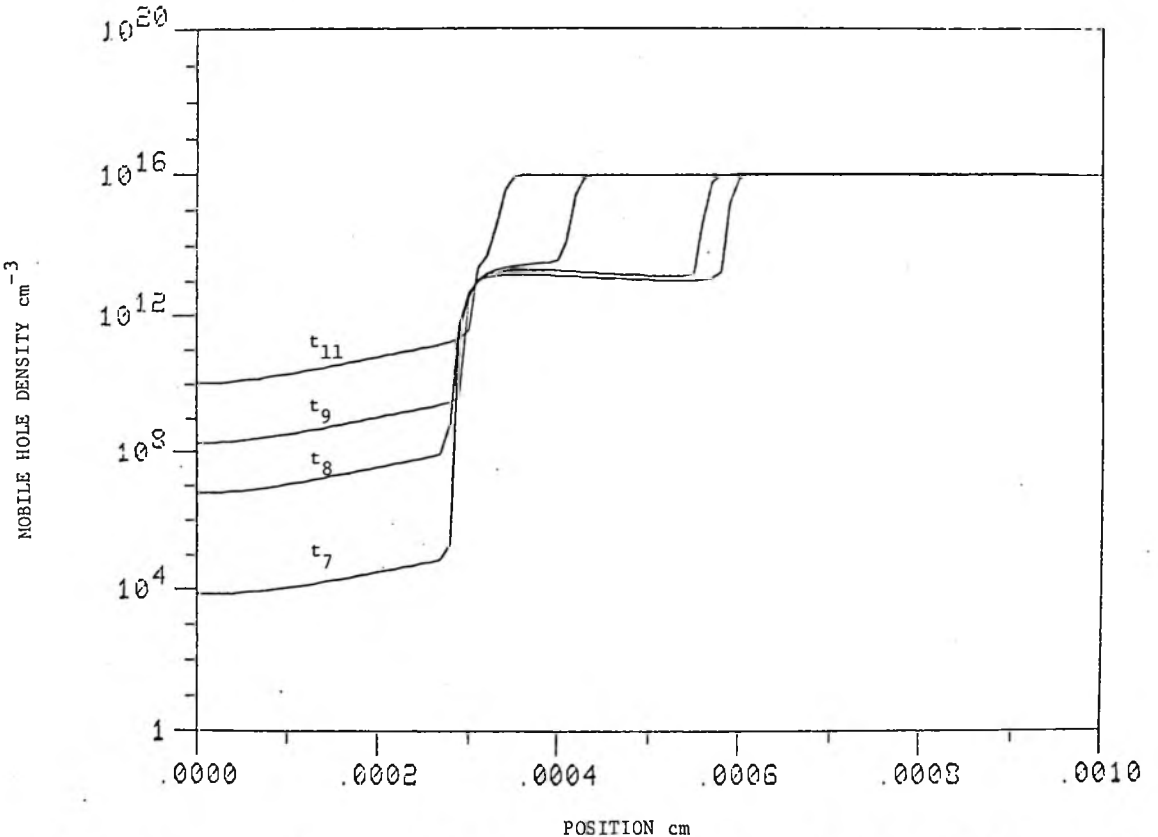


Fig. 4.6. Mobile Hole Density as a Function of Position at Various Instants of Time After the Onset of Thermal Second Breakdown (t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec).

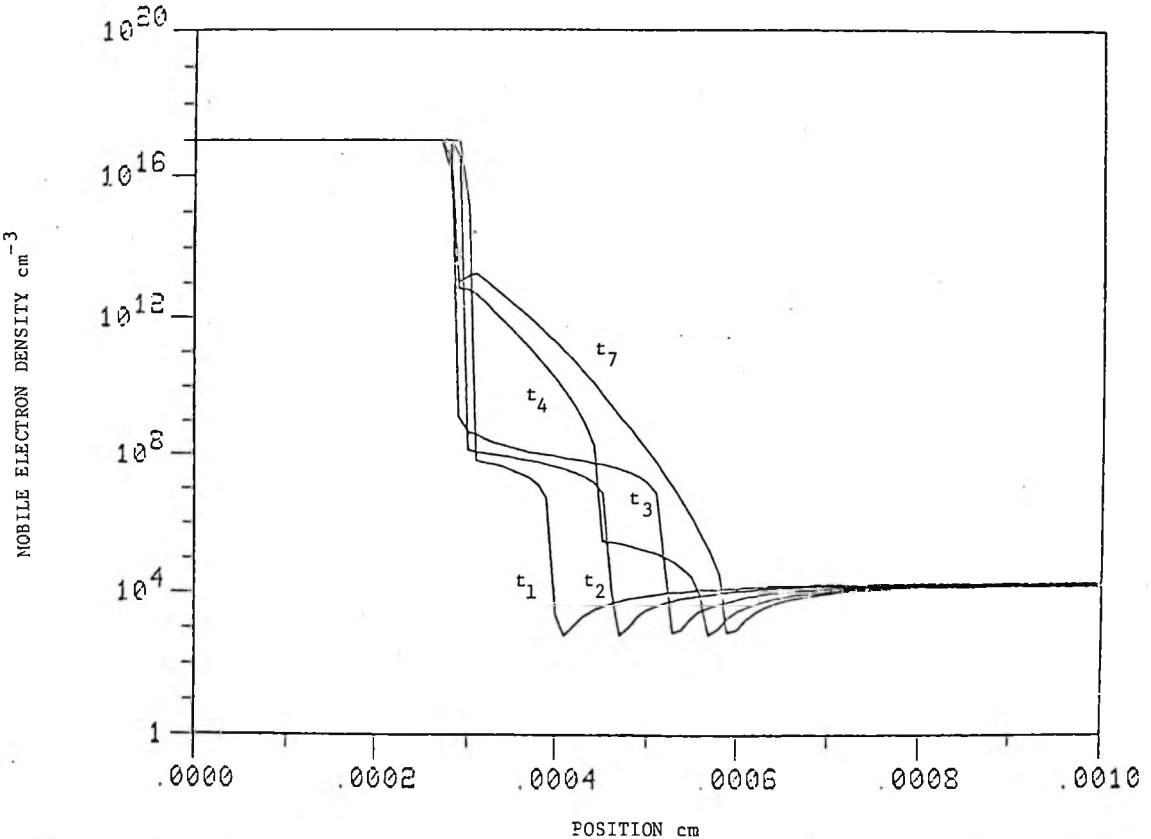


Fig. 4.7. Mobile Electron Density as a Function of Position at Various Instants of Time Prior to the Onset of Thermal Second Breakdown (t_1=0.0, t_2=1.0x10^{-8}, t_3=2.0x10^{-8}, t_4=5.06x10^{-8}, t_7=7.82x10^{-5} - sec).

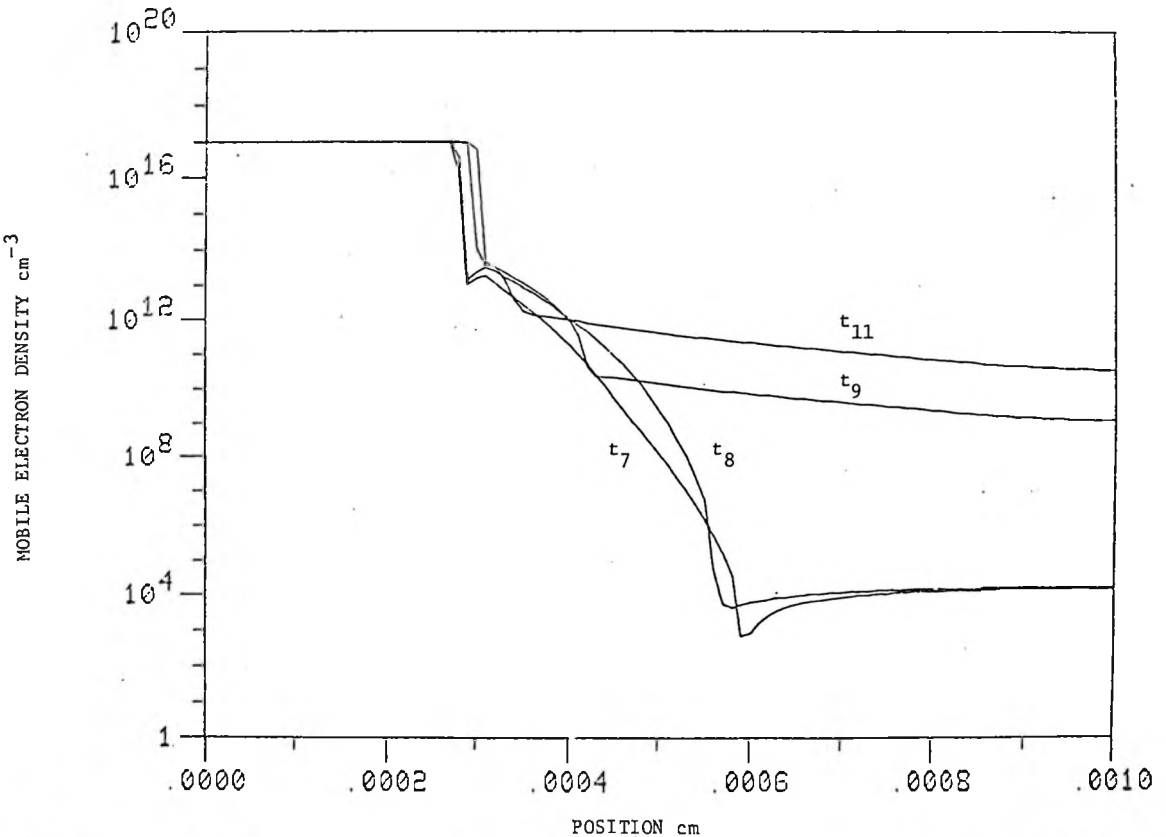


Fig. 4.8. Mobile Electron Density as a Function of Position at Various Instants of Time After the Onset of Thermal Second Breakdown (t_7=7.82x10^{-5}. t_8=1.2x10^{-4}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec).

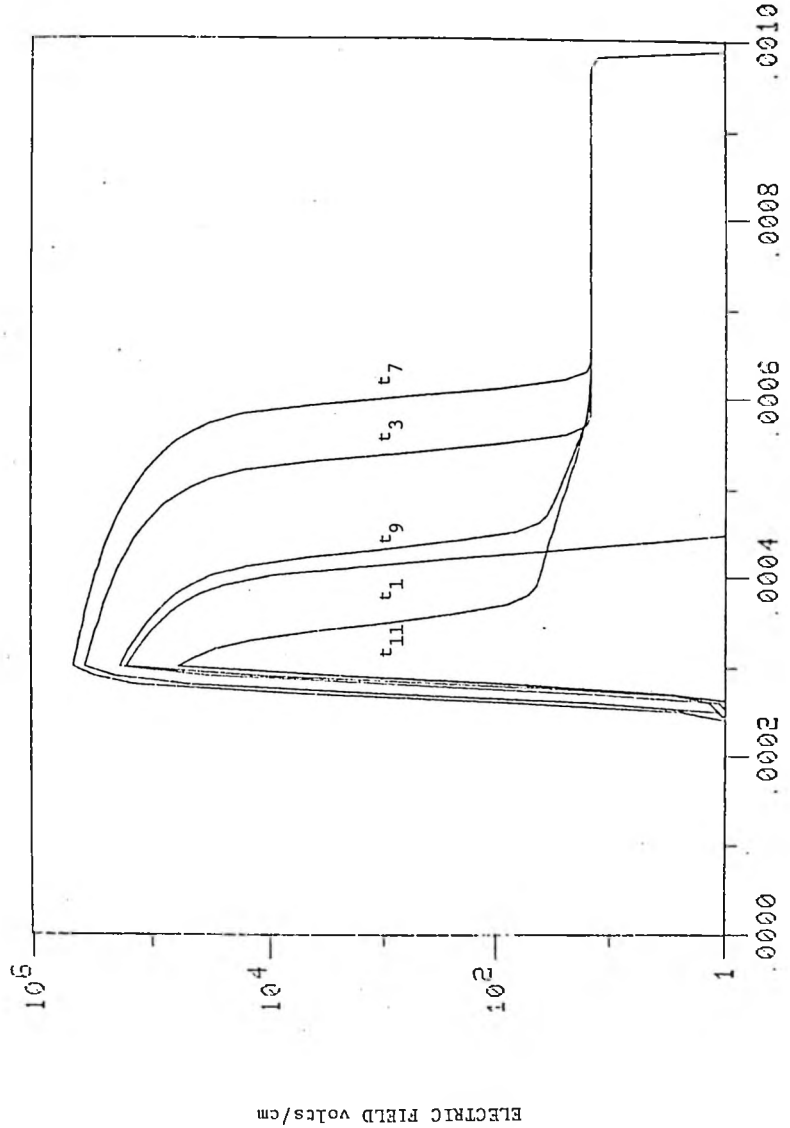


Fig. 4.9. Electric Field as a Function of Position at Various Instants of Time (t_1=0.0, t_3=2.0x10^{-8}, t_7=7.82x10^{-5}, t_9=1.35x10^{-4} ; t_{11}=1.11x10^{-3} - sec).

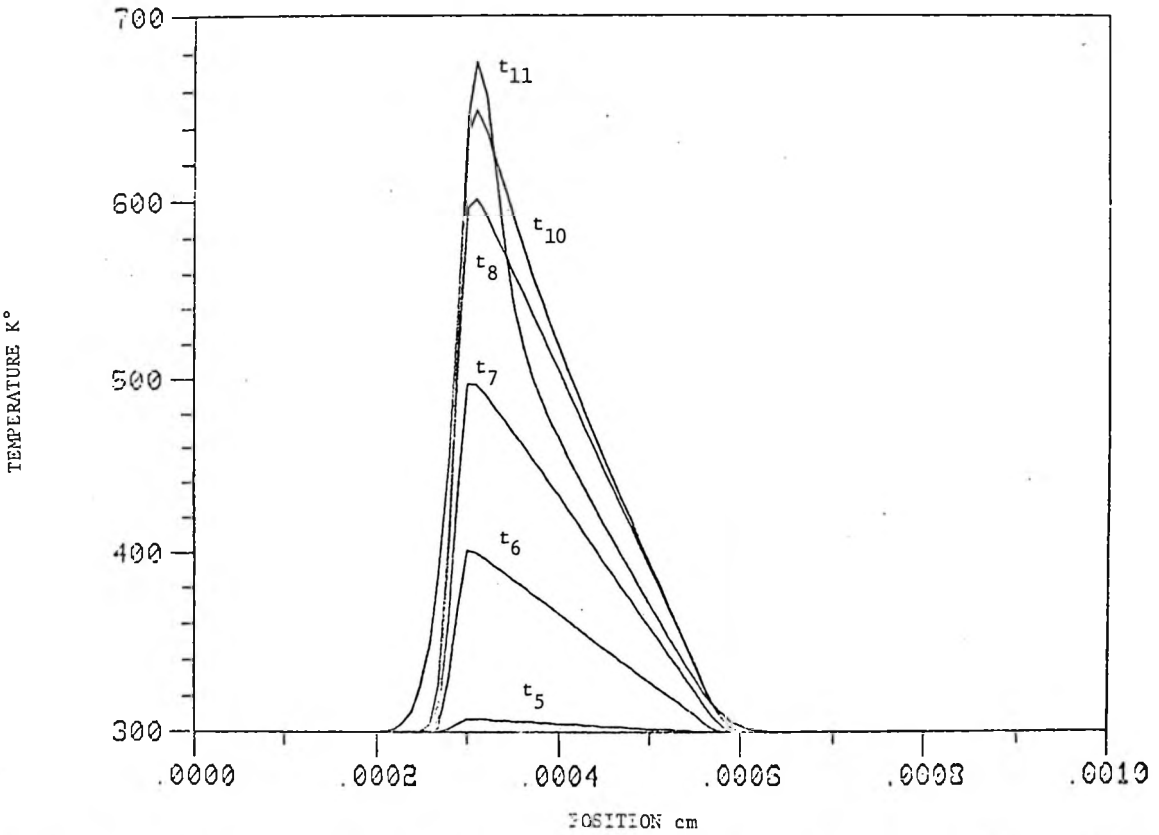


Fig. 4.10. Temperature as a Function of Position at Various Instants of Time (t_5=3.0x10^{-6}, t_6=4.0x10^{-5}, t_7=7.82x10^{-5}, t_8=1.2x10^{-4}, t_{10}=1.78x10^{-4}, t_{11}=1.11x10^{-3} - sec).

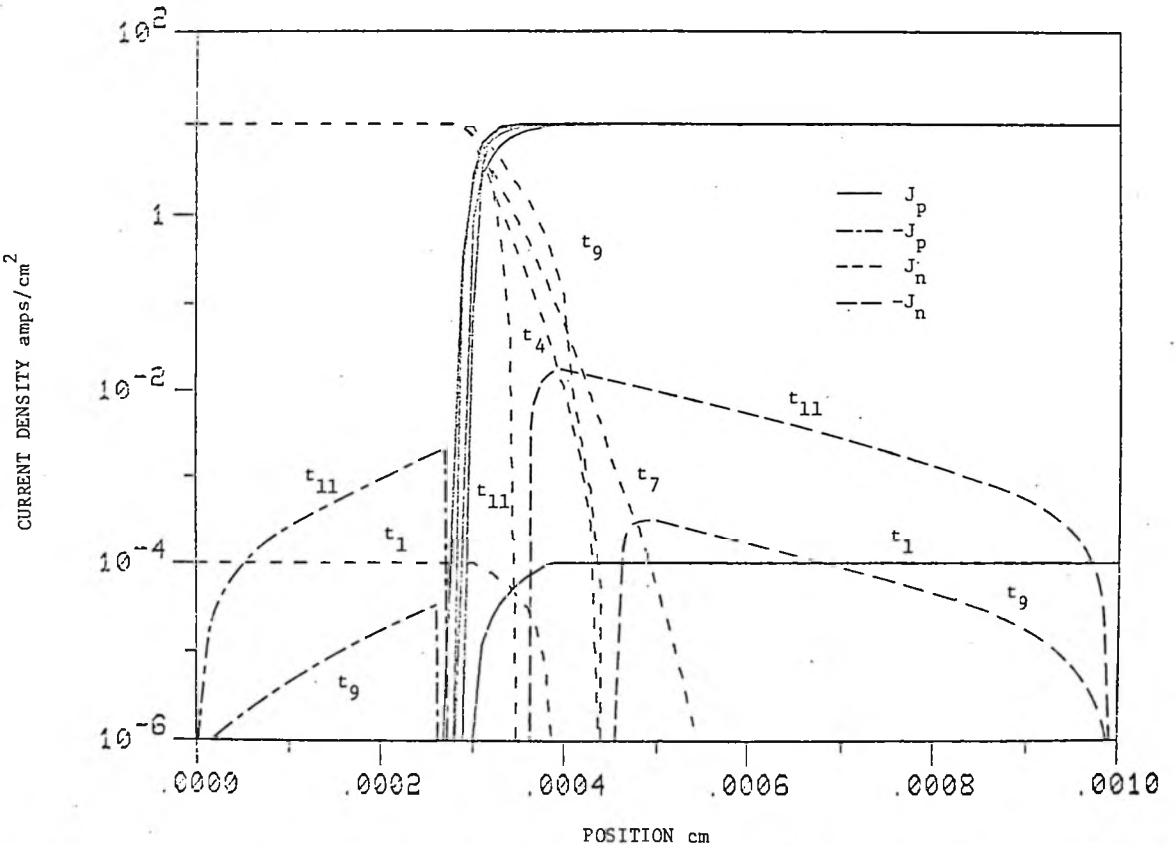


Fig. 4.11. Hole and Electron Current Densities as Functions of Position at Various Instants of Time (t_1=0.0, t_4=5.06x10^{-8}, t_7=7.82x10^{-5}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec).

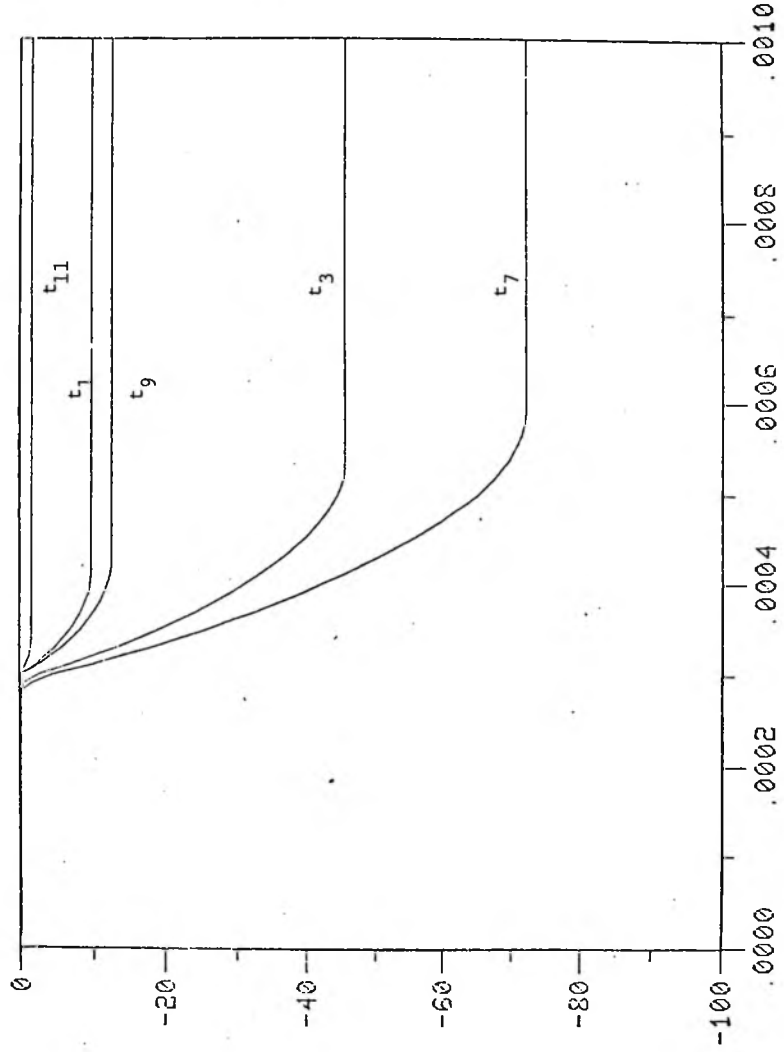


Fig. 4.12. Voltage as a Function of Position at Various Instants of Time (t_1=0.0, t_3=2.0x10^{-8}, t_7=7.82x10^{-5}, t_9=1.35x10^{-4}, t_{11}=1.11x10^{-3} - sec).

region on the high doped side of the junction. On the other hand, the relatively short bulk regions for this diode design makes the diode model quite sensitive to mobile space change induced depletion region widing that occurs under high current conditions. If one of the depletion regions spans the respective bulk region the validity of the diode model is destroyed. The high temperatures associated with the thermal second breakdown require large power densities, and thus, high current densities which result in significant depletion region widening. This condition, however, is avoided by maintaining a reasonably high impurity concentration on the low doped side of the junction and by assigning an artifically low value to the semiconductor and substrate thermal conductivities. The decreased values for thermal conductivity permit the simulation to develop significant thermal effects at considerably reduced current densities. In essence, the temporal validity of the simulation is compromised in order to achieve the thermal conditions required to initiate and support thermal second breakdown.

The circuit configuration and sign conventions for the simulation are shown in Fig. 3.8. The simulation is performed in the reverse bias mode and is driven by a constant current source. Initially the diode model is in a steady state mode corresponding to a reverse bias current of 10^{-4} amps/cm^2. The simulation is initiated by instantaneously increasing the reverse bias current to 10 amps/cm^2. Accordingly, the diode model undergoes a dynamic transient and terminates in a post second breakdown state.

The resulting behavior of the diode model is presented in Figs. 4.1 through 4.12. A description of the thermal second breakdown transient is as follows. The diode model terminal voltage, as a function of time,

is shown in Fig. 4.1 for a logarithemic time scale and in Fig. 4.2 for a linear time scale. These curves exhibit the well established voltage transient characteristic of thermal second breakdown. Notice that Fig. 4.1 has several transient reference times marked. These times are used to coordinate the various aspects of the simulation. Furthermore, Fig. 4.1 clearly reveals four distinct phases which the simulation transient passes through.

First, the diode model is observed to undergo a rapid voltage change in response to the abrupt increase in current which initiated the simulation. The diode model depletion region expands with equal rapidity such that the avalanche generated current increases to compensate for the increased current load placed on the diode model. Fig. 4.3 shows that this transition is isothermal since there is no detectable change in device temperature. This phase terminates, short of time t_4, in a quasi-stable state determined by the diode model current amplitude in the absence of significant thermal effects.

Second, as the simulation progresses the junction area begins to heat up, through joule leating, as can be seen in Figs. 4.3 and 4.10. The increasing junction temperature is manifest in the diode voltage transient, Figs. 4.1 and 4.2, as a corresponding continuous increase in diode voltage. The negative temperature dependence of the avalanche ionization coefficients readily accounts for this effect. Furthermore, it can be observed in Figs 4.5 and 4.7 that the increasing junction temperature is also accompanied by a considerable increase in the carrier generation rate within the depletion region. In fact, the increased carrier generation rate is sufficient to yield minority carrier diffusion

currents flowing into the respective bulk regions, and thus, contrary to an avalanche dominated junction. The only other carrier generation mechanism available and the one responsible for the observed increase is the thermal generation mechanism. The fact that the total generation rate for the junction has increased, demonstrates that carrier generation is now dominated by thermal generation rather than avalanche generation. Nevertheless, at this point in the simulation, thermal generation is unable to account for the total device current since the device voltage is still maintained sufficiently high to support some degree of avalanche breakdown.

Third, shortly after time t_7, the onset of thermal second breakdown begins. The subsequent rapid collapse of the junction voltage occurs concurrently with a substantial increase in the rate of carrier generation within the reduced depletion region. The increased carrier generation rate is evident in the mobile carrier profiles, Figs. 4.6 and 4.8, and in the hole and electron current profiles, Fig. 4.10. Avalanche breakdown is completely extinguished as a consequence of the subsequent drop in diode voltage. Furthermore, it is observed in Figs. 4.3, 4.4, and 4.10 that the junction temperature continues to increase rapidly throughout most of the second breakdown transition.

Fourth, and finally, the diode approaches a stable post second breakdown state. Termination of the second breakdown transient occurs at time t_9 as is clearly evident in the diode voltage transient, Fig. 4.2, and maximum temperature transient, Fig. 4.4. The further decrease in device voltage is attributed to residual thermal effects.

4.2 CONCLUSIONS

A comprehensive numerical diode model for investigation of thermal second breakdown has been developed. In Chapter 2 a brief description of thermal second breakdown in thin film silicon-on-sapphire diodes was presented as an introduction to this phenomenon. The numerical diode model was developed in Chapter 3, and yielded a transient solution formulation for the complete set of time dependent partial differential equations that govern bipolar semiconductor behavior. None of the traditional assumptions and approximations commonly employed to simplify this system of state equations are required, i.e., a comprehensive solution is generated. The significant features of the diode model are summarized as follows:

1. One-dimension electrical effects
2. Simplified two-dimensional thermal conduction
3. A noniterative transient solution procedure
4. A generalized implicit formulation
5. Applicable to both high and low driving currents
6. Reverse or forward bias modes of operation
7. A contact-to-contact simulation
8. Thermal generation-recombination throughout device structure
9. Impurity, electric field and temperature dependent mobilities
10. Electric field and temperature dependent avalanche ionization coefficients
11. Current, or a combination of current and ohmic, terminal boundary conditions

The computer program version of the diode model consist of four main programs and a collection of subroutines. These programs are

presented in Appendix B. The main program which actually performs the simulation was written to facilitate a non-uniform spacial grid and an arbitrary impurity profile. However, the initial state generator, which is used to generate a thermal equilibrium initial state for starting a simulation, is restricted to an abrupt junction configuration and a uniform spacial grid. For the thermal second breakdown simulation presented in the previous section, these restrictions lead to a short diode structure which was undesirable in view of the high current values associated with thermal second breakdown. This situation was alleviated by assigning a considerably reduced value to the semiconductor and substrate thermal conductivities. Under this condition, appreciable thermal effects resulted at reduced current values, and significant mobile space charge induced depletion widing was avoided. This condition, however, compromised the temporal validity of the subsequent thermal second breakdown simulation. Nevertheless, in all other respects the simulation very closely approximated the expected thermal second breakdown behavior. The subsequent analysis of the simulation leads to the following conclusions:

1. Thermal second breakdown can be initiated and supported without the necessity of junction inhomogeneities, current constrictions, and variable perturbations through various mechanisms. This implies that thermal second breakdown is a fundamental property of the semiconductor state equations. Junction inhomogeneities, etc., simply serve to enhance and prematurely initiate this phenomenon.

2. Simulation results support the theory that thermal second breakdown is primarily a consequence of thermal quenching of avalanche breakdown by the temperature dependent diode leakage current.

3. Thermal second breakdown can result in all but a complete collapse in the junction voltage without the benefit of a melt filament.

4.3 RECOMMENDATIONS FOR FURTHER STUDY

The generality of the numerical diode model presented can be further expanded through addition of two features. One, an initial state generator capable of generating thermal equilibrium states for arbitrary impurity profiles. The other, an algorithm for generating an optimal spacial grid. These improvements in the diode model would facilitate simulations requiring arbitrary impurity profiles and long base diode structures.

There are a number of areas in thermal second breakdown research which require further investigation and to which the diode model is applicable. Some are listed below.

1. Effects of various type junction inhomogeneities on thermal second breakdown characteristics

2. Relationship between resistivity turn-over temperature for the low doped side of the junction and the junction temperature corresponding to the onset of thermal second breakdown

3. Critical energy versus delay time characteristics for initiation of thermal second breakdown

4. Relationship between junction leakage current and thermal second breakdown characteristics

5. Relationship between impurity concentration on the low doped side of the junction and the thermal second breakdown delay time

APPENDIX A

COEFFICIENT FORMULATION

This Appendix presents the detailed formulation of the coefficients for the matrix equation (3.70) which characterizes the numerical diode model developed in Chapter 3. The structure of the coefficient matrix for this system of equations is illustrated in Fig. 3.9, where the banded form of the matrix is apparent. The computer program implementation of the diode model, presented in Appendix B, takes full advantaged of this characteristic by storing only the banded section of the coefficient matrix along with the respective equation constant terms. The respective node equation coefficients and constant term are stored in a row-wise fashion with the same equation order depicted in Fig. 3.9. From this figure it is also determined that the modified coefficient array must have eleven columns for the equation coefficients and one column for the respective constant term. The array length is dependent on the number of N-nodes, P, employed by the diode model and is evaluated as 4P-8. Accordingly, the modified coefficient array is designated as the A array and has the dimensions (4P-8)x12. The formulation of the coefficients for this array and the required auxillary relations are presented below.

I. Notation

A. Variable and Parameter Definitions

A - Modified coefficient array, (4P-8)x12

N - Major node number (N-node)

M - Minor node number (M-node)

LP - Row number for hole continuity equation formulated at node N

LN - Row number for electron continuity equation formulated at node N

LE - Row number for Poisson equation formulated at node N

LT - Row number for energy continuity equation formulated at node M

B. Equation row indexes in terms of node numbers

LP = 1+4(N-2)

LN = 2+4(N-2)

LE = 3+4(N-2)

LT = 4+4(M-2)

II. Generalized Coefficient Formulation for the Hole Continuity Equation

A. Hole continuity equation functional term

$$F_p(N) = G_s(N) + G_I(N) + \frac{J_p(M-1)}{\Delta x(N)} - \frac{J_p(M)}{\Delta x(N)}$$

B. Coefficient formulation

$$A(LP,1) = -\frac{\partial F_p(N)}{\partial T(M-1)} = 0$$

$$A(LP,2) = -\frac{\partial F_p(N)}{\partial p(N-1)} = -\frac{\partial G_I(N)}{\partial p(N-1)} - \frac{1}{\Delta x(N)}\frac{\partial J_p(M-1)}{\partial p(N-1)}$$

$$A(LP,3) = -\frac{\partial F_p(N)}{\partial n(N-1)} = -\frac{\partial G_I(N)}{\partial n(N-1)}$$

$$A(LP,4) = -\frac{\partial F_p(N)}{\partial E(M-1)} = -\frac{\partial G_I(N)}{\partial E(M-1)} - \frac{1}{\Delta x(N)}\frac{\partial J_p(M-1)}{\partial E(M-1)}$$

$$A(LP,5) = -\frac{\partial F_p(N)}{\partial T(M-1)} = -\frac{\partial G_S(N)}{\partial T(M-1)} - \frac{\partial G_I(N)}{\partial T(M-1)} - \frac{1}{\Delta x(N)}\frac{\partial J_p(M-1)}{\partial T(M-1)}$$

$$A(LP,6) = \frac{1}{\theta\Delta t} - \frac{\partial F_p(N)}{\partial p(N)} = \frac{1}{\theta\Delta t} - \frac{\partial G_S(N)}{\partial p(N)} - \frac{\partial G_I(N)}{\partial p(N)} - \frac{1}{\Delta x(N)}\frac{\partial J_p(M-1)}{\partial p(N)}$$

$$- \frac{1}{\Delta x(N)}\frac{\partial J_p(M)}{\partial p(N)}$$

$$A(LP,7) = -\frac{\partial F_p(N)}{\partial n(N)} = -\frac{\partial G_S(N)}{\partial n(N)} - \frac{\partial G_I(N)}{\partial n(N)}$$

$$A(LP,8) = -\frac{\partial F_p(N)}{\partial E(M)} = -\frac{\partial G_I(N)}{\partial E(M)} + \frac{1}{\Delta x(N)}\frac{\partial J_p(M)}{\partial E(M)}$$

$$A(LP,9) = -\frac{\partial F_p(N)}{\partial T(M)} = -\frac{\partial G_S(N)}{\partial T(M)} - \frac{\partial G_I(N)}{\partial T(M)} + \frac{1}{\Delta x(N)}\frac{\partial J_p(M)}{\partial T(M)}$$

$$A(LP,10) = -\frac{\partial F_p(N)}{\partial p(N+1)} = -\frac{\partial G_I(N)}{\partial p(N+1)} + \frac{1}{\Delta x(N)}\frac{\partial J_p(M)}{\partial p(N+1)}$$

$$A(LP,11) = -\frac{\partial F_p(N)}{\partial n(N+1)} = -\frac{\partial G_I(N)}{\partial n(N+1)}$$

$$A(LP,12) = \frac{1}{\theta} F_p(N)$$

III. Generalized Coefficient Formulation for the Electron Continuity Equation

A. Electron continuity equation functional term

$$F_n(N) = G_S(N) + G_I(N) + \frac{J_n(M)}{\Delta x(N)} - \frac{J_n(M-1)}{\Delta x(N)}$$

B. Coefficient formulation

$$A(LN,1) = -\frac{\partial F_n(N)}{\partial p(N-1)} = -\frac{\partial G_I(N)}{\partial p(N-1)}$$

$$A(LN,2) = -\frac{\partial F_n(N)}{\partial n(N-1)} = -\frac{\partial G_I(N)}{\partial n(N-1)} + \frac{1}{\Delta x(N)} \frac{\partial J_n(M-1)}{\partial n(N-1)}$$

$$A(LN,3) = -\frac{\partial F_n(N)}{\partial E(M-1)} = -\frac{\partial G_I(N)}{\partial E(M-1)} + \frac{1}{\Delta x(N)} \frac{\partial J_n(M-1)}{\partial E(M-1)}$$

$$A(LN,4) = -\frac{\partial F_n(N)}{\partial T(M-1)} = -\frac{\partial G_S(N)}{\partial T(M-1)} - \frac{\partial G_I(N)}{\partial T(M-1)} + \frac{1}{\Delta x(N)} \frac{\partial J_n(M-1)}{\partial T(M-1)}$$

$$A(LN,5) = -\frac{\partial F_n(N)}{\partial p(N)} = -\frac{\partial G_S(N)}{\partial p(N)} - \frac{\partial G_I(N)}{\partial p(N)}$$

$$A(LN,6) = \frac{1}{\theta\Delta t} - \frac{\partial F_n(N)}{\partial n(N)} = \frac{1}{\theta\Delta t} - \frac{\partial G_S(N)}{\partial n(N)} - \frac{\partial G_I(N)}{\partial n(N)} + \frac{1}{\Delta x(N)} \frac{\partial J_n(M-1)}{\partial n(N)}$$

$$- \frac{1}{\Delta x(N)} \frac{\partial J_n(M)}{\partial n(N)}$$

$$A(LN,7) = -\frac{\partial F_n(N)}{\partial E(M)} = -\frac{\partial G_I(N)}{\partial E(M)} - \frac{1}{\Delta x(N)}\frac{\partial J_n(M)}{\partial E(M)}$$

$$A(LN,8) = -\frac{\partial F_n(N)}{\partial T(M)} = -\frac{\partial G_S(N)}{\partial T(M)} - \frac{\partial G_I(N)}{\partial T(M)} - \frac{1}{\Delta x(N)}\frac{\partial J_n(M)}{\partial T(M)}$$

$$A(LN,9) = -\frac{\partial F_n(N)}{\partial p(N+1)} = -\frac{\partial G_I(N)}{\partial p(N+1)}$$

$$A(LN,10) = -\frac{\partial F_n(N)}{\partial n(N+1)} = -\frac{\partial G_I(N)}{\partial n(N+1)} - \frac{1}{\Delta x(N)}\frac{\partial J_n(M)}{\partial n(N+1)}$$

$$A(LN,11) = -\frac{\partial F_n(N)}{\partial E(M+1)} = 0$$

$$A(LN,12) = \frac{1}{\theta} F_n(N)$$

IV. Generalized coefficient formulation for the Poisson equation

A. Poisson equation functional term

$$F_E(N) = E(M-1) - E(M) + \Delta x(N)[P(N) - n(N) + N_I(N)]$$

B. Coefficient formulation:

$A(LE,1) = 0$

$A(LE,2) = -1$

$A(LE,3) = 0$

$A(LE,4) = -\Delta x(N)$

$A(LE,5) = \Delta x(N)$

$A(LE,6) = 1$

$A(LE,7) = 0$

$A(LE,8) = 0$

$A(LE,9) = 0$

$A(LE,10) = 0$

$A(LE,11) = 0$

$A(LE,12) = F_E(N)$

V. Generalized Coefficient Formulation for the Energy Balance Equation

A. Energy balance equation functional term

$$F_T(M) = \sigma_1[T(M-1) - T(M)] + \sigma_2[T(M+1) - T(M)] + \sigma_3[T_o - T(M)]$$

$$+ \sigma_4|E(M)|\ [|J_p(M) + |J_n(M)|]$$

B. Coefficient formulation

$$A(LT,1) = -\frac{\partial F_T(M)}{\partial E(M-1)} = 0$$

$$A(LT,2) = -\frac{\partial F_T(M)}{\partial T(M-1)} = -\sigma_1$$

$$A(LT,3) = -\frac{\partial F_T(M)}{\partial p(N)} = -\sigma_4|E(M)|\ \frac{\partial|J_p(M)|}{\partial p(N)}$$

$$A(LT,4) = -\frac{\partial F_T(M)}{\partial n(N)} = -\sigma_4|E(M)|\ \frac{\partial|J_n(M)|}{\partial n(N)}$$

$$A(LT,5) = -\frac{\partial F_T(M)}{\partial E(M)} = -\sigma_4 \left[|J_p(M)| + |J_n(M)|\right] \frac{\partial |E(M)|}{\partial E(M)}$$

$$- \sigma_4 \, |E(M)| \left[\frac{\partial |J_p(M)|}{\partial E(M)} + \frac{\partial |J_n(M)|}{\partial E(M)}\right]$$

$$A(LT,6) = \frac{1}{\theta \Delta t} - \frac{\partial F_T(M)}{\partial T(M)} = \frac{1}{\theta \Delta t} - \sigma_1 - \sigma_2 - \sigma_3$$

$$- \sigma_4 \, E(M) \left[\frac{\partial |J_p(M)|}{\partial T(M)} + \frac{\partial |J_n(M)|}{\partial T(M)}\right]$$

$$A(LT,7) = -\frac{\partial F_T(M)}{\partial p(N+1)} = -\sigma_4 \, |E(M)| \, \frac{\partial |J_p(M)|}{\partial p(N+1)}$$

$$A(LT,8) = -\frac{\partial F_T(M)}{\partial n(N+1)} = -\sigma_4 \, |E(M)| \, \frac{\partial |J_n(N)|}{\partial n(N+1)}$$

$$A(LT,9) = -\frac{\partial F_T(M)}{\partial E(M+1)} = 0$$

$$A(LT,10) = -\frac{\partial F(M)}{\partial T(M+1)} = -\sigma_2$$

$$A(LT,11) = -\frac{\partial F_T(M)}{\partial p(M+2)} = 0$$

$$A(LT,12) = \frac{1}{\theta} F_T(M)$$

Where σ_1, σ_2, σ_3, and σ_4 are defined in terms of the unnormalized parameters[1] K_D, K_H, ρ, c, x_{DT}, and x_{HT} as follows[2]:

$$\sigma_1 = \frac{TN}{xN^2} \frac{K_D}{\rho \; c \; \Delta x(M)\Delta x(N)}$$

$$\sigma_2 = \frac{TN}{xN^2} \frac{K_D}{\rho \; c \; \Delta x(M)\Delta x(N+1)}$$

$$\sigma_3 = TN \frac{K_D}{x_{DT} x_{HT} \; \rho \; c}$$

$$\sigma_4 = \frac{EN \cdot CURN \cdot TN}{TEMPN} \frac{1}{\rho c}$$

VI. Hole and Electron Current and Subsequent Derivative Formulation

A. $\Delta x(M)E(M)/T(M) >$ EXTCRI (current formulation switching variable)

$$J_p(M) = \mu_p(M)E(M) \left[\frac{p(N+1)}{1 - e^{\frac{\Delta x(M)E(M)}{T(M)}}} + \frac{p(N)}{1 - e^{-\frac{\Delta x(M)E(M)}{T(M)}}} \right]$$

[1]The computer diode model presented in Appendix B maintains these parameters in unnormalized form.

[2]Normalization constants appear in the subsequent equations to compensate for unnormalized parameters.

$$\frac{\partial J_p(M)}{\partial p(N)} = \frac{\mu_p(M)E(M)}{1 - e^{-\frac{\Delta x(M)E(M)}{T(M)}}}$$

$$\frac{\partial J_p(M)}{\partial p(N+1)} = \frac{\mu_n(M)E(M)}{1 - e^{\frac{\Delta x(M)E(M)}{T(M)}}}$$

$$\frac{\partial J_p(M)}{\partial E(M)} = \frac{J_p(M)}{\mu_p(M)} \frac{\partial \mu_p(M)}{\partial E(M)} + \frac{J_p(M)}{E(M)} - \frac{\Delta x(M)}{T(M)} \left[\frac{p(N+1) - p(N)}{\frac{1}{\frac{\partial J_p(M)}{\partial p(N)}} - \frac{1}{\frac{\partial J_p(M)}{\partial p(N+1)}}} \right]$$

$$\frac{\partial J_p(M)}{\partial T(M)} = \frac{J_p(M)}{\mu_p(M)} \frac{\partial \mu_p(M)}{\partial T(M)} + \frac{\Delta x(M)E(M)}{T(M)^2} \left[\frac{p(N+1) - p(N)}{\frac{1}{\frac{\partial J_p(M)}{\partial p(N)}} + \frac{1}{\frac{\partial J_p(M)}{\partial p(N+1)}}} \right]$$

$$J_n(M) = \mu_n(M)E(M) \left[\frac{n(N+1)}{1 - e^{-\frac{\Delta x(M)E(M)}{T(M)}}} + \frac{n(N)}{1 - e^{\frac{\Delta x(M)E(M)}{T(M)}}} \right]$$

$$\frac{\partial J_n(M)}{\partial n(N)} = \frac{\mu_n(M)E(M)}{1 - e^{\frac{\Delta x(M)E(M)}{T(M)}}}$$

$$\frac{\partial J_n(M)}{\partial n(N+1)} = \frac{\mu_n(M)E(M)}{1 - e^{-\frac{\Delta x(M)E(M)}{T(M)}}}$$

$$\frac{\partial J_n(M)}{\partial E(M)} = \frac{J_n(M)}{\mu_n(M)} \frac{\partial \mu_n(M)}{\partial E(M)} + \frac{J_n(M)}{E(M)} + \frac{\Delta x(M)}{T(M)} \left[\frac{n(N+1) - n(N)}{\frac{1}{\frac{\partial J_n(M)}{\partial n(N)}} + \frac{1}{\frac{\partial J_n(M)}{\partial n(N+1)}}} \right]$$

$$\frac{\partial J_n(M)}{\partial T(M)} = \frac{J_n(M)}{\mu_n(M)} \frac{\partial \mu_n(M)}{\partial T(M)} - \frac{\Delta x(M)E(M)}{T(M)^2} \left[\frac{n(N+1) - n(N)}{\frac{1}{\frac{\partial J_n(M)}{\partial n(N+1}} + \frac{1}{\frac{\partial J_n(M)}{\partial n(N)}}} \right]$$

B. $\Delta x(M)E(M)/T(M) <$ EXTCRI (Current formulation switching variable).

$$\alpha(M) \equiv \frac{\Delta x(M)E(M)}{T(M)}$$

$$\frac{\alpha(M)}{1 - e^{\alpha(M)}} = -1 + \frac{\alpha(M)}{2} - \frac{\alpha(M)^2}{12} + \ldots$$

$$\frac{\alpha(M)}{1 - e^{-\alpha(M)}} = 1 + \frac{\alpha(M)}{2} + \frac{\alpha(M)^2}{12} + \ldots$$

$$g(M) \equiv -1 + \frac{\alpha(M)}{2} - \frac{\alpha(M)^2}{12}$$

$$h(M) \equiv 1 + \frac{\alpha(M)}{2} + \frac{\alpha(M)^2}{12}$$

$$J_p(M) \simeq \frac{\mu_p(M)T(M)}{\Delta x(M)} [g(M)p(N+1) + h(M)p(N)]$$

$$\frac{\partial J_p(M)}{\partial p(N)} \simeq \frac{\mu_p(M)T(M)h(M)}{\Delta x(M)}$$

$$\frac{\partial J_p(M)}{\partial p(N+1)} \simeq \frac{\mu_p(M)T(M)g(M)}{\Delta x(M)}$$

$$\frac{\partial J_p(M)}{\partial E(M)} \simeq \frac{J_p(M)}{\mu_p(M)} \frac{\partial \mu_p(M)}{\partial E(M)} + \frac{\mu_p(M)T(M)}{\Delta x(M)} \left[p(N+1) \frac{\partial g(M)}{\partial E(M)} + p(N) \frac{\partial h(M)}{\partial E(M)} \right]$$

$$\frac{\partial J_p(M)}{\partial T(M)} \simeq \frac{J_p(M)}{T(M)} + \frac{\mu_p(M)T(M)}{\Delta x(M)} \left[p(N+1) \frac{\partial g(M)}{\partial T(M)} + p(N) \frac{\partial h(M)}{\partial T(M)} \right]$$

$$J_n(M) \simeq \frac{\mu_n(M)T(M)}{\Delta x(M)} [h(M)n(N+1) + g(M)n(N)]$$

$$\frac{\partial J_n(M)}{\partial n(N)} \simeq \frac{\mu_n(M)T(M)g(M)}{\Delta x(M)}$$

$$\frac{\partial J_n(M)}{\partial n(N+1)} \simeq \frac{\mu_n(M)T(M)h(M)}{\Delta x(M)}$$

$$\frac{\partial J_n(M)}{\partial E(M)} \simeq \frac{J_n(M)}{\mu_n(M)} \frac{\partial \mu_n(M)}{\partial E(M)} + \frac{\mu_n(M)T(M)}{\Delta x(M)} \left[n(N+1) \frac{\partial h(M)}{\partial E(M)} + n(N) \frac{\partial g(M)}{\partial E(M)} \right]$$

$$\frac{\partial J_n(M)}{\partial T(M)} \simeq \frac{J_n(M)}{T(M)} + \frac{\mu_n(M)T(M)}{\Delta x(M)} \left[n(N+1) \frac{\partial h(M)}{\partial T(M)} + n(N) \frac{\partial g(M)}{\partial T(M)} \right]$$

VII. Avalanche Generation Factor and Subsequent Derivative Formulation

$$G_I(M) = \alpha_p(M) \left| J_p(M) \right| + \alpha_n(M) \left| J_n(M) \right|$$

$$\lambda_m(N) \equiv \frac{\Delta x(M-1)}{\Delta x(M-1) + \Delta x(M)}$$

$$\lambda_p(N) \equiv \frac{\Delta x(M)}{\Delta x(M-1) + \Delta x(M)}$$

$$G_I(N) = \lambda_m(N)\ G_I(M-1) + \lambda_p(N)\ G_I(M)$$

$$\frac{\partial G_I(N)}{\partial p(N-1)} = \lambda_m(N)\ \alpha_p(M-1)\ \frac{\partial |J_p(M-1)|}{\partial p(N-1)}$$

$$\frac{\partial G_I(N)}{\partial n(N-1)} = \lambda_m(N)\ \alpha_n(M-1)\ \frac{\partial |J_n(M-1)|}{\partial n(N-1)}$$

$$\frac{\partial G_I(N)}{\partial E(M-1)} = \lambda_m(N) \left[|J_p(M-1)|\ \frac{\partial \alpha_p(M-1)}{\partial E(M-1)} + \alpha_p(M-1)\ \frac{\partial |J_p(M-1)|}{\partial E(M-1)} \right.$$

$$\left. + |J_n(M-1)|\ \frac{\partial \alpha_n(M-1)}{\partial E(M-1)} + \alpha_n(M-1)\ \frac{\partial |J_n(M-1)|}{\partial E(M-1)} \right]$$

$$\frac{\partial G_I(N)}{\partial T(M-1)} = \lambda_m(N) \left[|J_p(M-1)|\ \frac{\partial \alpha_p(M-1)}{\partial T(M-1)} + \alpha_p(M-1)\ \frac{\partial |J_p(M-1)|}{\partial T(M-1)} \right.$$

$$\left. + |J_n(M-1)|\ \frac{\partial \alpha_n(M-1)}{\partial T(M-1)} + \alpha_n(M-1)\ \frac{\partial |J_n(M-1)|}{\partial T(M-1)} \right]$$

$$\frac{\partial G_I(N)}{\partial p(N)} = \lambda_m(N)\ \alpha_p(M-1)\ \frac{\partial |J_p(M-1)|}{\partial p(N)} + \lambda_p(N)\ \alpha_p(M)\ \frac{\partial |J_p(M)|}{\partial p(N)}$$

$$\frac{\partial G_I(N)}{\partial n(N)} = \lambda_m(N)\ \alpha_n(M-1)\ \frac{\partial |J_n(M-1)|}{\partial n(N)} + \lambda_n(N)\ \alpha_n(M)\ \frac{\partial |J_n(M)|}{\partial n(N)}$$

$$\frac{\partial G_I(N)}{\partial E(M)} = \lambda_p(N) \left[|J_p(M)|\ \frac{\partial \alpha_p(M)}{\partial E(M)} + \alpha_p(M)\ \frac{\partial |J_p(M)|}{\partial E(M)} \right.$$

$$\left. + |J_n(M)|\ \frac{\partial \alpha_n(M)}{\partial E(M)} + \alpha_n(M)\ \frac{\partial |J_n(M)|}{\partial E(M)} \right]$$

$$\frac{\partial G_I(N)}{\partial T(M)} = \lambda_p(N) \left[|J_p(M)|\ \frac{\partial \alpha_p(M)}{\partial T(M)} + \alpha_p(M)\ \frac{\partial |J_p(M)|}{\partial T(M)} \right.$$

$$\left. + |J_n(M)|\ \frac{\partial \alpha_n(M)}{\partial T(M)} + \alpha_n(M)\ \frac{\partial |J_n(M)|}{\partial T(M)} \right]$$

$$\frac{\partial G_I(N)}{\partial p(N+1)} = \lambda_p(N)\ \alpha_p(M)\ \frac{\partial |J_p(M)|}{\partial p(N+1)}$$

$$\frac{\partial G_I(N)}{\partial n(N+1)} = \lambda_p(N)\ \alpha_n(M)\ \frac{\partial |J_n(M)|}{\partial n(N+1)}$$

VIII. Shockley-Read-Hall Thermal Generation Factor and Subsequent Derivative Formulation

$$G_S(N) = \frac{n_i(N)^2 - p(N)n(N)}{\tau_n[p(N) + n_i(N)] + \tau_p[n(N) + n_i(N)]}$$

$$n_i(N) = \lambda_m(N)\ n_i(M-1) + \lambda_p(N)n_i(M)$$

$$\frac{\partial G_S(N)}{\partial p(N)} = \frac{-[\tau_n n_i(N) + \tau_p n(N)][n_i(N) + n(N)]}{\{\tau_n[p(N) + n_i(N)] + \tau_p[n(NO + n_i(N)]\}^2}$$

$$\frac{\partial G_S(N)}{\partial n(N)} = \frac{-[\tau_p n_i(N) + \tau_n p(N)][n_i(N) + p(N)]}{\{\tau_n[p(N) + n_i(N)] + \tau_p[n(N) + n_i(N)]\}^2}$$

$$\delta(N) \equiv \Big[2n_i(N)\ \{\tau_n[p(N) + n_i(N)] + \tau_p[n(N) + n_i(N)]\} - (\tau_n + \tau_p)\ [n_i(N)^2 - p(N)n(N)] \Big] \Big/ \{\tau_n[p(N) + n_i(N)] + \tau_p[n(N) + n_i(N)]\}^2$$

$$\frac{\partial G_S(N)}{\partial T(M-1)} = \delta(N)\ \lambda_m(N)\ \frac{\partial n_i(M-1)}{\partial T(M-1)}$$

$$\frac{\partial G_S(N)}{\partial T(M)} = \delta(N)\ \lambda_p(N)\ \frac{\partial n_i(M)}{\partial T(M)}$$

APPENDIX B

COMPUTER DIODE MODEL

This appendix reports the computer model developed to implement the numerical diode model formulated in Chapter 3. The subsequent computer programs are written in FORTRAN V for execution on a Univac 1110 computer system in conjunction with a Tektronix Display Terminal, and include both interactive and batch mode programs. The system of programs which compose the computer model consist of the four main programs: DS, COMP, GDG, and GRAPH. Program DS is the simulation control program which defines the simulation to be performed and is usually executed in the interactive mode. COMP, a slave program to DS, is executed in batch mode and performs the simulation specified by DS. When a graphic analysis of simulation results is desired, GDG (graph-data-generator) is executed to condition the simulation summary, stored by COMP, to comply with the data format required by the graphics display program GRAPH. GDG may be executed in either batch or interactive mode, whichever is most convenient. GRAPH must be executed interactively from a Tektronix Display Terminal and employs Tektronix Advance Graphics II software [1,2].

Data, in unnormalized form, is communicated between the four main programs through a collection of magnetic disk data files. DS and COMP employ seven of these data files of which 7 and 8 are used

by COMP for storing a simulation summary, 9 is used by DS for printer output, and 10, 11, 12 and 13 are used for storing simulation states which are referenced by both DS and COMP. GDG reads data files 7 and 8, generated by COMP, and subdivides these two data files into twenty-eight new data files, 20 through 34 and 37 through 49, which comply with the data format required by GRAPH. Subsequently, these twenty-eight data files are used by GRAPH to generate desired data plots.

It is appropriate here to clarify the term "simulation state" which denotes an ordered collection of all the parameter and variable values required by COMP for the initiation of a simulation. These values are listed in Table B.1 and include sentinels which control simulation input/output, etc., as well as, parameters which describe the diode being modeled, along with the necessary boundary and initial conditions. Two simulation states are associated with each simulation. One, the initial state, is the state used to start the simulation. The other, or the final state, is the state established at the end of each simulation. It is important to note that the term "initial state" implies only that the state is designated to start the simulation and does not indicate the physical state of the diode.

This system for storing simulation states allows long simulations to be performed through a series of short simulations; successive simulations use the final state of the previous simulation as an initial state. Moreover, a library of simulation initial states can be compiled by storing the various simulation final states on magnetic tape. Such a library is further enhanced by storing the simulation

TABLE B.1

SIMULATION STATE DATA FORMAT AND VARIABLE DEFINITIONS

Position	Name	Type	Definition
1	NSF	I[1]	Number of new state (simulation final state) file
2	T	I	Time step counter
3	TMAX	I	Maximum number of time steps allowed
4	RCMPB	I	Printer code for printer output from COMP
5	P	I	Number of N or M nodes
6	LNORC	I	1-Output listing of normalization constant values
7	TLINC	I	Number of time steps skipped before printing transient data values
8	TSINC	I	Number of time steps skipped before storing transient data values
9	LCS	I	1-List simulation cross section summary
10	LSCS	I	1-Store simulation cross section summary
11	LCSPI	I	Number of N or M nodes to skip before printing cross section data values
12	LSCSPI	I	Number of N or M nodes to skip before storing cross section data values
13	LFREAD	I	Number of last data file read
14	LFSTOR	I	Number of last data file written
15	NTYBND	I	0-Current boundary conditions, 1-hybrid boundary conditions
16	NTHDEP	I	0-Isothermal, 1-thermally dependent

[1] I indicates an integer variable and R indicates a real double precision variable.

TABLE B.1 (Continued)

Position	Name	Type	Definition
17	NCS	I	Number of simulation cross sections inaddition to initial and final simulation cross sections
18	IDATE	I	Date of simulation state generation
19	ITIME	I	Time of simulation state generation
20 : 29	IBLANK : IBLANK	I	Dummy interger variables to facilitate system expansion
30	DIEL	R	Semiconductor dielectric constant
31	TEMPO	R	Diode initial temperature
32	CARINT	R	Intrinsic carrier concentration for diode initial temperature
33	DONOR	R	Donor impurity concentration level
34	ACCEPT	R	Acceptor impurity concentration level
35	XMET	R	Location of metallurgical junction with respect to n-side contact
36	XL	R	Total length of diode
37	TAUN	R	Electron lifetime
38	TAUP	R	Hole lifetime
39	AREAD	R	Diode cross sectional area
40	DT	R	Incremental time step
41	TTIME	R	Maximum simulation time
42	TIME	R	Simulation time
43	THETA	R	Crank-Nicolson factor
44	VDBI	R	Diode built-in voltage used by COMP to evaluate diode bias voltage
45	DX	R	Spacial coordinate increment for uniform spacial grid

TABLE B.1 (Continued)

Position	Name	Type	Definition
46	DEPN	R	Depletion region width on n-side
47	DEPP	R	Depletion region width on p-side
48	DEPW	R	Depletion region total width
49	XDEPN	R	Location of depletion region boundary on n-side with respect to the n-side contact
50	XDEPP	R	Location of depletion region boundary on p-side with respect to the n-side contact
51	VDBIAN	R	Diode built-in voltage evaluated analytically
52	VDBISG	R	Diode built-in voltage evaluated by the initial state generator
53	CURTOT	R	Diode constant current density
54	EXTCRI	R	Current component formulation switching value $E(M)\Delta x(M)/T(M)$
55	FDTMUL	R	Time step multiplication factor
56	VDCOMP	R	Simulation final value for total diode voltage
57	CBEDS	R	Conduction band effective density of states
58	VBEDS	R	Valence band effective density of states
59	ENGAP	R	Semiconductor energy gap
60	THCOND	R	Semiconductor thermal conductivity
61	SPHEAT	R	Semiconductor specific heat
62	DENSITY	R	Semiconductor density
63	AITS	R	Temperature coefficient for hole and electron ionization coefficients
64	XDT	R	Semiconductor thickness

TABLE B.1 (Continued)

Position	Name	Type	Definition
65	XHT	R	Substrate thickness
66	THCONH	R	Semiconductor thermal conductivity
67 ⋮ 76	DBLANK ⋮ DBLANK	R	Dummy real variables to facilitate system expansion
77	XXN(1) ⋮ XXN(P)	R	N-node positions
77+P	DOPN(1) ⋮ DOPN(P)	R	Impurity cross section
77+2P	HOL(1) ⋮ HOL(P)	R	Hole concentration cross section
77+3P	ELE(1) ⋮ ELE(P)	R	Electron concentration cross section
77+4P	E(1) ⋮ E(P)	R	Electric field cross section
77+5P	V(1) ⋮ V(P)	R	Voltage cross section
77+6P	TEMP(1) ⋮ TEMP(P)	R	Temperature cross section
77+7P	CSTIME(1) ⋮ CSTIME(NCS)	R	Cross section output times inaddition to the initial and final simulation times

summary files 7 and 8 along with the corresponding final state; i.e., subsequent graphic examinations of the simulations that produced the respective final states are possible without the neccessity of repeating the simulations of interest.

The simulation summary stored in data files 7 and 8 contains a description of the simulation transient. Diode cross sections, or collections of spacially dependent quantities such as the dependent variables, impurity profiles, etc. are stored in data file 7 at specified points in the time during a simulation. Data file 8 contains quantities which are a function of time only, such as diode bias voltage, incremental time step, etc. These quantities, unlike the cross sections, are stored at equal intervals with respect to time step cycles.

The remainder of this appendix describes the four main programs and related subprograms which compose the computer diode model. Complete computer listings are provided for all algorithms along with flow charts for the more complex ones.

B.1 PROGRAM DS

Program DS is the simulation control program which defines the diode simulation to be performed by establishing the appropriate initial state in the initial state transfer data file 10; COMP is programmed to accept this file as the simulation initial state. DS is designed for the interactive mode of operation to eliminate the cumbersome card handling which characterizes batch mode operation. Nevertheless, when circumstances dictate, DS can be executed in a batch mode. DS is written in terms of unnormalized values and features five basic

operations. First, the desired initial state is chosen from one of four simulation state files 10, 11, 12 or 13 and the designated file is read. Otherwise, it is assumed that an appropriate initial state is not available and the program precedes to generate an initial state corresponding to a diode in thermal equilibrium with an abrupt impurity profile. This is accomplished by assigning nominal values to all simulation sentinels and parameters other than the fundamental parameters which characterize the basic diode design; values for these quantities are solicited by the program. A diode design which allows one of the depletion regions to reduce the respective bulk region to zero width is considered erroneous, causing an error message to this effect. The user is then presented an opportunity to redefine the diode design. After a valid diode design is established, subroutine ISTG (initial-state-generator) is called to generate a diode initial state through approximate analytic formulation. This operation completes the simulation initial state generation procedure. Next the simulation control and model parameters are optionally updated. With this activity completed the new or updated simulation initial state is written in data file 10, and optionally in a second data file specified by the user. This second data file is not restricted to the four data files required by the computer model, and thus can be an additional user defined data file. With the simulation initial state stored, a listing of the simulation initial state is available on an optional basis. If a listing is requested the user must supply the printer code to which the desired listing is to be directed. Finally, an optional remote start for COMP is presented. If requested, all pertinent data files are freed and a remote start of COMP is initiated.

A flow chart for DS is shown in Fig. B.1 and a complete listing of the program is presented in Fig. B.2. DS references directly or indirectly seven subroutines: DTMUL, CST, ISTG, THEQCA, INTRI, DEPL, and NTAB$ in conjunction with several input/output FORTRAN procedures which are included in the collection of input/output procedures RWLF. These algorithms are described below.

Procedure Collection RWLF

Individual procedures from this collection of FORTRAN procedures are employed by both DS and COMP for input/output operations pertaining to the parameter and variable values which compose a simulation state. This technique of handling these operations greatly facilitates program changes which involve the addition or removal of simulation state variables by minimizing the number of program changes required to implement a modification of this nature. Source listing for RWLF is presented in Fig. B.3.

Subroutine DTMUL

DTMUL only evaluates α, the factor by which each simulation time step is multiplied to obtain the suceeding time step. For this type time step formulation, simulation time may be represented as a finite geometric series. Accordingly, the time step behavior for a simulation can decrease, remain constant, or increase as a function of time depending on whether the value of α is less than, equal to, or greater than one, respectively. Subroutine DTMUL evaluates an approximate value for α which satisfies a finite geometric series for simulation time given the initial time, the initial time step, the

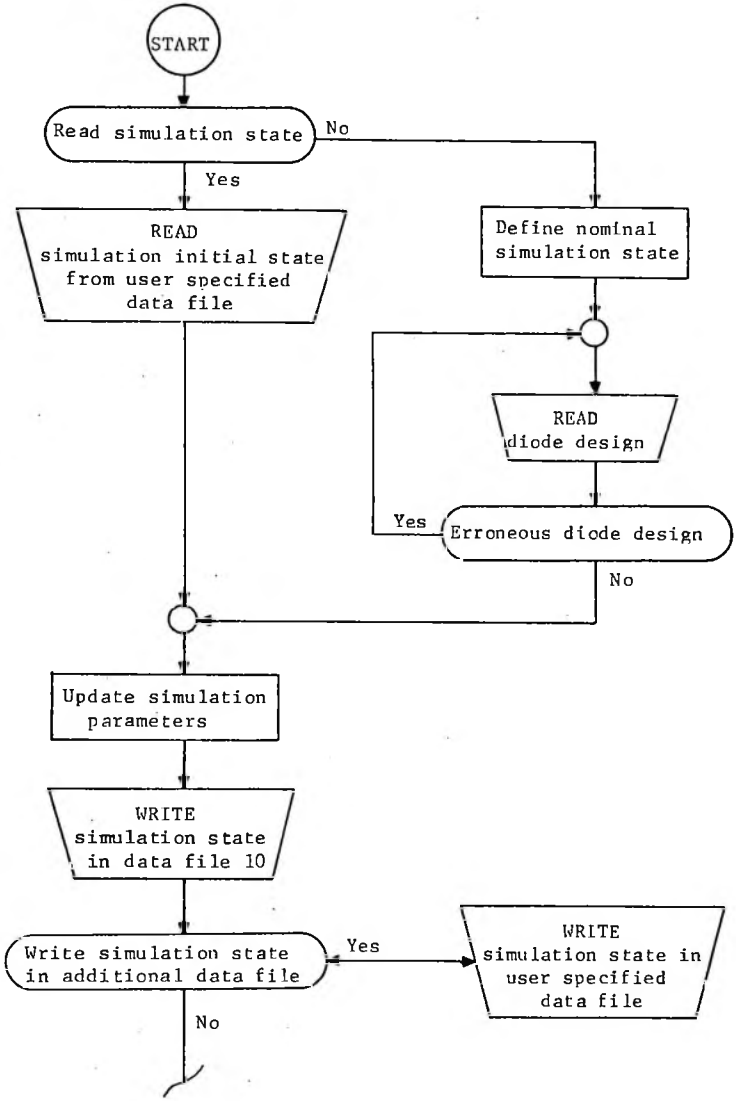


Fig. B.1. Flow Chart for Program DS

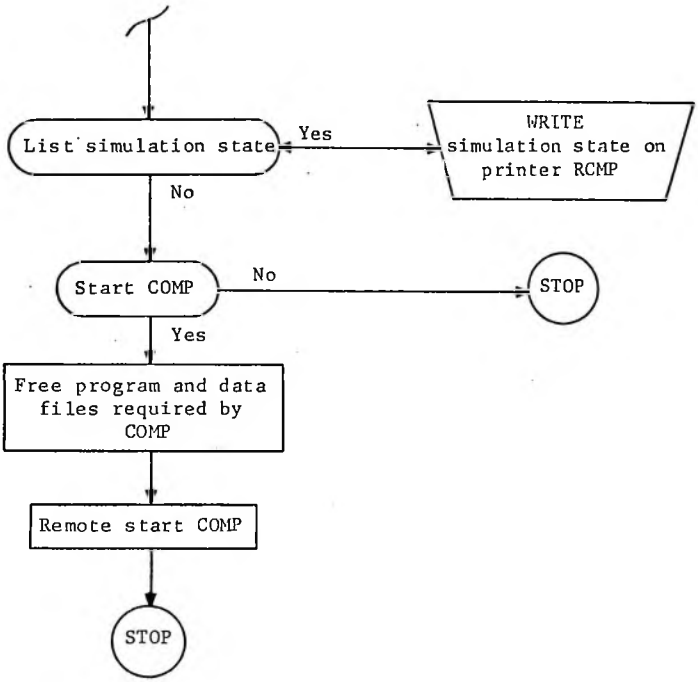


Fig. B.1. (Continued) Flow Chart for Program DS

```
      C**********  DS (DIODE SIMULATION)  **********
      C
      C DS INTERACTIVELY GENERATES AND/OR UPDATES INITIAL
      C STATES FOR THE DIODE SIMULATION PROGRAM COMP
      C THROUGH THE FOLLOWING OPERATIONS:
      C      1) UPDATING OF CONTROL AND MODEL PARAMETERS FOR AN
      C         EXISTING STATE
      C      2) GENERATION OF AN APPROXIMATE THERMAL EQUILIBRIUM
      C         STATE THROUGH ANALYTIC FORMULATION
      C      3) PRODUCE A STATE LISTING
      C THE DESIGNATED INITIAL STATE IS TRANSFERRED TO COMP
      C THROUGH DATA FILE 10.  DS PROVIDES A REMOTE START
      C OPTION FOR COMP, WHICH IS EXECUTED IN BATCH MODE.
      C
            IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      C
      C  CONTROL PARAMETERS
            INTEGER T,TMAX,RCMP,RCMPB,TLINC,TSINC
      C
      C  DIODE STRUCTURE AND PHYSICAL PARAMETERS
            INTEGER P
            DIMENSION XXN(101), DXM(110), DOPN(101)
      C
      C  INDEPENDENT VARIABLES
            DIMENSION HOL(101), ELE(101), E(101), V(101), TEMP(101)
      C
      C  SIMULATION PARAMETERS
            DIMENSION CSTIME(99)
      C
      C INITIAL STATE DATA
      C
      C ASSIGN DATA FILES
            CALL ERTRAN (6,'@ASG,AX 10. . ')
            CALL ERTRAN (6,'@ASG,AX 11. . ')
            CALL ERTRAN (6,'@ASG,AX 12. . ')
            CALL ERTRAN (6,'@ASG,AX 13. . ')
      C
      20    CONTINUE
      C
      C SPECIFY DATA FILE TO BE READ
            LF=10
            WRITE (6,30) LF
      30    FORMAT (I11,' STATE FILE TO BE READ')
      C
            READ (5,40) LF
      40    FORMAT (I11)
      C
      C THERMAL EQUILIBRIUM STATE GENERATION DEFAULT
            LFREAD=LF
            IF (LF.NE.0) GO TO 50
      C
      C  DATA ASSIGNMENTS
      C
      C  CONTROL PARAMETERS
            NSF=13
            T=0
```

Fig. B.2. Listing for Program DS

```
      TMAX=100
      TLINC=2
      TSINC=1
      RCMPB=136
      LCSPI=2
      LSCSPI=1
      NTYBND=0
      NTHDEP=1
      NCS=0
      LCS=1
      LSCS=0
      AITS=1.0D-4
C
C DIODE STRUCTURE AND PHYSICAL PARAMETERS
      P=101                          @ NO. OF N NODES
      DIEL=11.7D0                    @ SILICON
      TEMPO=300.0D0                  @ DEG. KEL.
      DONOR=1.0D16                   @ 1/CM**3
      ACCEPT=1.0D16                  @ 1/CM**3
      XMET=0.5D-4                    @ CM
      XL=1.0D-4                      @ CM
      CBEDS=2.8D19                   @ 1/CM**3
      VBEDS=1.04D19                  @ 1/CM**3
      ENGAP=1.082D0                  @ EV
      XDT=1.0D-5                     @ CM
      XHT=1.0D-5                     @ CM
C
C     SIMULATION PARAMETERS
      AREAD=1.0D-4                   @ CM**2
      DT=1.0D-12                     @ SEC
      TTIME=1.0D-0                   @ SEC
      THETA=1.0D0                    @ CRANK-NICOLSON FACTOR
      TIME=0.0D0                     @ SEC
      TAUN=1.0D-9                    @ SEC
      TAUP=1.0D-9                    @ SEC
      THCOND=1.5D0                   @ WATT/CM/DEG. KEL.
      THCONH=1.5D0                   @ WATT/CM/DEG. KEL.
      SPHEAT=0.7D0                   @ JOULE/G/DEG. KEL.
      DENSTY=2.33D0                  @ G/CM**3
      FDTMUL=1.4D0
C
      GO TO 90
50    CONTINUE
C
      LFRTEM=LFREAD
C
C  READ INITIAL STATE FILE LF
C
      INCLUDE RLF
C
      INCLUDE LFFORM
C
      LFREAD=LFRTEM
C
      I=1
      WRITE (6,60) I
60    FORMAT (I11,' I=1, STATE LISTING ONLY')
```

Fig. B.2. (Continued) Listing for Program DS

```
114             READ (5,70) I
115       70    FORMAT (I11)
116             IF (I.EQ.1) GO TO 280
117       C
118       C UPDATE CONTROL AND SIMULATION PARAMETERS ONLY
119             I=1
120             WRITE (6,80) I
121       80    FORMAT (I11,' I=1, UPDATE CONT. AND SIMUL. PARS. ONLY')
122             READ (5,70) I
123             IF (I.EQ.1) GO TO 170
124       C
125       90    CONTINUE
126       C
127       C  WRITE-READ DIODE SPEC. PARS.
128       C WRITE ON UNIT 6 AND READ NEW VALUES
129             LF=6
130             LRP=1
131             INCLUDE DSPECP
132             INCLUDE DSPECF
133             I=I
134       C
135       C EVALUATE AND TEST VALIDITY OF DEPLETION REGION
136       C
137       C EVALUATE INTRINSIC CARRIER CONCENTRATION
138             CALL INTRI (CBEDS,VBEDS,ENGAP,TEMPO,CARINT)
139       C
140             CALL DEPL (0,ACCEPT,DONOR,CARINT,XMET,DEPN,DEPP,DEPW,XDEPN,XDEPP,V
141            1DBIAN,DIEL,TEMPO)
142       C
143             WRITE (6,100) XMET,XL,DEPN,DEPP,XDEPN,XDEPP,VDBIAN,CARINT
144       100   FORMAT ('1***** DEPLETION REGION CHARACTERISTICS *****'//D11.4,' X
145            1MET, LOCATION OF MET. JUNCTION, CM'/D11.4,' XL, LOCATION OF P-CONT
146            2ACT, CM'/D11.4,' DEPN, DEPL REGION WIDTH ON N-SIDE, CM'/D11.4,' DE
147            3PP, DEPL. REGION WIDTH ON P-SIDE, CM'/D11.4,' XDEPN, DEPL. REG. HO
148            4UND. ON N-SIDE, CM'/D11.4,' XDEPP, DEPL. REG. BOUND. ON P-SIDE, CM
149            5'/D11.4,' VDBIAN, BUILT-IN VOLTAGE, VOLTS'/,D11.4,' CARINT, INTRIN.
150            6SIC CAR. CONC., 1/CM**3',//)
151             IF (XDEPN.LT.0.0) GO TO 110
152             IF (XDEPP.GT.XL) GO TO 110
153             GO TO 130
154       110   WRITE (6,120)
155       120   FORMAT (/,2(' ***** INVALID DIODE DESIGN *****'/),/' EITHER XDEPN<
156            10.0 OR XDEPP>XL'//)
157       C TERM. XQT, OR READ NEW DATA SET
158       C
159             GO TO 20
160       C
161       130   CONTINUE
162       C
163       C UPDATE DIODE AND/OR PHYSICAL PARS.
164             I=1
165             WRITE (6,140) I
166       140   FORMAT (I11,' I=1, UPDATE DIODE PARS.')
167             READ (5,70) I
168             IF (I.EQ.1) GO TO 90
169       C
170       C
```

Fig. B.2. (Continued) Listing for Program DS

```
171      C READ DIFFERENT FILE OR UPDATE THIS FILE ?
172            I=1
173            WRITE (6,150) I
174      150   FORMAT (I11,' I=1 READ DIFFERENT STATE FILE')
175            READ (5,70) I
176            IF (I.EQ.1) GO TO 20
177      C
178      C GENERATE APPROXIMATE INITIAL STATE
179            I=1
180            WRITE (6,160) I
181      160   FORMAT (I11,' I=1 GEN. APPROX. INIT. STATE')
182            READ (5,70) I
183            IF (I.NE.1) GO TO 190
184      C
185      C
186            CALL ISTG (P,ACCEPT,DONOR,XMET,XL,XDEPN,XD
187           1EPP,TEMPO,XXN,DXM,DOPN,HOL,ELE,E,V,TEMP,VDBISG,IDATE,ITIME,DIEL,CA
188           2RINT)
189      C
190            LFREAD=0
191      C
192      170   CONTINUE
193      C
194            I=1
195            WRITE (6,180) I
196      180   FORMAT (I11,' I=1, UPDATE CONT. PARS.')
197            READ (5,70) I
198            IF (I.NE.1) GO TO 210
199      C
200      190   CONTINUE
201      C
202      C WRITE-READ CONTROL PARS.
203      C WRITE ON UNIT 6 AND READ NEW VALUES
204            LF=6
205            LRP=1
206            INCLUDE DCONTP
207            INCLUDE DCONTF
208      C
209            I=1
210            WRITE (6,200) I
211      200   FORMAT (/,I11,' I=1, UPDATE CONT. PARS.')
212            READ (5,70) I
213            IF (I.EQ.1) GO TO 190
214      C
215      210   CONTINUE
216      C
217            I=1
218            WRITE (6,220) I
219      220   FORMAT (I11,' I=1, UPDATE MODEL PARS')
220            READ (5,70) I
221            IF (I.NE.1) GO TO 240
222      C
223      230   CONTINUE
224      C
225      C  WRITE-READ SIMULATION PARAMETERS
226      C WRITE ON UNIT 6 AND READ NEW VALUES
227            LF=6
```

Fig. B.2. (Continued) Listing for Program DS

```
      LRP=1
      INCLUDE DSIMP
      INCLUDE DSIMPF
C
C
      I=1
      WRITE (6,220) I
      READ (5,70) I
      IF (I.EQ.1) GO TO 230
C
240   CONTINUE
      I=1
      WRITE (6,180) I
      READ (5,70) I
      IF (I.EQ.1) GO TO 190
C
      I=1
      WRITE (6,250) I
250   FORMAT (I11,' I=1, READ DIFF. STATE FILE')
      READ (5,70) I
      IF (I.EQ.1) GO TO 20
C
      LF=11
      WRITE (6,260) LF
260   FORMAT (I11,' LF, FILE FOR NEW ST., 0 = TRANSFER FILE ONLY')
      READ (5,70) LF
      LFSTOR=LF
      IF (LF.EQ.0) GO TO 270
C
C WRITE VALUES INTO DATA FILE LF
      INCLUDE WLF
C
270   CONTINUE
C
C WRITE STATE TRANSFER FILE 10 FOR COMP
      LF=10
      INCLUDE WLF
      I=1
C
280   CONTINUE
C
C LIST INITIAL STATE PARAMETERS
      I=1
      WRITE (6,290) I
290   FORMAT (I11,' I=1, STATE PARAMETER LIST')
      READ (5,70) I
      IF (I.NE.1) GO TO 380
C
C ASSIGN OUTPUT SCRATCH DATA FILE 9.
      CALL ERTRAN (6,'@BRKPT 9 . ')
      CALL ERTRAN (6,'@FREE 9. . ')
      CALL ERTRAN (6,'@CAT 9(+1). . ')
      CALL ERTRAN (6,'@ASG,AX 9. . ')
C
      RCMP=136
      WRITE (6,300) RCMP
300   FORMAT (I11,' RCMP, SEL. PRINTER FOR STATE LISTING')
```

Fig. B.2. (Continued) Listing for Program DS

```
      READ (5,70) RCMP
C
C WRITE DIODE SPEC., CONT.,AND SIM. PARS. ON UNIT 9
      LF=9
      LRP=0
C
      WRITE (9,310) IDATE,ITIME
310   FORMAT ('1*************** DS **************',T98,'DATE ',A6,3X,'TI
     1ME ',A6,/)
C
      INCLUDE DSPECP
      INCLUDE DCONTP
      INCLUDE DSIMP
      I=1
C
C  DEPENDENT VARIABLE LIST
C
      I=1
      WRITE (6,320) I
320   FORMAT (I11,' I=1, DEPENDENT VARIABLE LIST')
      READ (5,70) I
      IF (I.NE.1) GO TO 390
C
C WRITE STATE PROFILE
      JJ=P-1
      DO 330 J=1,JJ
      DXM(J)=XXN(J+1)-XXN(J)
330   CONTINUE
      DXM(P)=DXM(JJ)
C
      IF(LPINT.LE.0)LPINT=1
      I=1
      K=51
340   CONTINUE
      IF(I.GT.P)I=P
      K=K+1
      IF (K.LT.52) GO TO 360
      K=1
      WRITE (9,350) IDATE,ITIME
350   FORMAT ('1*************** DS **************',T98,'DATE ',A6,3X,'T
     1IME ',A6,//,,T6,'I',T13,'XXN(I)',T25,'DXN(I)',T37,'DOPN(I)',T49,'H
     2OL(I)',T61,'ELE(I)',T73,'E(I)',T85,'V(I)',T97,'TEMP(I)',/)
360   WRITE (9,370) I,XXN(I),DXM(I),DOPN(I),HOL(I),ELE(I),E(I),V(I),TEMP
     1(I)
370   FORMAT (T2,I5,T9,8E12.5)
      IF (I.GE.P) GO TO 390
      I=I+LPINT
      GO TO 340
C
380   CONTINUE
C
      IF (RCMP.EQ.0) GO TO 400
C
390   CONTINUE
C
C SEND STATE LISTING TO DESIGNATED PRINTER
      CALL CLOSE (9,0)
```

Fig. B.2. (Continued) Listing for Program DS

```
342             CALL ERTRAN (6,'@FREE 9. . ')
343             IF (RCMP.EQ.100) CALL ERTRAN (6,'@SYM 9.,,PR . ')
344             IF (RCMP.EQ.101) CALL ERTRAN (6,'@SYM 9.,,RCMP01 . ')
345             IF (RCMP.EQ.102) CALL ERTRAN (6,'@SYM 9.,,RCMP02 . ')
346             IF (RCMP.EQ.136) CALL ERTRAN (6,'@SYM 9.,,RCMP36 . ')
347       C
348       400   CONTINUE
349       C
350             I=1
351             WRITE (6,410) I
352       410   FORMAT (I11,' I=1, INITIATE SIMULATION')
353             READ (5,70) I
354             IF (I.NE.1) STOP
355       C
356       C
357       C FREE RELAVENT FILES PRIOR TO REMOTE START OF COMP
358             CALL ERTRAN (6,'@FREE OSA. . ')
359             CALL ERTRAN (6,'@FREE C. . ')
360       C
361             CALL ERTRAN (6,'@FREE 7. . ')
362             CALL ERTRAN (6,'@FREE 8. . ')
363             CALL ERTRAN (6,'@FREE 10. . ')
364             CALL ERTRAN (6,'@FREE 11. . ')
365             CALL ERTRAN (6,'@FREE 12. . ')
366             CALL ERTRAN (6,'@FREE 13. . ')
367       C
368       C DESIGNATE PRINTER FOR COMP THROUGH REMOTE START
369              IF (RCMPB.EQ.100) CALL ERTRAN (6,'@START SB*OSA/J/V.SCOMPA,100 . '
370            1)
371             IF (RCMPB.EQ.101) CALL ERTRAN (6,'@START SB*OSA/J/V.SCOMPA,101 . '
372            1)
373             IF (RCMPB.EQ.102) CALL ERTRAN (6,'@START SB*OSA/J/V.SCOMPA,102 . '
374            1)
375             IF (RCMPB.EQ.136) CALL ERTRAN (6,'@START SB*OSA/J/V.SCOMPA,136 . '
376            1)
377       C
378              STOP
379              END
```

Fig. B.2. (Continued) Listing for Program DS

```
      RLF   PROC
      C
            READ (LF,1410) NSF,T,TMAX,RCMPB,P,LNORC,TLINC,TSINC,LCS,LSCS,LSCSP
     1I,LCSPI,LFREAD,LFSTOR,NTYBND,NTHDEP,NCS,IDATE,ITIME,IBLANK,IBLANK,
     2IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK
      C
            READ (LF,1420) DIEL,TEMPO,CARINT,DONOR,ACCEPT,XMET,XL,TAUN,TAUP,AR
     1EAD,DT,TTIME,TIME,THETA,VDBI,DX,DEPN,DEPP,DEPW,XDEPN,XDEPP,VDBIAN,
     2VDBISG,CURTOT,EXTCRI,FDTMUL,VDCOMP,CBEDS,VBEDS,ENGAP,THCOND,SPHEAT
     3,DENSTY,AITS,XDT,XHT,THCONH,DBLANK,DBLANK,DBLANK,DBLANK,DBLANK,DBL
     4ANK,DBLANK,DBLANK,DBLANK,DBLANK
      C
            READ (LF,1420) (XXN(I),DOPN(I),HOL(I),ELE(I),E(I),V(I),TEMP(I),I=1
     1,P)
      C
            IF (NCS.NE.0) READ (LF,1420) (CSTIME(I),I=1,NCS)
      C
            REWIND LF
      C
       END
      C
      WLF   PROC
      C
            WRITE (LF,1410) NSF,T,TMAX,RCMPB,P,LNORC,TLINC,TSINC,LCS,LSCS,LSCS
     1PI,LCSPI,LFREAD,LFSTOR,NTYBND,NTHDEP,NCS,IDATE,ITIME,IBLANK,IBLANK
     2,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK
      C
            WRITE (LF,1420) DIEL,TEMPO,CARINT,DONOR,ACCEPT,XMET,XL,TAUN,TAUP,A
     1READ,DT,TTIME,TIME,THETA,VDBI,DX,DEPN,DEPP,DEPW,XDEPN,XDEPP,VDBIAN
     2,VDBISG,CURTOT,EXTCRI,FDTMUL,VDCOMP,CBEDS,VBEDS,ENGAP,THCOND,SPHEA
     3T,DENSTY,AITS,XDT,XHT,THCONH,DBLANK,DBLANK,DBLANK,DBLANK,DBLANK,DB
     4LANK,DBLANK,DBLANK,DBLANK,DBLANK
      C
            WRITE (LF,1420) (XXN(I),DOPN(I),HOL(I),ELE(I),E(I),V(I),TEMP(I),I=
     11,P)
      C
            IF (NCS.NE.0) WRITE (LF,1420) (CSTIME(I),I=1,NCS)
      C
            END FILE LF
            REWIND LF
      C
       END
      C
      LFFORM PROC
      C
      C  DATA FILE READ-WRITE FORMATS
      1410  FORMAT (I30)
      1420  FORMAT (D30.18)
      C
       END
      C
      DSPECP PROC
      C
            WRITE (LF,1430)
            WRITE (LF,1440) DONOR
            IF (LRP.EQ.1) READ (5,1450) DONOR
```

Fig. B.3. Listing for FORTRAN Procedure Collection WRLF

```
57              WRITE (LF,1460) ACCEPT
58              IF (LRP.EQ.1) READ (5,1450) ACCEPT
59              WRITE (LF,1470) XL
60              IF (LRP.EQ.1) READ (5,1450) XL
61              WRITE (LF,1480) XMET
62              IF (LRP.EQ.1) READ (5,1450) XMET
63              WRITE (LF,1490) P
64              IF (LRP.EQ.1) READ (5,1550) P
65              WRITE (LF,1500) CBEDS
66              IF (LRP.EQ.1) READ (5,1450) CBEDS
67              WRITE (LF,1510) VBEDS
68              IF (LRP.EQ.1) READ (5,1450) VBEDS
69              WRITE (LF,1520) ENGAP
70              IF (LRP.EQ.1) READ (5,1450) ENGAP
71              WRITE (LF,1530) TEMPO
72              IF (LRP.EQ.1) READ (5,1450) TEMPO
73              WRITE (LF,1540) DIEL
74              IF (LRP.EQ.1) READ (5,1450) DIEL
75      C
76       END
77      C
78      DSPECF PROC
79      C
80      1430  FORMAT ('  DIODE STRUCTURE AND PHYSICAL PARAMETERS'/)
81      1440  FORMAT (D11.4,' DONOR, N-TYPE IMP. CONC.,1/CM**3')
82      1450  FORMAT (D11.4)
83      1460  FORMAT (D11.4,' ACCEPT, P-TYPE IMP. CONC., 1/CM**3')
84      1470  FORMAT (D11.4,' XL, LOCATION OF P-CONTACT, CM')
85      1480  FORMAT (D11.4,' XMET, LOCATION OF MET. JUNCT., CM')
86      1490  FORMAT (I11,' P, NUMBER OF N-NODES')
87      1500  FORMAT (D11.4,' CBEDS, COND. BAND EFFECTIVE DEN. STATES, 1/CM**3')
88      1510  FORMAT (D11.4,' VBEDS, VAL. BAND EFFECTIVE DEN. STATES, 1/CM**3')
89      1520  FORMAT (D11.4,' ENGAP, ENERGY GAP, EV')
90      1530  FORMAT (D11.4,' TEMPO, INITIAL TEMP., DEG. KEL.')
91      1540  FORMAT (D11.4,' DIEL, DIELECTRIC CONSTANT')
92      1550  FORMAT (I11)
93      C
94       END
95      C
96      DCONTP PROC
97      C
98              WRITE (LF,1560)
99              WRITE (LF,1570) NSF
100             IF (LRP.EQ.1) READ (5,1800) NSF
101             WRITE (LF,1580) CURTOT
102             IF (LRP.EQ.1) READ (5,1810) CURTOT
103             WRITE (LF,1590) NTYBND
104             IF (LRP.EQ.1) READ (5,1800) NTYBND
105             WRITE (LF,1600) NTHDEP
106             IF (LRP.EQ.1) READ (5,1800) NTHDEP
107             WRITE (LF,1610) RCMPB
108             IF (LRP.EQ.1) READ (5,1800) RCMPB
109             WRITE (LF,1620) TIME
110             IF (LRP.EQ.1) READ (5,1810) TIME
111             WRITE (LF,1630) TTIME
112             IF (LRP.EQ.1) READ (5,1810) TTIME
113             WRITE (LF,1640) DT
```

Fig. B.3. (Continued) Listing for FORTRAN Procedure Collection WRLF

```
114             IF (LRP.EQ.1) READ (5,1810) DT
115             WRITE (LF,1650) T
116             IF (LRP.EQ.1) READ (5,1800) T
117             WRITE (LF,1660) TMAX
118             IF (LRP.EQ.1) READ (5,1800) TMAX
119             WRITE (LF,1670) FDTMUL
120             IF (LRP.EQ.1) READ (5,1810) FDTMUL
121             NGALFA=0
122             IF(LRP.EQ.1.AND.FDTMUL.LT.0.500) NGALFA=1
123             IF(NGALFA.EQ.1) CALL DTMUL(20,TIME,TTIME,DT,T,TMAX,FDTMUL)
124             IF(NGALFA.EQ.1) WRITE(LF,1670) FDTMUL
125             IF(NGALFA.EQ.1) READ(5,1810) FDTMUL
126             WRITE (LF,1680) TLINC
127             IF (LRP.EQ.1) READ (5,1800) TLINC
128             WRITE (LF,1690) TSINC
129             IF (LRP.EQ.1) READ (5,1800) TSINC
130             WRITE (LF,1700) LCS
131             IF (LRP.EQ.1) READ (5,1800) LCS
132             IF (LCS.EQ.1) WRITE (LF,1710) LCSPI
133             IF (LRP.EQ.1.AND.LCS.EQ.1) READ (5,1800) LCSPI
134             WRITE (LF,1720) LSCS
135             IF (LRP.EQ.1) READ (5,1800) LSCS
136             IF (LSCS.EQ.1) WRITE (LF,1730) LSCSPI
137             IF (LRP.EQ.1.AND.LSCS.EQ.1) READ (5,1800) LSCSPI
138             WRITE (LF,1740) NCS
139             IF (LRP.EQ.1) READ (5,1800) NCS
140             LRPT=0
141             IF (LRP.EQ.1.AND.NCS.GT.0) WRITE (LF,1770) LRPT
142             IF (LRP.EQ.1.AND.NCS.GT.0) READ (5,1800) LRPT
143             IF (NCS.NE.0) CALL CST (NCS,LF,LRPT,CSTIME)
144             WRITE (LF,1750) LFREAD
145             WRITE (LF,1760) LFSTOR
146             WRITE (LF,1780) IDATE
147             WRITE (LF,1790) ITIME
148     C
149      END
150     C
151     DCONTF PROC
152     C
153     1560  FORMAT (/' CONTROL PARAMETERS',/)
154     1570  FORMAT (I11,' NSF, NEW ST. FILE')
155     1580  FORMAT (D11.4,' CURTOT, TERMINAL CURRENT DENSITY')
156     1590  FORMAT (I11,' NTYBND, TYPE BND. COND. X=XL, 0-CUR.,1-OHMIC')
157     1600  FORMAT (I11,' NTHDEP, THERMAL DEPENDENCE, 0-NO, 1-YES')
158     1610  FORMAT (I11,' RCMPB, SEL. PRINTER FOR COMP.')
159     1620  FORMAT (D11.4,' INITIAL TIME, DEPN. VAR.')
160     1630  FORMAT (D11.4,' TTIME, MAX. SIMULATION TIME, SEC')
161     1640  FORMAT (D11.4,' DT, INITIAL TIME INCREMENT, SEC')
162     1650  FORMAT (I11,' T, TIME INC. COUNTER, INITIAL VALUE')
163     1660  FORMAT (I11,' TMAX, MAX. T')
164     1670  FORMAT (D11.4,' FDTMUL, FORWARD DT MULTIPLICATION FACTOR')
165     1680  FORMAT (I11,' TLINC, TIME STEP PRINT INC.')
166     1690  FORMAT (I11,' TSINC, TIME STEP STORAGE INC.')
167     1700  FORMAT (I11,' LCS, 1-LIST CROSS SECTIONS')
168     1710  FORMAT (I11,' LCSPI, CROSS SECTION PRINT INTERVAL ')
169     1720  FORMAT (I11,' LSCS, 1-STORE CROSS SECTIONS')
170     1730  FORMAT (I11,' LSCSPI, CROSS SECTION STORE INTERVAL')
```

Fig. B.3. (Continued) Listing for FORTRAN Procedure Collection WRLF

```
      1740  FORMAT (I11,' NCS, NO. OF ADDITIONAL CROSS SECTIONS')
      1750  FORMAT (I11,' LFREAD, DATA FILE READ')
      1760  FORMAT (I11,' LFSTOR, DATA FILE WRITTEN')
      1770  FORMAT (I11,' LRPT, 1 - UPDATE CROSS SECTION TIMES')
      1780  FORMAT (A11,' IDATE, STATE GENERATION DATE')
      1790  FORMAT (A11,' ITIME, STATE GENERATION TIME')
      1800  FORMAT (I11)
      1810  FORMAT (D11.4)
      C
       END
      C
      DSIMP PROC
      C
            WRITE (LF,1820)
            WRITE (LF,1830) CARINT
            WRITE (LF,1840) AREAD
            IF (LRP.EQ.1) READ (5,1970) AREAD
            WRITE (LF,1850) XDT
            IF (LRP.EQ.1) READ (5,1970) XDT
            WRITE (LF,1860) XHT
            IF (LRP.EQ.1) READ (5,1970) XHT
            WRITE (LF,1870) TAUN
            IF (LRP.EQ.1) READ (5,1970) TAUN
            WRITE (LF,1880) TAUP
            IF (LRP.EQ.1) READ (5,1970) TAUP
            WRITE (LF,1890) AITS
            IF (LRP.EQ.1) READ (5,1970) AITS
            WRITE (LF,1900) THCOND
            IF (LRP.EQ.1) READ (5,1970) THCOND
            WRITE (LF,1910) THCONH
            IF (LRP.EQ.1) READ (5,1970) THCONH
            WRITE (LF,1920) SPHEAT
            IF (LRP.EQ.1) READ (5,1970) SPHEAT
            WRITE (LF,1930) DENSTY
            IF (LRP.EQ.1) READ (5,1970) DENSTY
            WRITE (LF,1940) LNORC
            IF (LRP.EQ.1) READ (5,1980) LNORC
            WRITE (LF,1950) VOBIAN,VOBISG,VDCOMP,VOBI
            IF (LRP.EQ.1) READ (5,1960) VOBI
      C
       END
      C
      DSIMPF PROC
      C
      1820  FORMAT (/,'  DIODE MODEL PARAMETERS '/)
      1830  FORMAT (D11.4,' CARINT, INTRINSIC CAR. CONC., 1/CM**3')
      1840  FORMAT (D11.4,' AREAD,DIODE AREA, CM**2')
      1850  FORMAT (D11.4,' XDT, DIODE THICKNESS, CM')
      1860  FORMAT (D11.4,' XHT, HEADER THICKNESS, CM')
      1870  FORMAT (D11.4,' TAUN, ELECTRON LIFETIME, SEC')
      1880  FORMAT (D11.4,' TAUP, HOLE LIFETIME, SEC')
      1890  FORMAT (D11.4,' AITS, IONIZATION TEMP COEFF.')
      1900  FORMAT (D11.4,' THCOND, DIODE THERMAL COND., WATT/CM/DEG. KEL.')
      1910  FORMAT (D11.4,' THCONH, HEADER THERMAL COND., WATT/CM/DEG. KEL.')
      1920  FORMAT (D11.4,' SPHEAT, SPECIFIC HEAT, JOULE/G/DEG. KEL.')
      1930  FORMAT (D11.4,' DENSTY, G/CM**3')
      1940  FORMAT (I11,' LNORC, 1 - LIST NORM CONSTANTS')
```

Fig. B.3. (Continued) Listing for FORTRAN Procedure Collection WRLF

```
228      1950  FORMAT (/,D30.18,' VDBIAN, ANALYTIC',/,D30.18,' VDBISG, IN. ST .A
229           1PPROX.',/,D30.18,' VDCOMP, VDT FROM COMP',/,D30.18,' VDBI, PARAMET
230           2ER')
231      1960  FORMAT (D30.18)
232      1970  FORMAT (D11.4)
233      1980  FORMAT (111)
234      C
235       END
```

Fig. B.3. (Continued) Listing for FORTRAN Procedure Collection WRLF

total number of time steps desired and the final time. DTMUL is called by the FORTRAN procedure DCONTP from program DS when the specified value for α is less than 0.5, an unusually low value; otherwise, the user specified value is accepted and DTMUL is not called. Source listing for DTMUL is presented in Fig. B.4.

Subroutine CST

CST is called by procedure DCONTP to input/output simulation cross section print/storage times. This operation is performed through a subroutine to maintain the general form of the input/output FORTRAN procedures. Source listing for CST is presented in Fig. B.4.

Subroutine NTAB$

NTAB$ is written in assembler language and is used by the FORTRAN V input/output routines to link the unit designations of the FORTRAN V input/output statements to a hardware device and external files on that device. NTAB$ source listing is presented in Fig. B.4.

Subroutine ISTG

ISTG generates a uniform spacial grid according to the diode total length, x_L, and the number of n-nodes, P. Next, hole and electron concentrations, electric field and voltage profiles are evaluated over the uniform grid through analytic formulation for thermal equilibrium conditions assuming an abrupt junction geometry. Furthermore, the temperature profile is assumed constant and assigned the diode initial temperature specified in calling program DS. These variable profiles are used as initial conditions by DS to generate a simulation initial state corresponding to thermal equilibrium. Source listing for ISTG is presented in Fig. B.5.

```
      SUBROUTINE DTMUL(NTRIS,TMIN,TMAX,DT,NMIN,NMAX,ALFA)
C
C EVALUATES OPTIMAL GEOMETRIC SERIES FACTOR, ALFA
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      N=NMAX-NMIN
      TA=(TMAX-TMIN)/DT
      DN=N
      NN=1000000
      IF(TA.LT.1000000) NN=TA
      IF(N.LE.NN) GO TO 5
      ALFAMA=0.5D0
      ALFAMI=1.0D0
      GO TO 9
5     CONTINUE
      ALFAMA=1.5D0
      ALFAMI=1.0D0
9     CONTINUE
C
      DO 15 K=1,NTRIS
      ALFA=(ALFAMA+ALFAMI)/2.0D0
      DIF=(ALFA**DN-1.0D0)-TA*DLOG(ALFA)
C
      IF(DIF.GT.0.0D0) GO TO 10
      ALFAMI=ALFA
      GO TO 15
10    CONTINUE
      ALFAMA=ALFA
15    CONTINUE
C
      RETURN
      END
```

(a) Listing for DTMUL

```
      SUBROUTINE CST(NCS,LF,LRP,CSTIME)
C
C INPUT/OUTPUT OF SIMULATION CROSS SECTION PRINT AND/OR
C STORAGE TIMES
C
      DOUBLE PRECISION CSTIME(10)
C
C
      DO 10 I=1,NCS
      WRITE(LF,1457) CSTIME(I),I
1457  FORMAT(D11.4,' CSTIME(',I2,') CROSS SECTION TIME, SEC')
      IF(LRP.EQ.1) READ(5,1460) CSTIME(I)
1460  FORMAT(D11.4)
10    CONTINUE
C
      RETURN
      END
```

(b) Listing for CST

```
N$TAB 50,1,1,1,1,1 6 1 5 4 9
END
```

(c) Listing for NTAB$

Fig. B.4. Listing for Subroutines DTMUL, CST and NTAB$

```
      SUBROUTINE ISTG (NP,ACCEPT,DONOR,XMET,XL,X
     1DEPN,XDEPP,TEMPO,XN,DXM,DOPN,HOL,ELE,E,V,TEMP,VOBISG,IDATE,ITIME,D
     2IEL,CARINT)
C
C SUB ISTG GENERATES AN ANALYTIC THERMAL EQUILIBRIUM
C INITIAL STATE WITH UNIFORM GRID.
C
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
      DIMENSION XN(1), DXM(1), DOPN(1), HOL(1), ELE(1), E(1), V(1), TEMP
     1(1)
C
C SET IDATE AND ITIME
      CALL ERTRAN (9,IDATE,ITIME)
C
C PHYSICAL CONSTANTS
      Q=1.6D-19
      BOZ=1.381D-23
      PERM=8.854D-14
      QKT=Q/BOZ/TEMPO
C
C EVALUATION OF THERMAL EQUILIBRIUM CARRIER CONC. VALUES
      TDON=DONOR/CARINT
      TACC=ACCEPT/CARINT
C
C TEMPERATURE DEPENDENCE FOR SUB. THEQCA CONVEYED
C THROUGH NORMALIZATION OF CARRIER CONCS.  IMPURTIES
C ASSUMED FULLY IONIZED.
      CALL THEQCA (TDON,TACC,HOLXO,ELEXO,HOLXL,ELEXL,VOBIAN)
C
C UNNORMALIZE CONCS.
      HOLXO=HOLXO*CARINT
      ELEXO=ELEXO*CARINT
      HOLXL=HOLXL*CARINT
      ELEXL=ELEXL*CARINT
C
C
C GENERATE LINEAR GRID AND ABRUPT IMPURITY PROFILE
      NPM1=NP-1
      XN(1)=0.0
      DOPN(1)=DONOR
      DXN=XL/NPM1
      DO 40 K=2,NP
      XN(K)=XN(K-1)+DXN
      IF (XN(K).GT.XMET) GO TO 20
      DOPN(K)=DONOR
      GO TO 30
20    CONTINUE
      DOPN(K)=-ACCEPT
30    CONTINUE
      DXM(K-1)=XN(K)-XN(K-1)
40    CONTINUE
      XN(NP)=XL
C
C GENERATE ANALYTIC ELECTRIC FIELD
      TN=Q*DONOR/(PERM*DIEL)
```

Fig. B.5. Listing for Subroutine ISTG

```
      TP=Q*ACCEPT/(PERM*DIEL)
      EN=TN*(XMET-XDEPN)
C
      DO 80 K=1,NP
      IF (XN(K).GT.XDEPN) GO TO 50
C N-SIDE BULK REGION
      E(K)=0.0
      GO TO 80
50    CONTINUE
      IF (XN(K).GT.XMET) GO TO 60
C N-SIDE DEPLETION REGION
      E(K)=TN*(XN(K)-XDEPN)
      GO TO 80
60    CONTINUE
      IF (XN(K).GT.XDEPP) GO TO 70
C P-SIDE DEPLETION REGION
      E(K)=EN-TP*(XN(K)-XMET)
      GO TO 80
70    CONTINUE
C P-SIDE BULK REGION
      E(K)=0.0
80    CONTINUE
C
C EVALUATE ANALYTICALLY: HOL, ELE, V, AND INITIALIZE TEMP
C
      TA=(XDEPN**2)/2.0
      TB=XMET+DONOR/ACCEPT*(XMET-XDEPN)
      TC=TN*((1.0+ACCEPT/DONOR)*XMET**2-XDEPN**2)/2.0
C
      DO 120 K=1,NP
      TEMP(K)=TEMPO
      IF (XN(K).GT.XDEPN) GO TO 90
C N-SIDE BULK REGION
      DOPN(K)=DONOR
      E(K)=0.0
      V(K)=0.0
      HOL(K)=HOLXO
      ELE(K)=ELEXO
      GO TO 120
90    CONTINUE
      IF (XN(K).GT.XMET) GO TO 100
C N-SIDE DEPLETION REGION
      DOPN(K)=DONOR
      E(K)=TN*(XN(K)-XDEPN)
      V(K)=TN*((XDEPN-XN(K)/2.0)*XN(K)-TA)
      HOL(K)=HOLXO*DEXP(-QKT*V(K))
      ELE(K)=ELEXO*DEXP(QKT*V(K))
      GO TO 120
100   CONTINUE
      IF (XN(K).GT.XDEPP) GO TO 110
C P-SIDE DEPLETION REGION
      DOPN(K)=-ACCEPT
      E(K)=EN-TP*(XN(K)-XMET)
      V(K)=TP*(XN(K)/2.0-TB)*XN(K)+TC
      HOL(K)=HOLXO*DEXP(-QKT*V(K))
      ELE(K)=ELEXO*DEXP(QKT*V(K))
      GO TO 120
```

Fig. B.5. (Continued) Listing for Subroutine ISTG

```
      110   CONTINUE
C P-SIDE BULK REGION
      DOPN(K)=-ACCEPT
      E(K)=0.0
      V(K)=V(K-1)
      HOL(K)=HOLXL
      ELE(K)=ELEXL
120   CONTINUE
C
      VOBISG=V(NP)
C
      RETURN
      END
```

Fig. B.5. (Continued) Listing for Subroutine ISTG

Subroutine THEQCA

THEQCA assumes an abrupt junction diode configuration and evaluates thermal equilibrium hole and electron concentration values for the acceptor and donor concentrations. The corresponding built-in voltage is also calculated. THEQCA source listing is presented in Fig. B.6.

Subroutine INTRI

INTRI evaluates the intrinsic carrier concentration. INTRI source listing is presented in Fig. B.6.

Subroutine DEPL

DEPL assumes an abrupt junction diode configuration. It evaluates the respective depletion region edges with respect to the n-side contact. The two depletion widths are also calculated along with the built-in voltage. DEPL source listing is presented in Fig. B.7.

B.2 PROGRAM COMP

COMP is the computer program implementation of the numerical diode model developed in Chapter 3. Accordingly, the diode simulation is performed by COMP and is most conveniently executed in batch mode since the average run time is several minutes. COMP obtains all input data from the simulation initial state data file 10, which is designated as the transfer data file between DS and COMP. Although it is most convenient to define data file 10 through DS, it is not necessary as long as the simulation state data format shown in Table B.1 is maintained. COMP is designed to facilitate an arbitary impurity profile and a

```
      SUBROUTINE THEQCA(DONOR,ACCEPT,HOLXO,ELEXO,HOLXL,
     1ELEXL,VDBIAN)
C
C SUB. THEQCA GENERATES THERMAL EQUILIBRIUM HOLE AND
C ELECTRON CONCENTRATION FOR THE DONOR AND ACCEPTOR
C IMPURITY LEVELS RESPECTIVELY.  THE CORRESPONDING BUILT-
C IN VOLTAGE IS ALSO EVALUATED.  ALL ARGUMENTS ARE
C ASSUMED APPROPRIATELY NORMALIZED BY EITHER INTRINSIC
C CAR. CONC. OR THERMAL VOLT. CORRESPONDING TO SPECIFIED
C TEMPERATURE.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C FUNCTION 'ROOT' EVALUATES MAJORITY CAR. CONC.
      DEFINE ROOT(TA)=DABS(TA)/2.0D0+DSQRT(TA*
     1TA/4.0D0+1.0D0)
C
C EVALUATE MAJORITY CARRIER CONC. ON N-SIDE
      ELEXO=ROOT(DONOR)
C
C EVALUATE MINORITY CARRIER CONC. ON N-SIDE
      HOLXO=1.0D0/ELEXO
C
C EVALUATE MAJORITY CARRIER CONC. ON P-SIDE
      HOLXL=ROOT(ACCEPT)
C
C EVALUATE MINORITY CARRIER CONC. ON P-SIDE
      ELEXL=1.0D0/HOLXL
C
C EVALUATE DIODE BUILT-IN VOLTAGE
      VDBIAN=-DLOG(ELEXO/ELEXL)
C
      RETURN
      END
```

(a) Listing for THEQCA

```
      SUBROUTINE INTRI(CBEDS,VBEDS,ENGAP,TEMP,CARINT)
C
C SUB. INTRI COMPUTES INTRINSIC CAR. CONC.
C
C CBEDS   - COND. BAND EFFECTIVE DENSITY OF STATES, 1/CM**3
C VBEDS   - VALANCE BAND EFFICTIVE DENSITY OF STATES, 1/CM**3
C ENGAP   - ENERGY GAP, EV
C TEMP    - TEMPERATURE, DEG. KEL.
C CARINT  - INTRINSIC CAR. CONC., 1/CM**3
C Q       - UNIT CHARGE, COULOMBS
C BOZ     - BOLTZMANN'S CONST., JOULES/DEG. KEL.
C
      DOUBLE PRECISION CBEDS,VBEDS,ENGAP,TEMP,CARINT
      DOUBLE PRECISION Q,BOZ
C
      Q=1.6D-19
      BOZ=1.381D-23
      CARINT=DSQRT(CBEDS*VBEDS)*DEXP(-ENGAP*Q/(TEMP*BOZ*2.0D0))
C
      RETURN
      END
```

(b) Listing for INTRI

Fig. B.6. Listing for Subroutine THEQCA and INTRI

```
      SUBROUTINE DEPL(L,ACCEPT,DONOR,CARINT,XMET,DEPN,DEPP,DEPW,XDEPN,
     1XDEPP,VDBIAN,DIEL,TEMP)
C
C EVALUATES DEPLETION REGION CHARACTERISTICS THROUGH
C ANALYTIC FORMULATION FOR AN ABRUPT JUNCTION CONFIGURATION
C
      DOUBLE PRECISION ACCEPT,DONOR,CARINT,XMET,DIEL,TEMP
      DOUBLE PRECISION DEPN,DEPP,DEPW,XDEPN,XDEPP,VDBIAN
      DOUBLE PRECISION Q,BOZ,PERM
      DOUBLE PRECISION HOLXO,ELEXO,HOLXL,ELEXL
      DOUBLE PRECISION TA,TB
C PHYSICAL CONSTANTS
      Q=1.6D-19                          @ COULOMBS
      BOZ=1.381D-23                      @ JOULES/DEG. KEL.
      PERM=8.854D-14                     @ FARADS/CM, FREE SPACE PERM
C
C EVALUATE DIODE BUILT-IN VOLTAGE, VDBIAN
      TA=ACCEPT/CARINT
      TB=DONOR/CARINT
C
      CALL THEQCA(TB,TA,HOLXO,ELEXO,HOLXL,ELEXL,VDBIAN)
C
      VDBIAN=VDBIAN*BOZ*TEMP/Q
C
C EVALUATION OF DEPLETION REGION BOUNDARIES
      TA=ACCEPT*DONOR
      TB=DABS(2.D00*DIEL*PERM*VDBIAN/Q)
      DEPN=(TB*ACCEPT/(TA+DONOR*DONOR))**0.5
      DEPP=(TB*DONOR/(TA+ACCEPT*ACCEPT))**0.5
      DEPW=DEPN+DEPP
      XDEPN=XMET-DEPN
      XDEPP=XMET+DEPP
C
      IF(L.NE.1) RETURN
C
      WRITE(9,1001)
 1001 FORMAT('1 ***** SUBROUTINE DEPL *****'//
     1'  SUB. DATA'/)
      WRITE(9,1002) ACCEPT
 1002 FORMAT(12,D15.4,' ACCEPT')
      WRITE(9,1003) DONOR
 1003 FORMAT(12,D15.4,' DONOR')
      WRITE(9,1004) CARINT
 1004 FORMAT(12,D15.4,' CARINT')
      WRITE(9,1005) XMET
 1005 FORMAT(12,D15.4,' XMET')
      WRITE(9,1006) DIEL
 1006 FORMAT(12,D15.4,' DIEL')
      WRITE(9,1007) TEMP
 1007 FORMAT(12,D15.4,' TEMP')
      WRITE(9,1008) Q
 1008 FORMAT(12,D15.4,' Q')
      WRITE(9,1009) BOZ
 1009 FORMAT(12,D15.4,' BOZ')
      WRITE(9,1010) PERM
 1010 FORMAT(12,D15.4,' PERM')
```

Fig. B.7. Listing for Subroutine DEPL

```
57            WRITE(9,1011)
58       1011 FORMAT(//'  SUB. OUTPUT'/)
59            WRITE(9,1012) VOBIAN
60       1012 FORMAT(T2,D15.4,' VOBIAN')
61            WRITE(9,1013) DEPN
62       1013 FORMAT(T2,D15.4,' DEPN')
63            WRITE(9,1014) DEPP
64       1014 FORMAT(T2,D15.4,' DEPP')
65            WRITE(9,1015) DEPW
66       1015 FORMAT(T2,D15.4,' DEPW')
67            WRITE(9,1016) XDEPN
68       1016 FORMAT(T2,D15.4,' XDEPN')
69            WRITE(9,1017) XDEPP
70       1017 FORMAT(T2,D15.4,' XDEPP')
71            WRITE(9,1018) HOLXO,ELEXO,HOLXL,ELEXL
72      1018  FORMAT(4(T2,D30.16,/))
73      C
74      C ERRONEOUS CALCULATION TO SUPPRESS DIAGNOSTICS IN
75      C RFOR
76            TA=HOLXO*ELEXO/HOLXL/ELEXL
77      C
78            RETURN
79            END
```

Fig. B.7. (Continued) Listing for Subroutine DEPL

nonuniform spacial grid. These model features are not presently available, however, since DS is not capable of generating appropriate simulation initial states. Two of the boundary condition systems considered in Chapter 3 are available. One, the current boundary condition system, is assumed by default. The other, a hybrid boundary condition system must be specified. In conjunction with these boundary conditions, a constant current excitation is used by COMP. Temperature may be included as a dependent variable on an optional basis. If not specified as a dependent variable, the temperature profile obtained from the simulation initial state is maintained constant, independent of time; i.e., an isothermal simulation is performed. The mobilities and ionization coefficients for holes and electrons are evaluated through four respective subroutines which are all formulated for silicon. Simulations for a different type semiconductor would require redefining these four subroutines. Output from COMP for a simulation may be divided into three catagories: printer simulation summary, stored simulation summary for graphic analysis, and stored simulation final state. The printer and stored versions of the simulation summary contain similar information, and one, or the other, or both may be requested. In either case, the simulation summary contains diode cross sections at arbitrarily specified points in time and a transient data summary acquired by sampling transient quantities at equal intervals of iteration cycles. An example of the printer simulation summary is presented in Fig. B.8 along with respective symbol definitions in Tables B.1 and B.2. The simulation final state is stored in the

```
                                                                                    DATE 061775        PAGE     1
********** COMP **********                                                          TIME 114554

 DIODE STRUCTURE AND PHYSICAL PARAMETERS

 .1000+018 DONOR, N-TYPE IMP. CONC.,1/CM**3
 .1000+018 ACCEPT, P-TYPE IMP. CONC., 1/CM**3
 .3000-003 XL, LOCATION OF P-CONTACT, CM
 .1500-003 XMET, LOCATION OF MET. JUNCT., CM
       101 P, NUMBER OF N-NODES
 .2800+020 CBEDS, COND. BAND EFFECTIVE DEN. STATES, 1/CM**3
 .1040+020 VBEDS, VAL. BAND EFFECTIVE DEN. STATES, 1/CM**3
 .1082+001 ENGAP, ENERGY GAP, EV
 .3000+003 TEMPO, INITIAL TEMP., DEG. KEL.
 .1170+002 DIEL, DIELECTRIC CONSTANT

CONTROL PARAMETERS

        12 NSF, NEW ST. FILE
 .1000-003 CURTOT, TERMINAL CURRENT DENSITY
         0 NTTBND, TYPE BND. COND. X=AL, 0-CUR.,1-OHMIC
         1 NTHDEP, THERMAL DEPENDENCE, 0-NO, 1-YES
       136 RCMPD, SEL. PRINTER FOR COMP.
 .0000     INITIAL TIME, DEPN. VAR.
 .2500+002 TTIME, MAX. SIMULATION TIME, SEC
 .1000-007 DT, INITIAL TIME INCREMENT, SEC
         0 T, TIME INC. COUNTER, INITIAL VALUE
       100 TMAX, MAX. T
 .1222+001 FDTMUL, FORWARD DT MULTIPLICATION FACTOR
         2 TLINC, TIME STEP PRINT INC.
         2 TSINC, TIME STEP STORAGE INC.
         1 LCS, 1-LIST CROSS SECTIONS
         2 LCSPI, CROSS SECTION PRINT INTERVAL
         0 LSCS, 1-STORE CROSS SECTIONS
         0 NCS, NO. OF ADDITIONAL CROSS SECTIONS
        10 LFREAD, DATA FILE READ
         0 LFSTOR, DATA FILE WRITTEN
    060675 IDATE, STATE GENERATION DATE
    004241 ITIME, STATE GENERATION TIME

 DIODE MODEL PARAMETERS

 .1440+011 CARINT, INTRINSIC CAR. CONC., 1/CM**3
 .1000-003 AREAD,DIODE AREA, CM**2
 .1000-004 XDT, DIODE THICKNESS, CM
 .2500-004 XHT, HEADER THICKNESS, CM
 .1000-009 TAON, ELECTRON LIFETIME, SEC
 .1000-009 TAOP, HOLE LIFETIME, SEC
 .2000-003 AITS, IONIZATION TEMP COEFF.
 .5000-005 THCOND, DIODE THERMAL COND., WATT/CM/DEG. KEL.
 .5000-005 THCONH, HEADER THERMAL COND., WATT/CM/DEG. KEL.
 .7000+000 SPHEAT, SPECIFIC HEAT, JOULE/G/DEG. KEL.
 .2330+001 DENSTY, G/CM**3
         0 LNORC, 1 - LIST NORM CONSTANTS

     -.8158334698068295391+000 VDBIAN, ANALYTIC
     -.8034260137835950834+000 VDBISG, IN. ST .A PPROX.
      .0000000000000000000     VDCOMP, VDT FROM COMP
```

Fig. B.8. Simulation Summary Example

-.81563346986295391+000 VDBI, PARAMETER

Fig. B.8. (Continued) Simulation Summary Example

DIODE CROSS SECTION, Y= 0 TIME= .000 TIME 114554

N	XAN	DXN	DOPN	HOL	ELE	E	V	TEMP	CURHOL	CURELE	CURDIS	PIO	CI	GS	GI
1	.000	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	.000	.144+11	.398-03	.000
3	.600-05	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
5	.120-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
7	.180-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
9	.240-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
11	.300-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
13	.360-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
15	.420-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
17	.480-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
19	.540-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.432-03	.000
21	.600-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
23	.660-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
25	.720-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.432-03	.000
27	.780-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
29	.840-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
31	.900-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
33	.960-04	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.398-03	.000
35	.102-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
37	.108-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
39	.114-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.432-03	.000
41	.120-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
43	.126-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
45	.132-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
47	.138-03	.300-05	.100+18	.207+04	.100+18	.000	.000	.300+03	.000	.000	.100-03	-.314+00	.144+11	.360-03	.000
49	.144-03	.300-05	.100+18	.335+04	.619+17	.196+05	.000	.300+03	-.308-07	-.795+04	.795+04	.418+16	.144+11	.202-03	.000
51	.150-03	.300-05	.100+18	.144+11	.144+11	.112+06	-.256+00	.300+03	.187-01	.694-06	-.166-01	.203+02	.144+11	-.937-02	.000
53	.156-03	.300-05	-.100+18	.619+17	.335+04	.196+05	-.791+00	.300+03	.348+05	.230-08	-.348+05	-.619+17	.144+11	.407-03	.000
55	.162-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
57	.168-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
59	.174-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
61	.180-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
63	.186-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
65	.192-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
67	.198-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.398-03	.000
69	.204-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
71	.210-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
73	.216-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
75	.222-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.432-03	.000
77	.228-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
79	.234-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
81	.240-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.398-03	.000
83	.246-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.398-03	.000
85	.252-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
87	.258-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
89	.264-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.398-03	.000
91	.270-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
93	.276-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
95	.282-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.432-03	.000
97	.288-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.360-03	.000
99	.294-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.314+00	.144+11	.432-03	.000
101	.300-03	.300-05	-.100+18	.100+18	.207+04	.000	-.850+00	.300+03	.000	.000	.100-03	.000	.144+11	.398-03	.000

Fig. B.8. (Continued) Simulation Summary Example

DIODE CROSS SECTION. T= 100 TIME= .229+02 TIME 114554

N	XAN	DXN	DOPN	HOL	ELE	E	V	TEMP	CURHOL	CURELE	CURDIS	PIB	CI	GS	GI
1	.000	.300-05	.100+18	.205+04	.100+18	.000	.000	.300+03	.000	.100-03	.145-12	.000	.144+11	.195+12	.000
3	.600-05	.300-05	.100+18	.205+04	.100+18	.906-05-	.239-10	.300+03	.189-12	.100-03	.117-12-	.105+00	.144+11	.198+12	.000
5	.120-04	.300-05	.100+18	.205+04	.100+18	.926-05-	.789-10	.300+03	.368-12	.100-03	.793-13-	.105+00	.144+11	.211+12	.000
7	.180-04	.300-05	.100+18	.205+04	.100+18	.926-05-	.134-09	.300+03	.608-12	.100-03	.205-13-	.105+00	.144+11	.230+12	.000
9	.240-04	.300-05	.100+18	.205+04	.100+18	.926-05-	.190-09	.300+03	.860-12	.100-03	.251-12-	.105+00	.144+11	.273+12	.000
11	.300-04	.300-05	.100+18	.204+04	.100+18	.926-05-	.246-09	.300+03	.116-11	.100-03-	.209-12	.000	.144+11	.325+12	.000
13	.360-04	.300-05	.100+18	.203+04	.100+18	.926-05-	.301-09	.300+03	.152-11	.100-03	.741-13-	.105+00	.144+11	.385+12	.000
15	.420-04	.300-05	.100+18	.202+04	.100+18	.926-05-	.357-09	.300+03	.196-11	.100-03	.275-12	.000	.144+11	.449+12	.000
17	.480-04	.300-05	.100+18	.201+04	.100+18	.926-05-	.412-09	.300+03	.251-11	.100-03-	.273-12-	.105+00	.144+11	.602+12	.000
19	.540-04	.300-05	.100+18	.200+04	.100+18	.926-05-	.468-09	.300+03	.319-11	.100-03	.170-12-	.105+00	.144+11	.751+12	.000
21	.600-04	.300-05	.100+18	.198+04	.100+18	.926-05-	.523-09	.300+03	.405-11	.100-03	.120-12	.000	.144+11	.941+12	.000
23	.660-04	.300-05	.100+18	.196+04	.100+18	.926-05-	.579-09	.300+03	.512-11	.100-03	.335-12	.105+00	.144+11	.118+13	.000
25	.720-04	.300-05	.100+18	.192+04	.100+18	.926-05-	.634-09	.300+03	.647-11	.100-03	.113-12	.105+00	.144+11	.149+13	.000
27	.780-04	.300-05	.100+18	.189+04	.100+18	.926-05-	.690-09	.300+03	.817-11	.100-03	.188-12	.105+00	.144+11	.187+13	.000
29	.840-04	.300-05	.100+18	.184+04	.100+18	.926-05-	.746-09	.300+03	.103-10	.100-03-	.162-13	.000	.144+11	.235+13	.000
31	.900-04	.300-05	.100+18	.178+04	.100+18	.926-05-	.801-09	.300+03	.130-10	.100-03	.352-12	.000	.144+11	.296+13	.000
33	.960-04	.300-05	.100+18	.170+04	.100+18	.927-05-	.857-09	.300+03	.164-10	.100-03-	.139-12-	.105+00	.144+11	.373+13	.000
35	.102-03	.300-05	.100+18	.160+04	.100+18	.965-05-	.912-09	.300+03	.207-10	.100-03	.260-12	.000	.144+11	.470+13	.000
37	.108-03	.300-05	.100+18	.148+04	.100+18	.296-04-	.978-09	.300+03	.260-10	.100-03	.353-12	.000	.144+11	.593+13	.000
39	.114-03	.300-05	.100+18	.133+04	.100+18	.107-02-	.154-08	.300+03	.328-10	.100-03	.112-13-	.105+00	.144+11	.747+13	.000
41	.120-03	.300-05	.100+18	.113+04	.100+18	.556-01-	.279-07	.300+03	.414-10	.100-03	.675-08-	.105+00	.144+11	.942+13	.000
43	.126-03	.300-05	.100+18	.847+03	.100+18	.291+01-	.140-05	.300+03	.521-10	.100-03	.100-09-	.105+00	.144+11	.119+14	.000
45	.132-03	.300-05	.100+18	.560+03	.997+17	.152+03-	.732-04	.300+03	.657-10	.100-03-	.400-11	.000	.144+11	.150+14	.000
47	.138-03	.300-05	.100+18	.239+03	.864+17	.794+04-	.376-02	.300+03	.843-10	.100-03	.102-12-	.105+00	.144+11	.216+14	.000
49	.144-03	.300-05	.100+18	.239+04	.518+15	.829+05-	.136+00	.300+03	.202-08	.100-03	.125-12	.105+00	.144+11	.398+16	.000
51	.150-03	.300-05	.100+18	.327+08	.537+08	.176+06-	.772+00	.300+03	.500-04	.500-04	.125-12	.000	.144+11	.716+20	.291+17
53	.156-03	.300-05-	.100+18	.352+11	.988+07	.829+05-	.169+01	.300+03	.100-03	.207-08	.125-12	.210+00	.144+11	.324+20	.242+15
55	.162-03	.300-05-	.100+18	.366+17	.143+03	.740+04-	.205+01	.300+03	.100-03	.135-09	.102-12	.000	.144+11	.552+14	.000
57	.168-03	.300-05-	.100+18	.986+17	.279+03	.152+03-	.207+01	.300+03	.100-03	.116-09-	.109-11	.105+00	.144+11	.184+14	.000
59	.174-03	.300-05-	.100+18	.160+16	.511+03	.291+01-	.207+01	.300+03	.100-03	.100-09-	.105-10	.000	.144+11	.158+14	.000
61	.180-03	.300-05-	.100+18	.160+16	.719+03	.557-01-	.207+01	.300+03	.100-03	.868-10-	.752-08	.105+00	.144+11	.135+14	.000
63	.186-03	.300-05-	.100+18	.160+16	.859+03	.109-02-	.207+01	.300+03	.100-03	.751-10	.647-13	.000	.144+11	.117+14	.000
65	.192-03	.300-05-	.100+18	.160+16	.105+04	.446-04-	.207+01	.300+03	.100-03	.650-10	.283-13	.000	.144+11	.102+14	.000
67	.198-03	.300-05-	.100+18	.160+16	.119+04	.245-04-	.207+01	.300+03	.100-03	.561-10	.182-12	.000	.144+11	.885+13	.000
69	.204-03	.300-05-	.100+18	.160+16	.130+04	.241-04-	.207+01	.300+03	.100-03	.485-10	.143-12	.105+00	.144+11	.769+13	.000
71	.210-03	.300-05-	.100+18	.160+16	.141+04	.241-04-	.207+01	.300+03	.100-03	.419-10	.191-12	.000	.144+11	.668+13	.000
73	.216-03	.300-05-	.100+18	.160+16	.149+04	.241-04-	.207+01	.300+03	.100-03	.361-10	.146-12	.000	.144+11	.582+13	.000
75	.222-03	.300-05-	.100+18	.160+16	.157+04	.241-04-	.207+01	.300+03	.100-03	.312-10	.295-13	.105+00	.144+11	.507+13	.000
77	.228-03	.300-05-	.100+18	.160+16	.163+04	.241-04-	.207+01	.300+03	.100-03	.270-10	.105-12	.000	.144+11	.441+13	.000
79	.234-03	.300-05-	.100+18	.160+16	.169+04	.241-04-	.207+01	.300+03	.100-03	.233-10	.720-13	.000	.144+11	.384+13	.000
81	.240-03	.300-05-	.100+18	.160+16	.173+04	.241-04-	.207+01	.300+03	.100-03	.194-10	.115-12-	.105+00	.144+11	.341+13	.000
83	.246-03	.300-05-	.100+18	.160+16	.177+04	.241-04-	.207+01	.300+03	.100-03	.164-10	.119-12-	.105+00	.144+11	.301+13	.000
85	.252-03	.300-05-	.100+18	.160+16	.181+04	.241-04-	.207+01	.300+03	.100-03	.136-10	.148-12	.000	.144+11	.267+13	.000
87	.258-03	.300-05-	.100+18	.160+16	.183+04	.241-04-	.207+01	.300+03	.100-03	.114-10	.174-12	.000	.144+11	.239+13	.000
89	.264-03	.300-05-	.100+18	.160+16	.186+04	.241-04-	.207+01	.300+03	.100-03	.926-11	.166-12-	.105+00	.144+11	.216+13	.000
91	.270-03	.300-05-	.100+18	.160+16	.188+04	.241-04-	.207+01	.300+03	.100-03	.734-11	.883-13	.000	.144+11	.197+13	.000
93	.276-03	.300-05-	.100+18	.160+16	.189+04	.241-04-	.207+01	.300+03	.100-03	.556-11	.140-12	.105+00	.144+11	.182+13	.000
95	.282-03	.300-05-	.100+18	.160+16	.190+04	.241-04-	.207+01	.300+03	.100-03	.389-11	.199-12	.000	.144+11	.171+13	.000
97	.288-03	.300-05-	.100+18	.160+16	.191+04	.240-04-	.207+01	.300+03	.100-03	.230-11	.559-13	.000	.144+11	.164+13	.000
99	.294-03	.300-05-	.100+18	.160+16	.191+04	.208-04-	.207+01	.300+03	.100-03	.782-12	.268-13	.105+00	.144+11	.160+13	.000
101	.300-03	.300-05-	.100+18	.100+18	.191+04-	.661-13-	.207+01	.300+03	.100-03-	.114-25	.226-12	.000	.144+11	.159+13	.000

Fig. B.8. (Continued) Simulation Summary Example

TRANSIENT DATA TIME 114554

T	TIME	DTIME	DHOLM	DELEM	DEM	DTEMPM	PIBM	PIVMIN	TEMPM	CIM	OSGR	CDISM	VORIAS
0	.000	.100+07	.000	.000	.000	.000	-.619+17	-.100+01	.300+03	.144+11	.000	.355+05	-.339190857-01
2	.222-07	.149-07	-.107+16	.234+15	.590+03	.113-01	-.210+00	.182-04	.301+03	.148+11	.116+02	.213+02	-.427784654-01
4	.554-07	.223-07	-.212+15	.239+13	.175+01	-.830-02	-.419+00	.343-04	.301+03	.148+11	-.432+04	.184+03	-.428408063-01
6	.105-06	.335-07	-.317+15	.354+13	.262+01	-.118-01	.314+00	.518-04	.301+03	.148+11	-.182+04	.321+03	-.429088683-01
8	.179-06	.447-07	-.474+15	.525+13	.391+01	-.164-01	-.210+00	.768-04	.301+03	.148+11	-.787+03	.632+03	-.431810911-01
10	.269-06	.743-07	-.709+15	.777+13	.584+01	-.220-01	-.210+00	.114-03	.301+03	.148+11	-.341+03	.134+02	-.431613156-01
12	.454-06	.111-06	-.106+14	.115+14	.872+01	-.2e2-01	-.210+00	.169-03	.301+03	.148+11	-.150+03	.295+02	-.433672752-01
14	.761-06	.166-06	-.159+14	.169+14	.130+02	-.336-01	-.210+00	.203-03	.300+03	.147+11	-.650+02	.663+02	-.437247360-01
16	.107-05	.247-06	-.238+14	.246+14	.194+02	-.373-01	-.314+00	.204-03	.300+03	.147+11	-.284+02	.150+01	-.44228e308-01
18	.162-05	.369-06	-.357+14	.366+14	.290+02	-.370-01	-.210+00	.206-03	.300+03	.147+11	-.124+02	.338-01	-.449882e03-01
20	.244-05	.551-06	-.535+14	.541+14	.434+02	-.329-01	-.105+00	.209-03	.300+03	.146+11	-.545+01	.759-01	-.4610e0157-01
22	.366-05	.823-06	-.802+14	.805+14	.647+02	-.266-01	.314+00	.213-03	.300+03	.146+11	-.240+01	.169+00	-.477916610-01
24	.549-05	.123-05	-.120+15	.120+15	.966+02	-.205-01	.210+00	.221-03	.300+03	.146+11	-.105+01	.375+00	-.503111957-01
26	.822-05	.184-05	-.181+15	.180+15	.144+03	-.158-01	-.210+00	.233-03	.300+03	.145+11	-.452+00	.826+00	-.546862e22+-01
28	.123-04	.276-05	-.272+15	.271+15	.215+03	-.126-01	.419+00	.254-03	.300+03	.145+11	-.190+00	.181+01	-.597330163-01
30	.184-04	.409-05	-.410+15	.416+15	.321+03	-.103-01	.314+00	.295-03	.300+03	.145+11	-.751-01	.393+01	-.682093222-01
32	.276-04	.611-05	-.621+15	.621+15	.479+03	-.7e5-02	-.210+00	.377-03	.300+03	.145+11	-.243-01	.842+01	-.809465891-01
34	.411-04	.913-05	-.946+15	.946+15	.712+03	-.407-02	.524+00	.565-03	.300+03	.145+11	-.879-03	.17e+02	-.1001e0204+00
36	.614-04	.136-04	-.145+16	.145+16	.106+04	.204-01	-.210+00	.106-02	.300+03	.145+11	.116-01	.348+02	-.129111102+00
38	.917-04	.204-04	-.220+16	.220+16	.155+04	.894-01	-.419+00	.253-02	.300+03	.146+11	.201-01	.622+02	-.172734885+00
40	.137-03	.304-04	-.318+16	.318+16	.217+04	.2e2+00	-.210+00	.105-02	.301+03	.150+11	.269-01	.120+03	-.23e63e936+00
42	.204-03	.454-04	-.475+16	.475+16	.294+04	.349+00	-.210+00	.324-03	.301+03	.156+11	.273-01	.202+03	-.315444e0e+00
44	.305-03	.67e-04	-.345+16	.345+16	.241+04	.629-01	-.524+00	.341-03	.301+03	.166+11	.608-02	.212+03	-.401622437+00
46	.456-03	.101-03	-.333+16	.333+16	.248+04	-.320-01	.210+00	.633-03	.301+03	.159+11	.411-03	.251+03	-.4e65b03+00
48	.681-03	.151-03	-.343+16	.342+16	.284+04	.472+00	-.629+00	.106-02	.302+03	.167+11	.753-02	.362+03	-.5e4977596+00
50	.102-02	.226-03	-.299+16	.298+16	.300+04	.736+00	.314+00	.164-02	.304+03	.164+11	.707-02	.422+03	-.696247675+00
52	.152-02	.337-03	-.341+16	.341+16	.330+04	.443+00	-.210+00	.116-02	.305+03	.197+11	.273-02	.396+03	-.813785493+00
54	.227-02	.503-03	-.394+16	.393+16	.299+04	.102+00	-.314+00	.296-03	.305+03	.202+11	.482-03	.322+03	-.93677e5e0+00
56	.339-02	.752-03	-.458+16	.458+16	.283+04	-.5e5+00	-.210+00	.306-03	.304+03	.192+11	-.157-02	.266+03	-.10e098729+01
58	.506-02	.112-02	-.332+16	.332+16	.223+04	-.111+01	.524+00	.670-03	.302+03	.166+11	-.426-02	.133+03	-.116832100+01
60	.755-02	.166-02	-.176+16	.177+16	.120+04	-.643+00	.419+00	.134-02	.300+03	.148+11	-.704-02	.456+02	-.1235e3521+01
62	.113-01	.250-02	-.299+15	.300+15	.205+03	-.870-01	-.314+00	.263-02	.300+03	.144+11	-.240-01	.142+01	-.12547e149+01
64	.168-01	.374-02	-.566+13	.560+13	.344+01	-.327-03	-.210+00	.227-02	.300+03	.144+11	-.471-01	.401-03	-.1255e1216+01
66	.251-01	.556-02	.174+10	.174+10	.109+02	.693-05	-.419+00	.237-02	.300+03	.144+11	.000-03	-.97e-04	-.1255e1e40+01
68	.376-01	.833-02	.173+08	.173+08	.116-04	.136-08	.314+00	.245-02	.300+03	.144+11	.113-08	-.12e-08	-.1255e16e40+01
70	.561-01	.124-01	.161+05	.161+05	.111-07	.115-12	.419+00	.250-02	.300+03	.144+11	.665-11	-.152-07	-.1255e16e40+01
72	.837-01	.186-01	.449+03	.434+03	.242-09	.517-15	-.210+00	.253-02	.300+03	.144+11	.33e-13	-.7e3-08	-.1255e16e40+01
74	.125+00	.278-01	.202+04	.711+03	.137-08	.517-15	-.210+00	.256-02	.300+03	.144+11	.225-13	-.16e-07	-.1255e16e40+01
76	.187+00	.414-01	.253+04	.240+03	.136-08	.517-15	.419+00	.258-02	.300+03	.144+11	.151-13	-.79e-08	-.1255e16e40+01
78	.279+00	.619-01	.242+04	.306+04	.169-08	.517-15	-.210+00	.259-02	.300+03	.144+11	.101-13	-.14e-07	-.1255e16e40+01
80	.416+00	.924-01	.271+04	.391+03	.146-08	.517-15	-.210+00	.259-02	.300+03	.144+11	.67e-14	.719-08	-.1255e16e40+01
82	.622+00	.138+00	.e4e+03	.909+03	.489-09	.517-15	-.210+00	.260-02	.300+03	.144+11	.454-14	-.14e-07	-.1255e16e40+01
84	.926+00	.206+00	.267+04	.484+03	.143-08	.517-15	-.210+00	.260-02	.300+03	.144+11	.304-14	-.73?-08	-.1255e16e40+01
86	.138+01	.306+00	.624+03	.825+03	.443-09	.517-15	-.210+00	.261-02	.300+03	.144+11	.204-14	-.15e-07	-.1255e16e40+01
88	.207+01	.459+00	.413+03	.400+03	.222-09	.517-15	-.210+00	.261-02	.300+03	.144+11	.136-14	-.77e-08	-.1255e16e40+01
90	.309+01	.680+00	.292+04	.562+03	.135-08	.517-15	-.210+00	.261-02	.300+03	.144+11	.91e-15	-.80e-08	-.1255e16e40+01
92	.462+01	.102+01	.245+04	.222+04	.132-08	.517-15	-.210+00	.261-02	.300+03	.144+11	.612-15	.229-08	-.1255e16e40+01
94	.689+01	.153+01	.269+04	.500+03	-.144-08	.517-15	-.210+00	.261-02	.300+03	.144+11	.410-15	.72e-08	-.1255e16e40+01
96	.103+02	.228+01	.869+03	.243+04	-.123-08	.517-15	-.210+00	.261-02	.300+03	.144+11	.274-15	.237-07	-.1255e16e40+01
98	.154+02	.341+01	-.566+03	.213+04	-.102-08	.517-15	-.210+00	.261-02	.300+03	.144+11	.184-15	.731-08	-.1255e16e40+01
100	.229+02	.509+01	.487+03	.634+03	.313-09	.517-15	-.210+00	.261-02	.300+03	.144+11	.123-15	-.75e-08	-.1255e16e40+01

Fig. B.8. (Continued) Simulation Summary Example

TABLE B.2

SYMBOL DEFINITIONS FOR SIMULATION SUMMARY

Name	Definition
Diode Cross Section Data:	
N	N or M node number
XXN	N-node positions
DXN	N-node spacing
DOPN	Impurity concentration
HOL	Hole concentration
ELE	Electron concentration
E	Electric field
V	Voltage
TEMP	Temperature
CURHOL	Hole current component
CURELE	Electron current component
CURDIS	Displacement current component
PIB	Poission equation imbalance
CI	Intrinsic carrier concentration
GS	Thermal generation-recombination
GI	Avalanche ionization
Transient Data:	
T	Time step number
TIME	Simulation time
DTIME	Incremental time step
DHOLM	Maximum incremental change in hole concentration
DELEM	Maximum incremental change in electron concentration

TABLE B.2 (Continued)

Name	Definition
DEM	Maximum incremental change in electric field
DTEMPM	Maximum incremental change in temperature
PIBM	Maximum Poisson equation imbalance
PIVMIN	Minimum pivot value from subroutine BANDA3, minus 1.0
TEMPM	Maximum temperature
CIM	Maximum intrinsic carrier concentration
QSGR	Maximum thermal generation-recombination value
CDISM	Maximum displacement current
VDBIAS	Diode bias voltage

data file specified by the simulation initial state and is equivalent to the simulation initial state except for the parameter and variable values changed by the simulation.

A flow chart for COMP is presented in Fig. B.9 and the source listing for COMP is presented in Fig. B.10. COMP directly or indirectly references sixteen subroutines which are briefly described below and the hierarchy for these subroutines is shown in Fig. B.11.

Subroutine INTRI

INTRI is described in Appendix B.1.

Subroutine CST

CST is described in Appendix B.1.

Subroutine DTMUL

DTMUL is described in Appendix B.1.

Subroutine NTAB$

NTAB$ is described in Appendix B.1.

Subroutine NOR2

NOR2 formulates the normalization constants required by the diode model and provides an optional listing of these values. Source listing for NOR2 is presented in Fig. B.12.

Subroutine HOLION

HOLION evaluates the hole ionization coefficient and subsequent derivatives with respect to electric field and temperature at node M for silicon. Source listing for HOLION is presented in Fig. B.13.

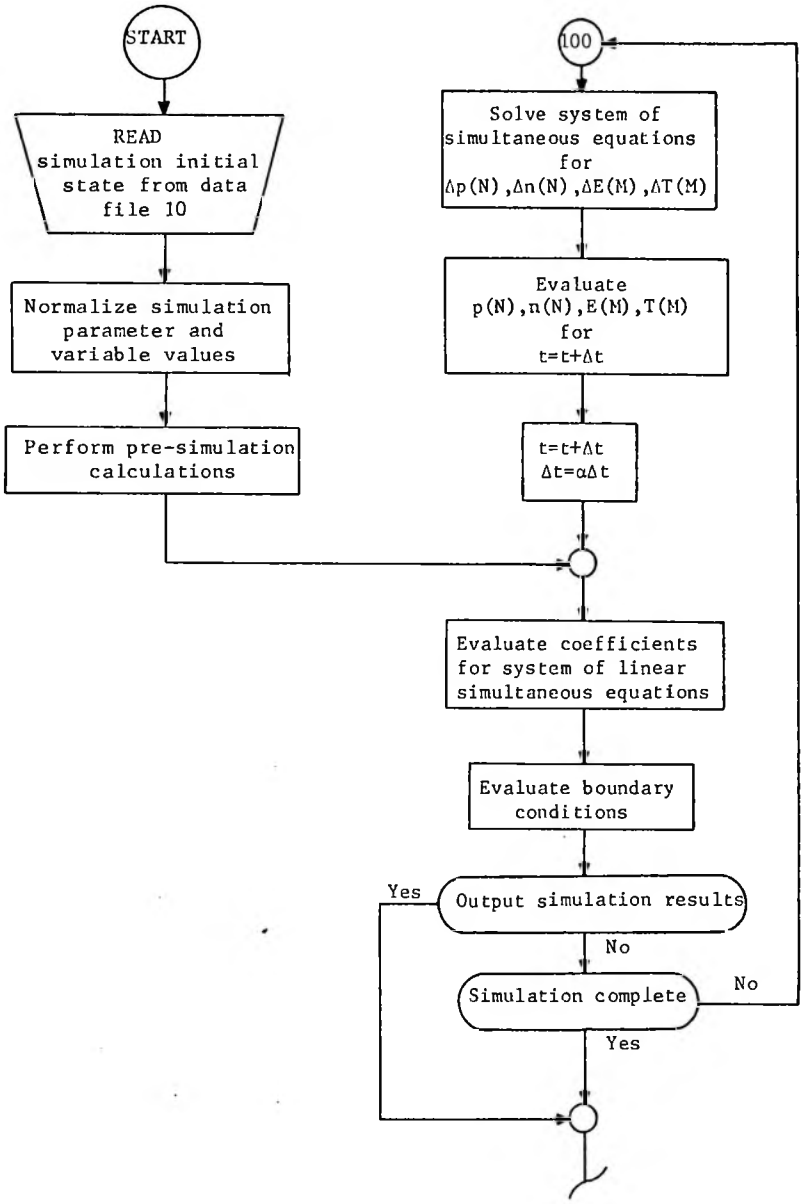


Fig. B.9. Flow Chart for Program COMP

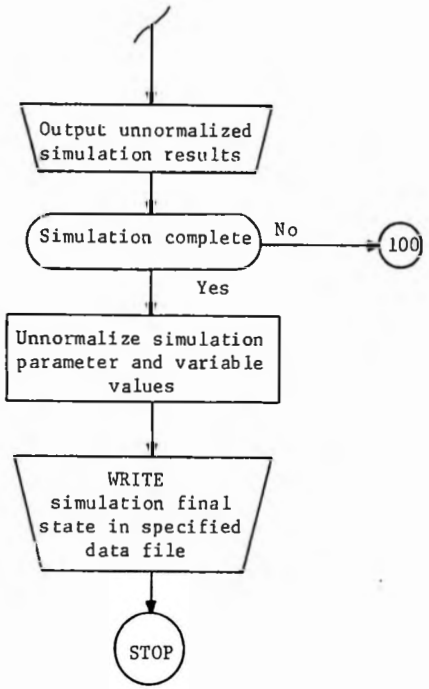


Fig. B.9. (Continued) Flow Chart for Program COMP

```
      C***** COMP *****
      C
      C SIMULATES A ONE-DIMENSIONAL TWO CONTACT SEMICONDUCTOR
      C DEVICE FOR CONSTANT CURRENT EXCITATION.  IMPURITY
      C PROFILE IS ARBITRARY EXCEPT FOR THE SPECIFIED TERMINAL
      C MATERIAL TYPES (X=0, N-TYPE AND X=XL, P-TYPE) AND
      C TEMPERATURE IS OPTIONALLY INCLUDED AS A DEPENDENT
      C VARIABLE.  MOBILITIES ARE IMPURITY, E-FIELD, AND
      C TEMPERATURE DEPENDENT; WHEREAS, IONIZATION COEFFICIENTS
      C ARE E-FIELD, AND TEMPERATURE DEPENDENT, BOTH BEING
      C FORMULATED FOR SILICON.
      C
      C INITIAL STATE VALUES ARE READ FROM DATA FILE
      C 10 WHICH CAN BE INTERACTIVELY GENERATED BY PROGRAM
      C DS.  COMP IS EXECUTED IN  A BATCH MODE AND WRITES THE
      C THE RESULTING STATE ON THE OUTPUT DATA FILE SPECIFIED
      C IN DATA FILE 10.  OPTIONALLY, ADDITIONAL DATA IS
      C WRITTEN IN DATA FILES 7, AND 8.
      C
      C TECH: SINGLE ITERATION QUASILINEARIZATION
      C UNKS: E-FIELD, HOLE AND ELECTRON CONCENTRATIONS, TEMPERATURE
      C BND: X=0, N-SIDE
      C       1)  TERMINAL E-FIELD EQUAL ZERO
      C       2)  TERMINAL MAJ. CAR. DIFF. CUR. EQUAL TOTAL CUR.
      C       3)  TERMINAL TEMPERATURE EQUAL TEMPO
      C       X=XL, P-SIDE
      C       1)  TERMINAL TEMPERATURE EQUAL TEMPO
      C       2)  TERMINAL MAJ. CAR. DIFF. CUR. EQUAL TOTAL CUR.
      C       OR
      C       2)  THERMAL EQUILIBRIUM CAR. CONCS. (OHMIC CONTACT)
      C TIME: GEOMETRIC IN 'FOTMUL'(FOTMUL=1, CONST. TIME STEP)
      C
      C
            IMPLICIT DOUBLE PRECISION (A-H,O-Z)
            INTEGER P,PM1,T,TMAX,RCMPB,P4,P4M8
            INTEGER TLINC,TSINC
      C
            COMMON /INTRIN/ CDEDS,VBEDS,ENGAP
            COMMON /NORM/ XN,TN,CARN,EN,CURN,VN,RECN,R40BN,DIFN,TEMPN
            COMMON /PHYCON/ Q,BOZ,PERM
            COMMON /GIONN/ GIPNMM,GINNMM,GIENM,GITNM,GINM,GIPN,GIN,GINN,GINP,G
           1IPNPP,GINNPP,GIENP,GITNP
            COMMON /JPNP/ CPNP,CPPNPM,CPPNPP,CPENP,CPTNP
            COMMON /JNNP/ CNNP,CNNNPM,CNNNPP,CNENP,CNTNP
            COMMON /JPNM/ CPNM,CPPNMM,CPPNMP,CPENM,CPTNM
            COMMON /JNNM/ CNNM,CNNNMM,CNNNMP,CNENM,CNTNM
            COMMON /IDATA/TIME,DT,DHOLM,DELEM,DEM,DTM,PIBM,PIVMIN,
           1TEMPM,CIM,QSGR,CDISM,VDBIAS
            COMMON /VAR/XXN(101),DXN(101),DOPN(101),HOL(101),ELE(101),E(101),
           1V(101),TEMP(101)
            COMMON /CURR/CURHOL(101),CURELE(101),CURDIS(101)
            COMMON /PARM/PIB(101),CI(101),GS(101),GI(101)
      C
            DOUBLE PRECISION DXM(101)
            DOUBLE PRECISION HMOB(101),EMOB(101)
            DOUBLE PRECISION ALFAP(101),ALFAN(101)
```

Fig. B.10. Listing for Program COMP

```
57            DOUBLE PRECISION A(404,12),DELT(404)
58            DOUBLE PRECISION CSTIME(99)
59      C
60      C     DOUBLE PRECISION B(404,12),ERROR(404)
61      C
62      C
63            DATA PERM,BOZ,Q /8.854D-4,1.381D-23,1.6D-19/
64      C
65            ABSDER(F,DERF)=DSIGN(1.0D0,F)*DERF
66      C
67      C GENERATE DATE AND TIME
68            CALL ERTRAN (9,IDATET,ITIMET)
69      C
70      C INITIAL STATE DATA
71      C
72      C ASSIGN NEW STATE AND INITIAL STATE TRANSFER DATA FILES
73            CALL ERTRAN (6,'WASG,AX 7. . ')
74            CALL ERTRAN (6,'WASG,AX 8. . ')
75            CALL ERTRAN (6,'WASG,AX 10. . ')
76            CALL ERTRAN (6,'WASG,AX 11. . ')
77            CALL ERTRAN (6,'WASG,AX 12. . ')
78            CALL ERTRAN (6,'WASG,AX 13. . ')
79      C
80      C WRITE DATE AND TIME ON OUTPUT FILES 7 AND 8
81            WRITE (7,10) IDATET,ITIMET
82            WRITE (8,10) IDATET,ITIMET
83      10    FORMAT (A8)
84      C
85      C WRITE ZERO DATA PT. COUNT ON DF 8.
86            WRITE(8,15) N
87      15    FORMAT(I15)
88      C
89      C  READ INITIAL STATE TRANSFER FILE
90            LF=10
91      C READ UNIT 10
92            INCLUDE RLF
93            INCLUDE LFFORM
94            I=I
95            WRITE (6,20) ITIMET
96      20    FORMAT ('1********** COMP **********',T98,'TIME ',A6,/)
97      C
98      C WRITE DIODE SPEC.,CONT.,AND SIM. PARS.
99            LF=6                                  @ WRITE ON UNIT 6
100           LRP=0                                 @ READS INHIBITED
101     C
102     C WRITE-READ DIODE SPEC. PARS.
103     C
104           INCLUDE DSPECP
105           INCLUDE DSPECF
106           I=I
107     C
108     C WRITE-READ CONTROL PARS.
109     C
110           INCLUDE DCONTP
111           INCLUDE DCONTF
112           I=I
113     C
```

Fig. B.10. (Continued) Listing for Program COMP

```
      C  WRITE-READ SIM. PARS.
      C
            INCLUDE DSIMP
            INCLUDE DSIMPF
            I=1
      C
      C*****************************************************
      C  PRELIMINARY COMPUTATIONS
      C*****************************************************
      C
      C SET NEW DATE AND TIME
            IDATE=IDATET
            ITIME=ITIMET
      C
      C  GENERATE NORMALIZATION CONSTANTS
            CALL INIR1 (CBEDS,VBEDS,ENGAP,TEMPO,CARINT)
            CALL NOR2 (ENORC,DIEL,TEMPO,CARINT,XN,TN,CARN,EN,CURN,VN,RECN,RMOB
           1N,DIFN,TEMPN)
      C
      C  NORMALIZE REQUIRED VALUES
      C
      C    ARRAY NORMALIZATION
            DO 30 I=1,P
            XXN(I)=XXN(I)/XN
            DOPN(I)=DOPN(I)/CARN
            ELE(I)=ELE(I)/CARN
            HOL(I)=HOL(I)/CARN
            E(I)=E(I)/EN
            V(I)=V(I)/VN
            TEMP(I)=TEMP(I)/TEMPN
      30    CONTINUE
      C
      C    PARAMETER NORMALIZATION
            TAUN=TAUN/TN
            TAUP=TAUP/TN
            VAPP=VAPP/VN
            VOBI=VOBI/VN
            DT=DT/TN
            DX=DX/XN
            TTIME=TTIME/TN
            TIME=TIME/TN
            HOLMO=HOLMO/RMOBN
            ELEMO=ELEMO/RMOBN
            CURTOT=CURTOT/CURN
            ACCEPT=ACCEPT/CARN
            DONOR=DONOR/CARN
            XMET=XMET/XN
            TEMPO=TEMPO/TEMPN
      C
            DO 40 I=1,NCS
            CSTIME(I)=CSTIME(I)/TN
      40    CONTINUE
      C
      C  PROGRAM CONSTANTS
            NNCS=1
            P4=P*4
            P4M8=P4-8
```

Fig. B.10. (Continued) Listing for Program COMP

```
171             PM1=P-1
172             RTHETA=1.0D0/THETA
173             RTHEDT=RTHETA/DT
174             TEMPNM=TEMP0
175             TEMPNP=TEMP0
176             EXTCRI=1.0E-6
177       C
178       C ELIMINATION OF 0 PRINT AND/OR STORE INTERVALS
179             IF(LCSPI.EQ.0) LCSPI=1000000
180             IF(LSCSPI.EQ.0) LSCSPI=1000000
181             IF(TLINC.EQ.0) TLINC=1000000
182             IF(TSINC.EQ.0) TSINC=1000000
183       C
184       C EVALUATION OF GRID SPACIAL INCREMENTS, DXN(N), DXM(N)
185             DO 80 N=1,PM1
186             DXM(N)=XXN(N+1)-XXN(N)
187       80    CONTINUE
188             DXM(P)=DXM(PM1)
189       C
190             DO 90 N=2,PM1
191             DXN(N)=0.5D0*(DXM(N-1)+DXM(N))
192       90    CONTINUE
193             DXN(1)=DXN(2)
194             DXN(P)=DXN(PM1)
195       C
196       C PRE-SIMULATION PARTIAL EVALUATION OF ENERGY BALANCE
197       C EQN. PARAMETERS
198             EB1T=TN*THCOND/(DENSTY*SPHEAT*XN*XN)
199             EB3=TN*THCONH/(ADT*XHT*DENSTY*SPHEAT)
200             EB4=TN*EN*CURN/(TEMPN*DENSTY*SPHEAT)
201       C
202             CALL CHECKC (0)
203       C
204       C LIPEST, INITIAL PROG. ENTRY STATUS
205             LIPEST=1
206             GO TO 150
207       C
208       C**********************************************
209       C START TIME STEP LOOP
210       C**********************************************
211       C
212       100   CONTINUE
213       C
214       C SOLVE SYSTEM OF 4*P-8 LINEAR HEPTA DIAGONAL EQUATIONS
215             CALL BANDA3 (P4M8,6,12,404,12,A,DELT,4,PIVMIN)
216       C
217       C EVALUATE BOUNDARY VALUES
218       C
219       C X=0, N-SIDE CONTACT, DELT(1)-P(1),DELT(2)-N(1),
220       C DELT(3)-E(1), DELT(4)-TEMP(1)
221             DELT(1)=0.0D0
222             DELT(2)=DELT(6)+BND8
223             DELT(3)=0.0D0
224             DELT(4)=0.0D0
225       C
226       C X=XL, P-SIDE CONTACT, DELT(LP)-P(P), DELT(LN)-N(N),
227       C DELT(LP-1)-E(P-1), DELT(4)=0.0
```

Fig. B.10. (Continued) Listing for Program COMP

```
228             LP=P4-3
229             LN=LP+1
230             LE=LN+1
231             LT=LE+1
232       C
233             DELT(LP)=0.000
234             DELT(LN)=0.000
235             DELT(LE)=0.000
236             DELT(LT)=0.000
237       C
238             IF(NTYBND.EQ.0) DELT(1P)=DELT(LP-4)+BNDC
239       C
240       C EVALUATE NEW VARIABLE VALUES
241             DO 140 N=1,P
242             LP=1+4*(N-1)
243             LN=1+LP
244             LE=1+LN
245             LT=1+LE
246       C
247             HOL(N)=HOL(N)+DELT(LP)
248             ELE(N)=ELE(N)+DELT(LN)
249             E(N)=E(N)+DELT(LE)
250             TEMP(N)=TEMP(N)+DELT(LT)
251       140   CONTINUE
252       C
253             HOL(1)=HOL(2)
254             IF(NTYBND.EQ.0) ELE(P)=ELE(PM1)
255             E(P)=E(PM1)
256       C
257       C INCREMENT TIME STEP COUNTER AND TIME
258             T=T+1
259             TIME=TIME+DT
260             DT=FDTMUL*DT
261       C
262       C*****************************************************
263       C ENTRY POINT FOR PRE-SIMULATION CALCULATIONS
264       C*****************************************************
265       C
266       150   CONTINUE
267       C
268       C EVALUATION OF PROG. PARS. REQUIRING 'TIME' AND 'DT'
269             RTHEDT=RTHETA/DT
270       C
271       C INITIALIZE COEFF. PARAMERTER SUBS.
272       C
273             V(1)=0.000
274             CALL CUR (EXTCRI,DXM(1),DOPN(1),HOL(1),HOL(2),
275            1ELE(1),ELE(2),E(1),TEMPO,V(1),
276            1V(2),HMOB(1),EMOB(1))
277             CURHOL(1)=CPNP
278             CURELE(1)=CNNP
279       C
280             CALL GION (AITS,0.5D0,0.5D0,E(1),TEMPO,ALFAP(1),
281            1ALFAN(1))
282       C
283       C EVALUATION OF DERIVATIVE COEFFICIENT MATRIX
284             QSR=0.000
```

Fig. B.10. (Continued) Listing for Program COMP

```
285             GGR=0.0D0
286             DO 160 N=2,PM1
287             LP=1+4*(N-2)
288             LN=LP+1
289             LE=LN+1
290             LT=LE+1
291             NM1=N-1
292             NP1=N+1
293             RDXN=1.0D0/DXN(N)
294             TA=DXM(NM1)+DXM(N)
295             DXRNM=DXM(NM1)/TA
296             DXRNP=DXM(N)/TA
297             DOPM=(DOPN(N)+DOPN(NP1))/2.0D0
298       C
299             IF(NTHOEP.NE.1) GO TO 151
300             TEMPNM=TEMP(NM1)
301             TEMPNP=TEMP(N)
302       151   CONTINUE
303       C
304       C CALL COEFF. PARAMETER SUBS.
305       C
306             CALL CICONC (DXRNM,DXRNP,TEMPNM,TEMPNP,CIN,CITNM,CITNP)
307       C
308             CALL CUR (EXTCRI,DXM(N),DOPM,HOL(N),HOL(NP1),
309            1ELE(N),ELE(NP1),E(N),TEMPNP,V(N),
310            1V(NP1),HMOB(N),EMOB(N))
311             CURHOL(N)=CPNP
312             CURELE(N)=CNNP
313       C
314             CALL GSHR (TAUP,TAUN,HOL(N),ELE(N),TEMPNM,TEMPNP,
315            1CIN,CITNM,CITNP,GSN,GSPN,GSNN,GSTNM,GSTNP)
316             CI(N)=CIN
317             GS(N)=GSN
318       C
319             CALL GION (AITS,DXRNM,DXRNP,E(N),TEMPNP,ALFAP(N),
320            1ALFAN(N))
321             GI(N)=GIN
322       C
323       C COEFFS. FOR HOLE CONTINUITY EQN. AT MAJOR NODE NO. N
324             A(LP,1)=0.0D0
325             A(LP,2)=-RDXN*CPPNMM-GIPNMM
326             A(LP,3)=-GINNMM
327             A(LP,4)=-RDXN*CPENM-GTENM
328             A(LP,5)=-GSTNM-GITNM-RDXN*CPTNM
329             A(LP,6)=-GSPN-RDXN*(CPPNMP-CPPNPM)-GIPN
330             A(LP,7)=-GSNN-GINN
331             A(LP,8)=+RDXN*CPENP-GTENP
332             A(LP,9)=-GSTNP-GITNP+RDXN*CPTNP
333             A(LP,10)=+RDXN*CPPNPP-GIPNPP
334             A(LP,11)=-GINNPP
335             A(LP,12)=GSN+RDXN*(CPNM-CPNP)+GIN
336       C
337       C COEFFS. FOR ELECTRON CONTINUITY EQN. OF MAJOR NODE NO.
338             A(LN,1)=-GIPNMM
339             A(LN,2)=+RDXN*CNNMM-GINNMM
340             A(LN,3)=+RDXN*CNENM-GIENM
341             A(LN,4)=-GSTNM-GITNM+RDXN*CNTNM
```

Fig. B.10. (Continued) Listing for Program COMP

```
342             A(LN,5)=-GSPN-GIPN
343             A(LN,6)=-GSNN-RDXN*(CNNNPM-CNNNMP)-GINN
344             A(LN,7)=-RDXN*CNENP-GIENP
345             A(LN,8)=-GSTNP-GITNP-RDXN*CNTNP
346             A(LN,9)=-GIPNPP
347             A(LN,10)=-RDXN*CNNNPP-GINNPP
348             A(LN,11)=0.0D0
349             A(LN,12)=GSN+RDXN*(CNNP-CNNM)+GIN
350       C
351       C COEFFS. FOR POISSON'S EQN. AT MAJOR NODE NO. N
352             A(LE,1)=0.0D0
353             A(LE,2)=-1.0D0
354             A(LE,3)=0.0D0
355             A(LE,4)=-DXN(N)
356             A(LE,5)=DXN(N)
357             A(LE,6)=1.0D0
358             A(LE,7)=0.0D0
359             A(LE,8)=0.0D0
360             A(LE,9)=0.0D0
361             A(LE,10)=0.0D0
362             A(LE,11)=0.0D0
363             A(LE,12)=E(NM1)-E(N)+DXN(N)*(HOL(N)-ELE(N)+DOPN(N))
364       C
365       C FINAL UPDATE OF ENERGY BALANCE EQUATION PARAMETERS
366             TA=EB1T/DXM(N)
367             EB1=TA/DXN(N)
368             EB2=TA/DXN(N+1)
369       C
370       C COEFFS. FOR ENERGY BALANCES EQN. AT MAJOR NODE (M)
371             TA=EB4*DABS(E(N))
372             A(LT,6)=EB1+EB2+EB3-TA*(ABSDER(CPNP,CPTNP)+ABSDER(CNNP,CNTNP))
373             IF(NTRDEP.NE.1) GO TO 158
374       C
375             A(LT,1)=0.0D0
376             A(LT,2)=-EB1
377             A(LT,3)=-TA*ABSDER(CPNP,CPPNPM)
378             A(LT,4)=-TA*ABSDER(CNNP,CNNNPM)
379             TB=DABS(CPNP)+DABS(CNNP)
380             A(LT,5)=-EB4*TB*ABSDER(E(N),1.0D0)-TA*(ABSDER(CPNP,CPENP)+ABSDER(C
381            1NNP,CNENP))
382             A(LT,7)=-TA*ABSDER(CPNP,CPPNPP)
383             A(LT,8)=-TA*ABSDER(CNNP,CNNNPP)
384             A(LT,9)=0.0D0
385             A(LT,10)=-EB2
386             A(LT,11)=0.0D0
387             A(LT,12)=EB1*(TEMP(NM1)-TEMP(N))+EB2*(TEMP(NP1)-TEMP(N))+EB3*(TEMP
388            10-TEMP(N))+TA*TB
389       C
390       C PARTIAL EVALUATION OF HEAT STORAGE AND GENERATION RATES
391             QSR=QSR+DXM(N)*DELT(LT+4)
392             QGR=QGR+DXM(N)*DABS(E(N))*TB
393             GO TO 159
394       C
395       158   CONTINUE
396             A(LT,1)=0.0D0
397             A(LT,2)=0.0D0
398             A(LT,3)=0.0D0
```

Fig. B.10. (Continued) Listing for Program COMP

```
399             A(LT,4)=0.000
400             A(LT,5)=0.000
401       C
402             A(LT,7)=0.000
403             A(LT,8)=0.000
404             A(LT,9)=0.000
405             A(LT,10)=0.000
406             A(LT,11)=0.000
407             A(LT,12)=0.000
408       C
409       159   CONTINUE
410       160   CONTINUE
411       C
412             CI(1)=CI(2)
413             GS(1)=GS(2)
414             GI(1)=GI(2)
415             CURHOL(P)=CURHOL(PM1)
416             CURELE(P)=CURELE(PM1)
417             CI(P)=CI(PM1)
418             GS(P)=GS(PM1)
419             GI(P)=GI(PM1)
420       C-----------------------------------------------------
421       C INCLUSION OF RTHEDT TERM IN DERIVATIVE COEFFICIENT
422       C MATRIX AND RTHETA TERM IN CONSTANT ARRAY
423       C-----------------------------------------------------
424             DO 170 N=2,PM1
425             LP=1+4*(N-2)
426             LN=LP+1
427             LT=LN+2
428       C
429       C HOLE CONTINUITY EQN.
430             A(LP,6)=A(LP,6)+RTHEDT
431             A(LP,12)=A(LP,12)*RTHETA
432       C
433       C ELECTRON CONTINUITY EQN.
434             A(LN,6)=A(LN,6)+RTHEDT
435             A(LN,12)=A(LN,12)*RTHETA
436       C
437       C ENERGY BALANCE EQN.
438             A(LT,6)=A(LT,6)+RTHEDT
439             A(LT,12)=A(LT,12)*RTHETA
440       C
441       170   CONTINUE
442       C-----------------------------------------------------
443       C INCLUSION  OF BOUNDARY  CONDITIONS
444       C-----------------------------------------------------
445       C X=0, N-SIDE CONTACT
446       C
447       C E(0)=0
448       C CONTACT MAJ. CARRIER CURRENT EQUALS TERMINAL CURRENT
449       C
450             BNDB=-DXM(1)/EMOB(1)*CURTOT/TEMP(1)+(ELE(2)-ELE(1))
451       C
452       C HOLE CONTINUITY EQN.
453             A(1,6)=A(1,6)+A(1,2)
454             A(1,7)=A(1,7)+A(1,3)
455             A(1,12)=A(1,12)-A(1,3)*BNDB
```

Fig. B.10. (Continued) Listing for Program COMP

```
      C
      C ELECTRON CONTINUITY EQN.
            A(2,5)=A(2,5)+A(2,1)
            A(2,6)=A(2,6)+A(2,2)
            A(2,12)=A(2,12)-A(2,2)*BNDB
      C
      C X=XL, P-SIDE CONTACT
      C NTYBND=0 - CURRENT BND. COND., NTYBND=1 - OHMIC BND. COND.
            IF (NTYBND.EQ.1) GO TO 180
      C
            LP=4*P-11
            LN=LP+1
            LE=LN+1
            LT=LE+1
            BNDC=-DXM(PM1)/HMOB(PM1)*CURTOT/TEMP(PM1)+(-HOL(P)+HOL(PM1))
      C
      C HOLE CONTINUITY EQN.
            A(LP,6)=A(LP,6)+A(LP,10)
            A(LP,7)=A(LP,7)+A(LP,11)
            A(LP,12)=A(LP,12)-A(LP,10)*BNDC
      C
      C ELECTRON CONTINUITY EQN.
            A(LN,5)=A(LN,5)+A(LN,9)
            A(LN,6)=A(LN,6)+A(LN,10)
            A(LN,12)=A(LN,12)-A(LN,9)*BNDC
      C
      C ENERGY BALANCE EQN.
            A(LT,3)=A(LT,3)+A(LT,7)
            A(LT,4)=A(LT,4)+A(LT,8)
            A(LT,12)=A(LT,12)-A(LT,7)*BNDC
      C
      180   CONTINUE
      C
      C     EVALUATION OF DIODE BIAS VOLTAGE
            VDBIAS=V(P)-VDBI
      C
      C EVALUATE HEAT STORAGE / GENERATION RATIO
            IF(NTHDEP.EQ.1) QSGR=QSR/QGR/EB4/DT
      C
      C*****************************************
      C DATA OUTPUT
      C*****************************************
      C
            IF(T.GE.TMAX.OR.TIME.GE.ITIME.OR.LIPEST.EQ.1) GO TO 185
            IF (NCS.EQ.0.OR.NNCS.GT.NCS) GO TO 190
            IF (TIME.LT.CSTIME(NNCS).OR.LCS.EQ.0.AND.LSCS.EQ.0) GO TO 190
            NNCS=NNCS+1
      C
      185   CONTINUE
            NCSYES=1
            GO TO 200
      190   CONTINUE
      C
            IF (T/TLINC*TLINC-T.EQ.0) GO TO 200
            IF (T/TSINC*TSINC-T.NE.0.OR.LSCS.EQ.0) GO TO 100
      C
      200   CONTINUE
```

Fig. B.10. (Continued) Listing for Program COMP

```
      C
      C DETERMINE  MAXIMUM 'DELT' FOR HOL, ELE, E, TEMP
            DHOLM=0.000
            DELEM=0.000
            DEM=0.000
            DTM=0.000
            DO 210 N=1,P
            LP=1+4*(N-1)
            LN=LP+1
            LE=LN+1
            LT=LE+1
            IF (DABS(DELT(LP)).GT.DABS(DHOLM)) DHOLM=DELT(LP)
            IF (DABS(DELT(LN)).GT.DABS(DELEM)) DELEM=DELT(LN)
            IF (DABS(DELT(LE)).GT.DABS(DEM)) DEM=DELT(LE)
            IF (DABS(DELT(LT)).GT.DABS(DTM)) DTM=DELT(LT)
      210   CONTINUE
      C
      C EVALUATE POISSON EQN. IMBALANCE AND DISPLACEMENT CURRENT
            PIBM=0.000
            TEMPM=0.000
            CIM=0.000
            CURDIS(1)=CURTOT-CURHOL(1)-CURELE(1)
            CDISM=CURDIS(1)
            DO 230 N=2,PM1
            PIB(N)=(E(N)-E(N-1))/DXN(N)-HOL(N)+ELE(N)-DOPN(N)
            IF (DABS(PIB(N)).GT.DABS(PIBM)) PIBM=PIB(N)
            CURDIS(N)=CURTOT-CURHOL(N)-CURELE(N)
            IF (DABS(CURDIS(N)).GT.DABS(CDISM)) CDISM=CURDIS(N)
            IF(TEMP(N).GT.TEMPM) TEMPM=TEMP(N)
            IF(CI(N).GT.CIM) CIM=CI(N)
      230   CONTINUE
            CURDIS(P)=CURDIS(PM1)
      C
            IF (NCSYES.NE.1) GO TO 250
      C
      C WRITE AND/OR STORE DIODE CROSS SECTIONS
            CALL CSOP(ITIME,T,TIMF,LCS,LCSPI,LSCS,LSCSPI,P)
      C
      250   CONTINUE
      C
      C BIAS MINIMUM PIVOT VALUE
            PIVMIN=PIVMIN-1.000
      C
      C WRITE AND/OR STORE TRANSIENT DATA
            CALL TNDAOP(T,TMAX,ITIME,TLINC,TSINC,LSCS,NCSYES)
      C
            LIPEST=0
            NCSYES=0
      C
            IF(T.LT.TMAX.AND.TIME.LT.TTIME) GO TO  100
      C
      C**********************************************
      C SIMULATION COMPLETED
      C**********************************************
      C
      C WRITE EOF'S ON DATA FILES 7 AND 8
            END FILE 7
```

Fig. B.10. (Continued) Listing for Program COMP

```
570             END FILE 8
571       C
572       C  UNNORMALIZED VARIABLES AND PARAMETERS
573       C
574       C     ARRAY UNNORMALIZATION
575             DO 350 I=1,P
576             XXN(I)=XXN(I)*XN
577             DOPN(I)=DOPN(I)*CARN
578             ELE(I)=ELE(I)*CARN
579             HOL(I)=HOL(I)*CARN
580             E(I)=E(I)*EN
581             V(I)=V(I)*VN
582             TEMP(I)=TEMP(I)*TEMPN
583       350   CONTINUE
584       C
585       C     PARAMETER UNNORMALIZATION
586             TAUN=TAUN*TN
587             TAUP=TAUP*TN
588             VAPP=VAPP*VN
589             VOBI=VOBI*VN
590             DT=DT*TN
591             DX=DX*XN
592             TTIME=TTIME*TN
593             TIME=TIME*TN
594             HOLMO=HOLMO*RMOBN
595             ELEMO=ELEMO*RMOBN
596             CURTOT=CURTOT*CURN
597             ACCEPT=ACCEPT*CARN
598             DONOR=DONOR*CARN
599             XMET=XMET*XN
600             TEMPO=TEMPO*TEMPN
601       C
602             DO 340 I=1,NCS
603             CSTIME(I)=CSTIME(I)*TN
604       340   CONTINUE
605       C
606       C DEFINE FINAL DIODE VOLTAGE (BUILT-IN VOLTAGE FOR
607       C THERMAL EQUILIBRIUM STATE)
608             VDCOMP=V(P)
609       C
610       C WRITE NEW STATE ON FILE NSF
611             IF (NSF.EQ.0) GO TO 350
612             LF=NSF
613             INCLUDE WLF
614       C
615       350   CONTINUE
616       C
617       C CHECK FOR OVERFLOW AND UNDERFLOW
618             CALL CHECKC (1)
619       C
620             END
```

Fig. B.10. (Continued) Listing for Program COMP

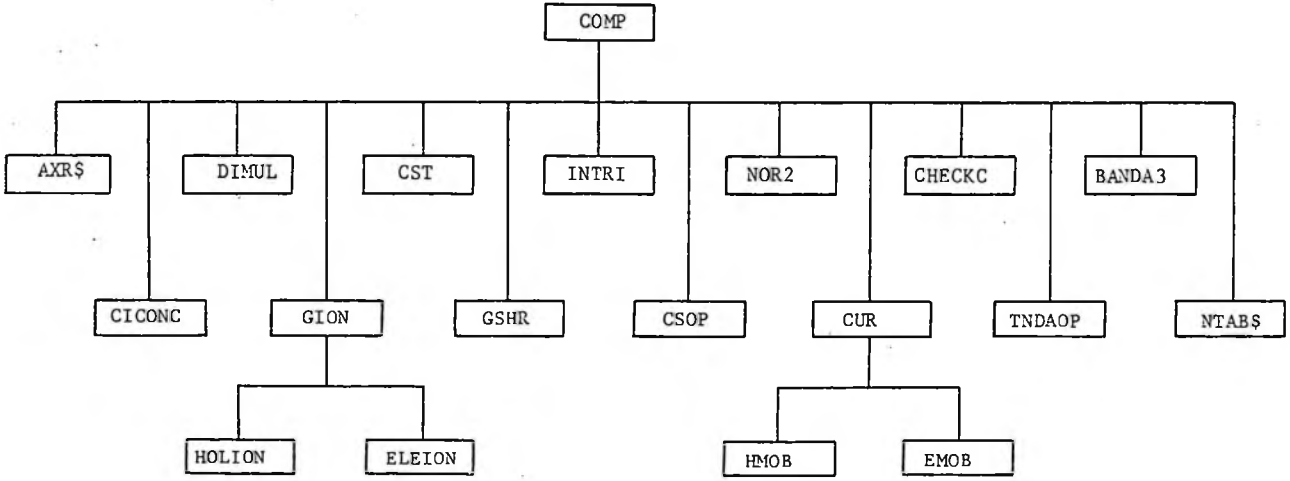


Fig. B.11. Subroutine Hierachy for Program COMP

```
      SUBROUTINE NOR2(L,DIEL,TEMPO,CARINT,XN,TN,CARN,EN,CURN,
     1VN,RECN,MOBN,DIFN,TEMPN)
C
C EVALUATION OF NORMALIZATION CONSTANTS
C L.EQ.1, LISTING OF NORMALIZATION CONSTANTS IS GENERATED
C
C     NORMALIZATION CONSTANT CODE
C     XN-SPACIAL
C     TN-TIME
C     CARN-CARRIER
C     EN-ELECTRIC FIELD
C     CURN-CURRENT
C     VN-VOLTAGE
C     RECN-RECOMBINATION
C     MOBN-MOBILITY
C     DIFN-DIFFUSION
C     TEMPN-TEMPERATURE
C
      REAL*8 MOBN
      DOUBLE PRECISION XN,TN,CARN,EN,CURN,VN,RECN,DIFN,TEMPN
      DOUBLE PRECISION PERM,DIEL,BOZ,TEMPO,Q,TA,CARINT
C
C     DIEL-DILLECTRIC CONSTANT
C     TEMP-DEGREES KELVIN
C     CARINT-INTRINSIC CARRIER CONC., 1/CM**3
C
      PERM=8.854D-14                    @ FARADS/CM, FREE SPACE PERM.
      BOZ=1.381D-23                     @ JOULS/DEGREE KELVIN, BOLTZ.
      Q=1.6D-19                         @ COULOMBS
C
      DIFN=1.000                        @ CM**2/SEC
      CARN=CARINT                       @ 1/CM**3
      VN=BOZ*TEMPO/Q                     @ VOLTS
      MOBN=1.000/VN                     @ CM**2/SEC/VOLT
      TA=(PERM*DIEL*VN/Q/CARN)          @ CM**2, TA=LO**2
      TN=TA                             @ SEC, TN=LO**2/DO
      XN=TA**0.5                        @ CM, XN=LO
      EN=VN/XN                          @ VOLTS/CM
      CURN=Q*CARN/XN                    @ COULS/SEC/CM**2
      RECN=CARN/TA                      @ 1/SEC/CM**3
      TEMPN=TEMPO                       @ DEG. KEL.
C
      IF(L.LT.1.0) GO TO 10
C
      WRITE(6,5) PERM,BOZ,DIEL,TEMPO,CARINT
    5 FORMAT('1 PROGRAM CONSTANTS'/
     1 5X,'FREE SPACE PERMITTIVITY=',T35,'PERM=',T41,D23.16,'  FARADS/CM'
     2/,5X,'BOLTZMANN CONSTANT=',T35,'BOZ=',T41,D23.16,'  JOULES/DEGREE
     3KELVIN',//
     4' PROGRAM PARAMETERS'//
     55X,'DIELECTRIC CONSTANT=',T35,'DIEL=',T41,D23.16,'  FOR SILICON'/
     65X,'TEMPERATURE=',T35,'TEMPO=',T41,D23.16,'  DEGREES KELVIN'/
     75X,'INTRINSIC CARRIER CONC.=',T35,'CARINT=',T41,D23.16,' 1/CM**3')
C
      WRITE(6,8) XN,TN,CARN,EN,CURN,VN,RECN,MOBN,DIFN,TEMPN
    8 FORMAT(//,' NORMALIZATION CONSTANTS'//
```

Fig. B.12. Listing for Subroutine NOR2

```
57            15X,'XN=',T12,D23.18,'  CM'/
58            25X,'TN=',T12,D23.18,'  SEC'/
59            35X,'CARN=',T12,D23.18,'  1/CM**3'/
60            45X,'EN=',T12,D23.18,'  VOLT/CM'/
61            55X,'CURN=',T12,D23.18,'  COUL/SEC/VOLT'/
62            65X,'VN=',T12,D23.18,'  VOLTS'/
63            75X,'RECN=',T12,D23.18,'  1/SEC/CM**3'/
64            85X,'MOBN=',T12,D23.18,'  CM**2/SEC/VOLT'/
65            95X,'DIFN=',T12,D23.18,'  CM**2/SEC'/
66            15X,'TEMPN=',T12,D23.18,'  DEG. KEL.')
67      C
68         10 RETURN
69            END
```

Fig. B.12. (Continued) Listing for Subroutine NOR2

```
      SUBROUTINE HOLION(AITS,E1,TEMP,AIPM,AIPEM,AIPTM)
C
C AITS - IONIZATION COEFF. THERMAL DEPENDENCE, 1/DEG. KEL.
C AIPM - HOLE IONIZATION COEFF. AT NODE (M)
C AIPEM - DERIVATIVE OF AIP WITH RESPECT TO E-FIELD
C AIPTM - DERIVATIVE OF AIP WITH RESPECT TO TEMPERATURE
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
      DATA HA,HB/2.25D7,3.26D6/
C
      E=DABS(E1)
      IF(E.LT.2.7D4) GO TO 15
      IF(IFIT.NE.0) GO TO 10
      A=XN*HA*(1.0D0+AITS*300.D0)
      B=HB/EN
      C=XN*HA*AITS*TEMPN
C
10    CONTINUE
      TEXP=DEXP(-B/E)
      AIPM=(A-C*TEMP)*TEXP
      AIPEM=AIPM*B/E/E
      AIPTM=-C*TEXP
C
      IFIT=1
      RETURN
C
15    CONTINUE
C
      AIPM=0.0D0
      AIPEM=0.0D0
      AIPTM=0.0D0
C
      RETURN
      END
```

Fig. B.13. Listing for Subroutine HOLION

Subroutine ELEION

ELEION evaluates the electron ionization coefficient and subsequent derivatives with respect to electric field and temperature at node M for silicon. Source listing for ELEION is presented in Fig. B.14.

Subroutine HMOB

HMOB evaluates hole mobility and the subsequent derivatives with respect to electric field and temperature at node M for silicon. Source listing for HMOB is presented in Fig. B.15.

Subroutine EMOB

EMOB evaluates electron mobility and the subsequent derivatives with respect to electric field and temperature at node M for silicon. Source listing for EMOB is presented in Fig. B.16.

Subroutine TNDAOP

TNDAOP outputs the simulation transient data summary on either a printer or data file 8, or both. Separate write intervals with respect to the time step counter are maintained for the two cases. Source listing for TNDAOP is presented in Fig. B.17.

Subroutine CSOP

CSOP outputs diode cross sections at the specified cross section times on either a printer or data file 7, or both. Separate write intervals with respect to node points are maintained for the two cases. Source listing for CSOP is presented in Fig. B.18.

```
      SUBROUTINE ELEION(AITS,E1,TEMP,AINM,AINEM,AINTM)
C
C AITS - IONIZATION COEFF. THERMAL DEPENDENCE, 1/DEG. KEL.
C AINM - ELECTRON IONIZATION COEFF. AT NODE (M)
C AINEM - DERIVATIVE OF AINM WITH RESPECT TO E-FIELD
C AINTM - DERIVATIVE OF AINM WITH RESPECT TO TEMPERATURE
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
      DATA EA,EB/3.8D6,1.75D6/
C
      E=DABS(E1)
      IF(E.LT.1.7D4) GO TO 15
      IF(IFIT.NE.0) GO TO 10
      A=XN*EA*(1.0D0+AITS*300.D0)
      B=EB/EN
      C=XN*EA*AITS*TEMPN
C
10    CONTINUE
      TEXP=DEXP(-B/E)
      AINM=(A-C*TEMP)*TEXP
      AINEM=AINM*B/E/E
      AINTM=-C*TEXP
C
      IFIT=1
      RETURN
C
15    CONTINUE
C
      AINM=0.0D0
      AINEM=0.0D0
      AINTM=0.0D0
C
      RETURN
      END
```

Fig. B.14. Listing for Subroutine ELEION

```
      SUBROUTINE HMOB(DOP1,E1,TEMP,HMO,HMOE,HMOT)
C
C EVALUATES HOLE MOBILITY, E-FIELD DERIVATIVE AND
C TEMPERATURE DERIVATIVE AT NODE M
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
C
      DATA HMOO,HN,HS,HA,HF,HB,ALFA/480.0D0,4.0D16,81.0D0,6.1D3,
     11.6D0,2.5D4,2.3D0/
C
      E=DABS(E1)
      DOP=DABS(DOP1)
      IF(IFIT.NE.0) GO TO 10
      TA=RMOBN/HMOO*(TEMPN/300.0D0)**ALFA
      TB=1.0D0/HS
      TC=HN/CARN
      TD=HA/EN
      TE=HF*TD*TD
      TF=(EN/HB)**2
C
10    CONTINUE
      G=TA*TEMP**ALFA
      GT=ALFA*G/TEMP
C
      TG=1.0D0/(TD*E+TE)
      ETE=E*E
      H=1.0D0+DOP/(TB*DOP+TC)+(TG+TF)*ETE
      HE=2.0D0*(TG+TF)*E-TG*TG*ETE*TD
C
      HMO=1.0D0/(G*DSQRT(H))
      HMOT=-GT*HMO/G
      HMOE=-HE/(2.0D0*G*H**1.5D0)
C
      IFIT=1
      RETURN
      END
```

Fig. B.15. Listing for Subroutine HMOB

```
      SUBROUTINE EMOB(DOP1,E1,TEMP,EMO,EMOE,EMOT)
C
C EVALUATES ELECTRON MOBILITY, E-FIELD DERIVATIVE AND
C TEMPERATURE DERIVATIVE AT NODE M
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
C
      DATA EMOO,ENN,ES,EA,EF,EB,ALFA/1400.0D0,3.0D16,350.0D0,
     13.5D3,8.8D0,7.4D3,2.5D0/
C
      E=DABS(E1)
      DOP=DABS(DOP1)
      IF(IFIT.NE.0) GO TO 10
      TA=RMOBN/EMOO*(TEMPN/300.0D0)**ALFA
      TB=1.0D0/ES
      TC=ENN/CARN
      TD=EA/EN
      TE=EF*TD*TD
      TF=(EN/EB)**2
C
10    CONTINUE
      G=TA*TEMP**ALFA
      GT=ALFA*G/TEMP
C
      TG=1.0D0/(TD*E+TE)
      ETE=E*E
      H=1.0D0+DOP/(TB*DOP+TC)+(TG+TF)*ETE
      HE=2.0D0*(TG+TF)*E-TG*TG*ETE*TD
C
      EMO=1.0D0/(G*DSQRT(H))
      EMOT=-GT*EMO/G
      EMOE=-HE/(2.0D0*G*H**1.5D0)
C
      IFIT=1
      RETURN
      END
```

Fig. B.16. Listing for Subroutine EMOB

```
      SUBROUTINE TNDAOP(T,TMAX,ITIME,TLINC,TSINC,LSCS,NCSYES)
C
C     OUTPUTS TRANSIENT DATA ON UNIT 6 (PRINTER) AND ON
C UNIT 8 (DATA FILE).  DATE IS WRITTEN ON UNIT 6 IN
C BLOCKS OF 51/50 LINES THROUGH TEMPORARY ARRAY STORAGE.
C OUTPUT INTERVALS ARE TLINC AND TSINC, RESPECTIVELY.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /NORM/ XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
      COMMON /TDATA/TIME,DT,DHOLM,DELEM,DEM,DTM,PIBM,PIVMIN,
     1TEMPM,CIM,QSGR,CDISM,VDBIAS
      INTEGER T,TMAX,TLINC,TSINC,TL(51)
      REAL DL(51,13),D(13)
C
      DATA NLLIM/51/
C
      MS=TSINC
      ML=TLINC
      IF(MS.LE.0) MS=1000000
      IF(ML.LE.0) ML=1000000
C
      IS=T/MS*MS-T
      IL=T/ML*ML-T
C
C OUTPUT LINE OF DATA?
      IF(IS.NE.0.OR.LSCS.EQ.0.AND.IL.NE.0.AND.NCSYES.NE.1) RETURN
C
C UNNORMALIZED TRANSIENT DATA
      D(1)=TIME*TN
      D(2)=DT*TN
      D(3)=DHOLM*CARN
      D(4)=DELEM*CARN
      D(5)=DEM*EN
      D(6)=DTM*TEMPN
      D(7)=PIBM*CARN
      D(8)=PIVMIN
      D(9)=TEMPM*TEMPN
      D(10)=CIM*CARN
      D(11)=QSGR
      D(12)=CDISM*CURN
      D(13)=VDBIAS*VN
C
C WRITE DATA ON UNIT 8?
      IF(IS.NE.0.AND.NCSYES.NE.1.OR.LSCS.NE.1) GO TO 15
      WRITE(8,10) T,D
10    FORMAT(I15,13(/,E15.8))
C
15    CONTINUE
C
C STORE DATA TO BE WRITTEN ON UNIT 6?
      IF(IL.NE.0.AND.NCSYES.NE.1) RETURN
      NL=NL+1
C
C TRANSFER DATA TO TEMPORARY ARRAY STORAGE.
      TL(NL)=T
      DO 20 K=1,13
```

Fig. B.17. Listing for Subroutine TNDAOP

```
57              DL(NL,K)=D(K)
58        20    CONTINUE
59        C
60        C DUMP TEMPORARILY STORED DATA ON UNIT 6?
61              IF(NL.LT.NLLIM.AND.T.LT.TMAX) RETURN
62        C
63        C WRITE TRANSIENT DATA HEADER ON UNIT 6
64              WRITE(6,30) ITIME
65        30    FORMAT('1',T8,'TRANSIENT DATA',T98,'TIME ',A6,//,
66             1T5,'I',T9,'TIME',T17,'DTIME',T25,'DHOLM',T33,'DELEM',
67             2T41,'DEM',T48,'DTEMPM',T57,'PIBM',T64,'PIVMIN',
68             3T73,'TEMPM',T81,'CIM',T89,'QSGR',T97,'CDISM',
69             4T107,'VDBIAS',/)
70        C
71        C WRITE TRANSIENT DATA BLOCK ON UNIT 6.
72              WRITE(6,35) (TL(I),(DL(I,J),J=1,13),I=1,NL)
73        35    FORMAT(1X,I5,12E8.3,E15.9)
74        C
75              NL=0
76              NLLIM=50
77        C
78              RETURN
79              END
```

Fig. B.17. (Continued) Listing for Subroutine TNDAOP

```
      SUBROUTINE CSOP(ITIME,T,TIME,LCS,LCSPI,LSCS,LSCSPI,P)
C
C OUTPUTS DIODE CROSS SECTIONS ON UNIT 6 (PRINTER) AND
C ON UNIT 7 (DATA FILE). OUTPUT INTERVALS ARE LCSPI
C AND LSCSPI, RESPECTIVELY.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INTEGER T,P
      COMMON /NORM/ XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
      COMMON /VAR/XXN(101),DXN(101),DOPN(101),HOL(101),ELE(101),E(101),
     1V(101),TEMP(101)
      COMMON /CURR/CURHOL(101),CURELE(101),CURDIS(101)
      COMMON /PARM/PIB(101),CI(101),GS(101),GI(101)
C
      REAL UNTIME,D(15)
C
      ML=LCSPI
      MS=LSCSPI
      IF(ML.LE.0) ML=1000000
      IF(MS.LE.0) MS=1000000
C
C WRITE DATA FILE HEADER ON UNIT 7
      UNTIME=TIME*TN
      IF(LSCS.EQ.1) WRITE(7,10) T,UNTIME,P
10    FORMAT(I15/E15.8/I15)
C
      TA=CARN/TN
      K=0
      KL=51
15    CONTINUE
      K=K+1
      IS=(K-1)/MS*MS-(K-1)
      IL=(K-1)/ML*ML-(K-1)
C
C WRITE OR SKIP LINE OF DATA?
      IF(IS.NE.0.AND.IL.NE.0.AND.K.LT.P) GO TO 15
C
C UNNORMALIZE AND WRITE DATA ON APPROPRIATE UNIT.
      D(1)=XXN(K)*XN
      D(2)=DXN(K)*XN
      D(3)=DOPN(K)*CARN
      D(4)=HOL(K)*CARN
      D(5)=ELE(K)*CARN
      D(6)=E(K)*EN
      D(7)=V(K)*VN
      D(8)=TEMP(K)*TEMPN
      D(9)=CURHOL(K)*CURN
      D(10)=CURELE(K)*CURN
      D(11)=CURDIS(K)*CURN
      D(12)=PIB(K)*CARN
      D(13)=CI(K)*CARN
      D(14)=GS(K)*TA
      D(15)=GI(K)*TA
C
C WRITE DATA ON UNIT 7?
      IF(IS.NE.0.AND.K.LT.P.OR.LSCS.NE.1) GO TO 30
```

Fig. B.18. Listing for Subroutine CSOP

```
57              WRITE(7,25) K,D
58        25    FORMAT(I15,15(/,E15.8))
59        30    CONTINUE
60        C
61        C WRITE DATA ON UNIT 6?
62              IF(IL.NE.0.AND.K.LT.P) GO TO 50
63              KL=KL+1
64              IF(KL.LT.52) GO TO 40
65              KL=1
66              WRITE(6,35) T,UNTIME,ITIME
67         35   FORMAT('1 DIODE CROSS SECTION,',5X,'T=',I7,5X,
68             1'TIME=',E10.3,T98,'TIME ',A6,//,
69             1T4,'N',T9,'XXN',T17,'DXN',T26,
70             1'DOPN',T34,'HOL',T41,'ELE',T51,'E',T59,'V',
71             1T65,'TEMP',
72             2T72,'CURHOL',T80,'CURELE',T88,'CURDIS',T97,
73             3'PIB',T105,'CI',T113,'GS',T121,'GI',/)
74        C
75        40    CONTINUE
76              WRITE(6,45) K,D
77        45    FORMAT(1X,I4,15E8.3)
78        C
79        50    CONTINUE
80              IF(K.LT.P) GO TO  15
81              RETURN
82              END
```

Fig. B.18. (Continued) Listing for Subroutine CSOP

Subroutine CICONC

CICONC evaluates the intrinsic carrier concentration at node N and its derivative with respect to temperature at nodes M and M-1. Source listing for CICONC is presented in Fig. B.19.

Subroutine CUR

CUR evaluates the hole and electron current components at nodes M and M-1 along with the subsequent derivatives with respect to hole concentration, electron concentration, electric field, and temperature. The formulation used in these calculations depends on the value of the term $\Delta x(M)E(M)/T(M)$, i.e., if it is greater than $1x10^{-6}$ direct evaluation is used, and if it is less than $1x10^{-6}$ Taylor series approximations are used. Moreover, the program is economical in that each time it is referenced the required current component values are evaluated about the M node only; the M node values generated by the previous reference becomes the M-1 node values for the present reference and are used as such. Accordingly, CUR must be referenced once to initialize this procedure, such that the desired values are available on subsequent references. Source listing for CUR is presented in Fig. B.20.

Subroutine GION

GION evaluates carrier generation through avalanche ionization at node N along with the subsequent derivatives with respect to hole concentration, electron concentration, electric field, and temperature. Since avalanche generation is nonlinear in the model dependent variables and depends mainly on quantities available at the

```
      SUBROUTINE CICONC(DXRNM,DXRNP,TEMPMM,TEMPM,CIN,
     1CITNM,CITNP)
C
C EVALUATES INTRINSIC CARRIER CONC. AT NODE N AND
C TEMPERATURE DERIVATIVE AT NODES M-1 AND M
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /INTRIN/CBEDS,VBEDS,ENGAP
      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
      COMMON /PHYCON/Q,BOZ,PERM
C
      IF(IFIT.NE.0) GO TO 10
      A=1.0D0/CARN*DSQRT(CBEDS*VBEDS*(TEMPN/300.0D0)**3)
      B=ENGAP*Q/(2.0D0*BOZ*TEMPN)
C
10    CONTINUE
      CINM=A*TEMPMM**1.5*DEXP(-B/TEMPMM)
      CINP=A*TEMPM**1.5*DEXP(-B/TEMPM)
      TA=DXRNM*CINM
      TB=DXRNP*CINP
      CIN=TA+TB
      CITNM=TA/TEMPMM*(1.5D0+B/TEMPMM)
      CITNP=TB/TEMPM*(1.5D0+B/TEMPM)
C
      IFIT=1
      RETURN
      END
```

Fig. B.19. Listing for Subroutine CICONC

```
      SUBROUTINE CUR(EXTCRI,DXMNP,DOPNP,HOLNN,HOLNP,ELENN,ELENP,
     1ENP,TEMPNP,VNN,VNP,HMONP,EMONP)
C
C EVALUATION OF CURRENT COMPONENTS, CURRENT COMPONENT
C DERIVATIVES, AND  DIODE VOLTAGE ABOUT NODE (N)
C SUB. MUST BE REF. FOR NODE N=1 TO INITIALIZE SYSTEM:
C DESIRED VALUES ARE THEN AVAILABLE ON SUBSEQUENT REFS.
C FOR N.GE.2
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /JPNP/CPNP,CPPNPM,CPPNPP,CPENP,CPTNP
      COMMON /JNNP/CNNP,CNNNPM,CNNNPP,CNENP,CNTNP
      COMMON /JPNM/CPNM,CPPNMM,CPPNMP,CPENM,CPTNM
      COMMON /JNNM/CNNM,CNNNMM,CNNNMP,CNENM,CNTNM
C
C GENERATE NEW (M) MOBILITY COMPONENTS
C
      CALL HMOB(DOPNP,ENP,TEMPNP,HMONP,HMOENP,HMOTNP)
      CALL EMOB(DOPNP,ENP,TEMPNP,EMONP,EMOENP,EMOTNP)
C
C SHIFT CURRENT COMPONENTS: C(M-1)=C(M)
C
      CPNM=CPNP
      CPPNMM=CPPNPM
      CPPNMP=CPPNPP
      CPENM=CPENP
      CPTNM=CPTNP
      CNNM=CNNP
      CNNNMM=CNNNPM
      CNNNMP=CNNNPP
      CNENM=CNENP
      CNTNM=CNTNP
C
C GENERATE NEW (M) CURRENT COMPONENTS
C
      TA=DXMNP*ENP
      VNP=VNN-TA
      TA=TA/TEMPNP
      IF(DABS(TA).LT.EXTCRI) GO TO 10
C
C DIRECT EVALUATIONS
C
      TA=DEXP(TA)
      TB=1.0D0-1.0D0/TA
      TA=1.0D0-TA
      TC=HMONP*ENP
      CPPNPP=TC/TA
      CPPNPM=TC/TB
      TC=EMONP*ENP
      CNNNPP=TC/TB
      CNNNPM=TC/TA
      CPNP=CPPNPP*HOLNP+CPPNPM*HOLNN
      CNNP=CNNNPP*ELENP+CNNNPM*ELENN
      TA=DXMNP/TEMPNP
      TB=TA*(HOLNP-HOLNN)/
     1(1.0D0/CPPNPM+1.0D0/CPPNPP)
```

Fig. B.20. Listing for Subroutine CUR

```
57              CPENP=CPNP/ENP-TB+CPNP/HMONP*HMOENP
58        C
59              TC=TA*(ELENP-ELENN)/
60             1(1.0D0/CNNNPM+1.0D0/CNNNPP)
61              CNENP=CNNP/ENP+TC+CNNP/EMONP*EMOENP
62              TD=ENP/TEMPNP
63              CPTNP=CPNP/HMONP*HMOTNP+TB*TD
64              CNTNP=CNNP/EMONP*EMOTNP-TC*TD
65        C
66              GO TO 15
67        C
68        C LIMITING VALUES AS E APPROACHES ZERO
69        C
70        10    CONTINUE
71              TB=0.5D0*TA
72              TC=TA*TA/12.0D0
73              G=-1.0D0+TB-TC
74              H= 1.0D0+TB+TC
75        C
76              TD=TEMPNP/DXMNP
77              TF=TD*HMONP
78              TG=TD*EMONP
79        C
80              CPPNPP=TF*G
81              CPPNPM=TF*H
82              CNNNPP=TG*H
83              CNNNPM=TG*G
84              CPNP=CPPNPP*HOLNP+CPPNPM*HOLNN
85              CNNP=CNNNPP*ELENP+CNNNPM*ELENN
86        C
87              TB=0.5*DXMNP/TEMPNP
88              TC=DXMNP*DXMNP
89              TD=TEMPNP*TEMPNP
90              TE=TC/TD/6.0D0*ENP
91              GE=TB-TE
92              HE=TB+TE
93        C
94              CPENP=CPNP/HMONP*HMOENP+TF*(GE*HOLNP+HE*HOLNN)
95              CNENP=CNNP/EMONP*EMOENP+TG*(HE*ELENP+GE*ELENN)
96        C
97              TB=TA*TA/12.0D0
98              GTT=-1.0D0+TB
99              HTT= 1.0D0-TB
100       C
101             CPTNP=CPNP/HMONP*HMOTNP+HMONP/DXMNP*(GTT*HOLNP+HTT*HOLNN)
102             CNTNP=CNNP/EMONP*EMOTNP+EMONP/DXMNP*(HTT*ELENP+GTT*ELENN)
103       C
104       15        CONTINUE
105       C
106             RETURN
107             END
```

Fig. B.20. (Continued) Listing for Subroutine CUR

M-nodes, separate avalanche ionization terms are evaluated at the M and M-1 nodes and are averaged together according to weighting factors dependent on the spacial grid to yield the desired avalanche ionization value at node N. Formulation in this manner facilitates a nonuniform spacial grid. Source listing for GION is presented in Fig. B.21.

Subroutine GSHR

GSHR evaluates Shockley-Read-Hall generation-recombination through mid-energy-band-gap defect centers and subsequent derivatives with respect to hole and electron concentrations at node N and derivatives with respect to temperature at nodes M and M-1. Source listing for GSHR is presented in Fig. B.22.

Subroutine BANDA3

BANDA3 uses the Gaussian elimination technique in conjunction with back substitution to solve the banded or diagional system of linear equations which characterizes the numerical model developed in Chapter 3. Source listing for BANDA3 is presented in Fig. B.23.

Subroutine CHECKC

CHECKC checks for arithmetic overflow, underflow and divide check faults. Upon detection of any of these faults a respective error message is printed. Source listing for CHECKC is presented in Fig. B.24.

Subroutine AXR$

AXR$ is written in assembler language and supplements the FORTRAN compiler by defining the intrinsic FORTRAN V functions OVERFL, DVCHK, and UNDFL. Source listing for AXR$ is presented in Fig. B.24.

```
      SUBROUTINE GION(AITS,DXRNM,DXRNP,ENP,TEMPNP,AIPNP,AINNP)
C
C GENERATION OF AVALANCHE IONIZATION FACTORS ABOUT NODE
C (N).  WEIGHTING FACTORS DXRNM AND DXRNP HAVE BEEN
C INCORPERATED TO FACILITATE A NONUNIFORM SPACIAL GRID.
C SUB. MUST BE REF. FOR NODE N=1 TO INITIALIZE SYSTEM:
C DESIRED VALUES ARE THEN AVAILABLE ON SUBSEQUENT REFS.
C FOR N.GE.2
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /JPNP/CPNP,CPPNPM,CPPNPP,CPENP,CPTNP
      COMMON /JNNP/CNNP,CNNNPM,CNNNPP,CNENP,CNTNP
      COMMON /GIONN/GIPNMM,GINNMM,GIENM,GITNM,
     1GINM,GIPN,GIN,GINN,GINP,GIPNPP,
     2GINNPP,GIENP,GITNP
C
      ABSDER(F,DERF)=DSIGN(1.0D0,F)*DERF
C
      IF(IFIT.EQ.0) TDXRNP=0.5D0
C
C GENERATE NEW (M) IONIZATION COEFFS.
C
      CALL HOLION(AITS,ENP,TEMPNP,AIPNP,AIPENP,AIPTNP)
      CALL ELEION(AITS,ENP,TEMPNP,AINNP,AINENP,AINTNP)
C
C SHIFT AND WEIGHT AVALANCHE FACTORS: GI(M-1)=GI(M)
C MODIFY WEIGHT FACTOR TO COMPENSATE FOR PREVIOUS WEIGHTING.
C
      TDXRNM=DXRNM/TDXRNP
      GINM=GINP*TDXRNM
      GIPNMM=GIPNPM*TDXRNM
      GIPNMP=GIPNPP*TDXRNM
      GINNMM=GINNPM*TDXRNM
      GINNMP=GINNPP*TDXRNM
      GIENM=GIENP*TDXRNM
      GITNM=GITNP*TDXRNM
C
C GENERATE NEW (NP) AVALANCHE FACTORS:
C
      ABCPNP=DABS(CPNP)
      ABCNNP=DABS(CNNP)
C
      GINP=DXRNP*(AIPNP*ABCPNP+AINNP*ABCNNP)
      GIPNPM=DXRNP*AIPNP*ABSDER(CPNP,CPPNPM)
      GIPNPP=DXRNP*AIPNP*ABSDER(CPNP,CPPNPP)
      GINNPM=DXRNP*AINNP*ABSDER(CNNP,CNNNPM)
      GINNPP=DXRNP*AINNP*ABSDER(CNNP,CNNNPP)
      GIENP=DXRNP*(ABCPNP*AIPENP+
     1AIPNP*ABSDER(CPNP,CPENP)+ABCNNP*AINENP+
     2AINNP*ABSDER(CNNP,CNENP))
      GITNP=DXRNP*(ABCPNP*AIPTNP+
     1AIPNP*ABSDER(CPNP,CPTNP)+ABCNNP*AINTNP+
     2AINNP*ABSDER(CNNP,CNTNP))
C
      GIN=GINM+GINP
      GIPN=GIPNMP+GIPNPM
```

Fig. B.21. Listing for Subroutine GION

```
57              GINN=GINNMP+GINNPM
58        C
59        C SAVE 'DXRNP' FOR NEXT PASS!
60        C
61              TDXRNP=DXRNP
62        C
63        C SET IFIT=1 TO PREVENT INITIALIZATIONS ON SUBSEQUENT
64        C PASSES!
65        C
66              IFIT=1
67        C
68              RETURN
69              END
```

Fig. B.21. (Continued) Listing for Subroutine GION

```
      SUBROUTINE GSHR(TAUP,TAUN,HOL,ELE,
     1TEMPMM,TEMPM,CIN,CITNM,CITNP,
     2G,GP,GN,GTNM,GTNP)
C
C EVALUATION OF SHOCKLEY-HALL-READ GENERATION-RECOMBINATION
C THROUGH MID-ENERGY-BAND-GAP GEN.-RECOMB. CENTERS, AND
C HOLE AND ELECTRON DERIVATIVES AT NODE (N) AND TEMPERATURE
C DERIVATIVES AT NODES (M-1) AND (M)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      TA=CIN+ELE
      TB=CIN+HOL
      TC=TAUN*TB+TAUP*TA
      TD=TC*TC
      TE=CIN*CIN-HOL*ELE
      TF=(2.0D0*CIN*TC-(TAUP+TAUN)*TE)/TD
C
      G=TE/TC
      GP=-(TAUN*CIN+TAUP*ELE)*TA/TD
      GN=-(TAUP*CIN+TAUN*HOL)*TB/TD
      GTNM=TF*CITNM
      GTNP=TF*CITNP
C
      RETURN
      END
```

Fig. B.22. Listing for Subroutine GSHR

```
      SUBROUTINE BANDA3(LRMAX,NCD,NHD,LROW,LCOL,A,X,NBNDTX,PIVMIN)
C
C SUB. 'BANDAG' EVALUATES THE SOLUTION OF A BANDED
C (OR DIAGONAL) SYSTEM OF (LRMAX) LINEAR SIMULTANEOUS
C EQUATIONS THROUGH THE GAUSSIAN ELIMINATION TECHNIQUE.
C RESULTING 'A' ARRAY OF NO USE TO USER!
C
C P      - SOLUTION ARRAY LENGTH, INCLUDES UNKNOWNS AND
C          BOUNDARY VALUES
C NCD    - COLUMN NUMBER OF CENTRAL DIAGONAL IN 'A'
C NHD    - COLUMN NUMBER FOR EQUATION CONSTANTS IN 'A'
C A      - COEFFICIENT AND CONSTANT ARRAY
C X      - SOLUTION ARRAY
C NBNDTX - NUMBER OF POSITIONS RESERVED FOR BND. VALUES AT TOP OF 'X' ARRAY
C LRMAX  - NUMBER OF EQUATIONS TO BE SOLVED SIMULTANEOUSLY
C NDB    - NUMBER OF COEFFICIENT DIAGONALS BELOW CENTRAL
C          (OR MAIN) DIAGONAL
C NDA    - NUMBER OF COEFFICIENT DIAGONALS ABOVE CENTRAL
C          (OR MAIN) DIAGONAL
C PIVMIN - MINIMUM PIVOT
C LROW   - ARRAY ROW DIMENSION
C LCOL   - ARRAY COLUMN DIMENSION
C
      DOUBLE PRECISION TA,X(LROW),A(LROW,LCOL),ALFA,PIVMIN
C
      NDB=NCD-1
      NDA=NHD-NCD-1
      PIVMIN=1.0D100
C
C UPPER TRIANGULATION OF ROWS (2)-(NDB)
      IF(NDB.EQ.1) GO TO 20
      DO 5 LR=2,NDB
      LCOF=NDB+2-LR
      DO 10 LCO=LCOF,NDB
      ALFA=A(LR,LCO)/A(LR+LCO-NCD,NCD)
      DO 15 LC=1,NDA
      A(LR,LC+LCO)=A(LR,LC+LCO)-ALFA*A(LR+LCO-NCD,LC+NCD)
15    CONTINUE
      A(LR,NHD)=A(LR,NHD)-ALFA*A(LR+LCO-NCD,NHD)
10    CONTINUE
5     CONTINUE
C
20    CONTINUE
C
C UPPER TRIANGULARIZATION OF ROWS (NDB+1)-(LRMAX)
      DO 25 LR=NCD,LRMAX
C SEARCH FOR MINIMUM DIAGONAL PIVOT ELEMENT
      TA=A(LR-NDB,NCD)
      IF(DABS(TA).LT.DABS(PIVMIN)) PIVMIN=TA
      DO 30 LCO=1,NDB
C
      ALFA=A(LR,LCO)/A(LR+LCO-NCD,NCD)
      DO 32 LC=1,NDA
      A(LR,LC+LCO)=A(LR,LC+LCO)-ALFA*A(LR+LCO-NCD,LC+NCD)
32    CONTINUE
      A(LR,NHD)=A(LR,NHD)-ALFA*A(LR+LCO-NCD,NHD)
```

Fig. B.23. Listing for Subroutine BANDA3

```
      30    CONTINUE
      25    CONTINUE
      C
      C BACK SUBSTITUTION FOR X(LRMAX)-X(LRMAX-NDA+1)
            LRSTOP=LRMAX-NDA+1
            DO 45 LR=LRMAX,LRSTOP,-1
            TA=A(LR,NHD)
            KK=LR+NBNDTX
            KSTOP=LRMAX-LR
            IF(KSTOP.EQ.0) GO TO 40
            DO 35 K=1,KSTOP
            TA=TA-X(K+KK)*A(LR,K+NCD)
      35    CONTINUE
      40    CONTINUE
            X(KK)=TA/A(LR,NCD)
      45    CONTINUE
      C
      C BACK SUBSTITUTION FOR X(LRMAX-NDA)- X(NDB+1)
            LRST=LRMAX-NDA
            DO 55 LR=LRST,1,-1
            KK=LR+NBNDTX
            TA=A(LR,NHD)
            DO 50 K=1,NDA
            TA=TA-X(K+KK)*A(LR,K+NCD)
      50    CONTINUE
            X(KK)=TA/A(LR,NCD)
      55    CONTINUE
      C
      C
            RETURN
            END
```

Fig. B.23. (Continued) Listing for Subroutine BANDA3

```
1            SUBROUTINE CHECKC(K)
2       C
3       C  SUBROUTINE CHECK CHECKS FOR FLOATING POINT
4       C  OVERFLOW AND DIVIDE FAULT.
5       C
6            CALL OVERFL(I)
7       C
8            IF(I.NE.1) GO TO 4
9            WRITE(6,1) K
10          1 FORMAT(/,' ***** OVERFLOW CHECK NO. ',
11           1I2,' *****',/)
12      C
13          4 CALL DVCHK(I)
14      C
15           IF(I.NE.1) GO TO 5
16           WRITE(6,2) K
17          2 FORMAT(/,' ***** DIVIDE FAULT CHECK NO. ',
18           1I2,' *****',/)
19      C
20          5 CALL UNDFL(I)
21      C
22           IF(I.NE.1) GO TO 6
23           WRITE(6,3) K
24          3 FORMAT(/,' ***** UNDERFLOW CHECK NO. ',
25           1I2,' *****',/)
26      C
27          6 CONTINUE
28           RETURN
29           END
```

(a) Listing for CHECKC

```
1       $(1)       AXR$       .
2       OVERFL*    . (I)
3                  . I=1 OVERFLOW
4                  . I=2 NO OVERFLOW
5                  L,U        A0,1            .
6                  JFO        $+2             .
7                  L,U        A0,2            .
8                  S          A0,*0,X11       .
9                  J          2,X11           .
10      DVCHK*     . (I)
11                 . I=1 DIVIDE FAULT
12                 . I=2 NO DIVIDE FAULT
13                 L,U        A0,1            .
14                 JDF        $+2             .
15                 L,U        A0,2            .
16                 S          A0,*0,X11       .
17                 J          2,X11           .
18      UNDFL*     . (I)
19                 . I=1 UNDERFLOW FAULT
20                 . I=2 NO UNDERFLOW FAULT
21                 L,U        A0,1            .
22                 JFU        $+2             .
23                 L,U        A0,2            .
24                 S          A0,*0,X11       .
25                 J          2,X11           .
26                 END        .
```

(b) Listing for AXR$

Fig. B.24. Listing for Subroutines CHECKC and AXR$

B.3 PROGRAM GDG

Program GDG (Graph-Data-Generator) converts the simulation summary stored in data files 7 and 8 into the format required by the graphic analysis program GRAPH. This intermediate data handling procedure is adopted to facilitate tape storage and management of simulation summaries. The natural division of this data between diode cross sections, data file 7, and transient data, data file 8, is also beneficial in this respect. GDG processes the two divisions of data on a separate and optional basis, i.e., only the division of data to be graphically analyzed need be broken down into individual data files. The program is designed for interactive execution, but may be conveniently executed in batch mode in view of the minimal amount of user supplied data required. A flow chart for GDG is shown in Fig. B.25 and the source listing for GDG is presented in Fig. B.26.

Subroutine NTAB$ is the only subroutine called by GDG and is described in Appendix B.1.

B.4 PROGRAM GRAPH

Program GRAPH is designed to provide a comprehensive graphical analysis capability for diode simulations performed by program COMP. Execution must be through a Tektronix Display Terminal and thus in the interactive mode. GRAPH is capable of plotting three different variables on the same graph, assuming that each graph data file represents a single variable as is the case here. The number of curves plotted per variable is equivalent to the number of cross sections plotted for a given graph. For example, a graph may be generated

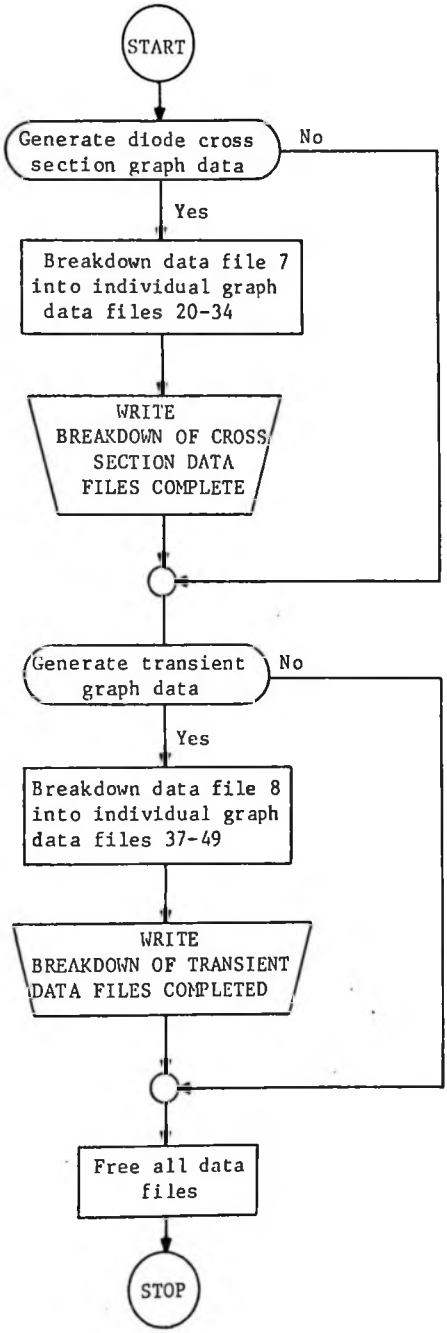


Fig. B.25. Flow Chart for Program GDG

```
      C***** GRAPH DATA GENERATOR *****
      C
      C OPTIONAL BREAKDOWN OF CROSS SECTION AND/OR TRANSIENT DATA FILES
      C (GENERATED BY 'COMP') INTO INDIVIDUAL GRAPH DATA FILES
      C REQUIRED BY 'GRAPH'.
      C
            DIMENSION LFCS(15), LFT(13), XMIN(20), XMAX(20), W(210,15)
      C
      C     OUTPUT DATA FILE DIRECTORIES
            DATA LFCS/20,21,22,23,24,25,26,27,28,29,30,31,32,33,34/
            DATA LFT/37,38,39,40,41,42,43,44,45,46,47,48,49/
      C
      C     INITIALIZE NUMBER OF CROSS SECTIONS AND TRANSIENT OUTPUT DF.
            DATA NCSDF,NTDF/15,13/
      C
      C     ASSIGN INPUT DATA FILES
            CALL ERTRAN (6,'@ASG,AX 7. . ')  @ CROSS SECTIONS
            CALL ERTRAN (6,'@ASG,AX 8. . ')  @ TRANSIENT
      C
      C     ASSIGN OUTPUT DATA FILES
      C     CROSS SECTION OUTPUT DF (SPACIAL)
            CALL ERTRAN (6,'@ASG,AX 20. . ') @ XXN
            CALL ERTRAN (6,'@ASG,AX 21. . ') @ DXN
            CALL ERTRAN (6,'@ASG,AX 22. . ') @ DOPN
            CALL ERTRAN (6,'@ASG,AX 23. . ') @ HOL
            CALL ERTRAN (6,'@ASG,AX 24. . ') @ ELE
            CALL ERTRAN (6,'@ASG,AX 25. . ') @ E
            CALL ERTRAN (6,'@ASG,AX 26. . ') @ V
            CALL ERTRAN (6,'@ASG,AX 27. . ') @ TEMP
            CALL ERTRAN (6,'@ASG,AX 28. . ') @ CURHOL
            CALL ERTRAN (6,'@ASG,AX 29. . ') @ CURELE
            CALL ERTRAN (6,'@ASG,AX 30. . ') @ CURDIS
            CALL ERTRAN (6,'@ASG,AX 31. . ') @ Q
            CALL ERTRAN (6,'@ASG,AX 32. . ') @ CI
            CALL ERTRAN (6,'@ASG,AX 33. . ') @ GS
            CALL ERTRAN (6,'@ASG,AX 34. . ') @ GI
      C
      C     TRANSIENT OUTPUT DF (TEMPORAL)
            CALL ERTRAN (6,'@ASG,AX 37. . ') @ TIME
            CALL ERTRAN (6,'@ASG,AX 38. . ') @ DTIME
            CALL ERTRAN (6,'@ASG,AX 39. . ') @ DHOLM
            CALL ERTRAN (6,'@ASG,AX 40. . ') @ DELEM
            CALL ERTRAN (6,'@ASG,AX 41. . ') @ DEM
            CALL ERTRAN (6,'@ASG,AX 42. . ') @ DTEMPM
            CALL ERTRAN (6,'@ASG,AX 43. . ') @ PIBM
            CALL ERTRAN (6,'@ASG,AX 44. . ') @ PIVMIN
            CALL ERTRAN (6,'@ASG,AX 45. . ') @ TEMPM
            CALL ERTRAN (6,'@ASG,AX 46. . ') @ CIM
            CALL ERTRAN (6,'@ASG,AX 47. . ') @ GSGR
            CALL ERTRAN (6,'@ASG,AX 48. . ') @ CDISM
            CALL ERTRAN (6,'@ASG,AX 49. . ') @ VCBIAS
      C
            WRITE (6,20)
      20    FORMAT ('1GENERATE CROSS SECTION GRAPH DATA?, 1=YES')
            READ (5,30) LGCSGD
      30    FORMAT ()
```

Fig. B.26. Listing for Program GDG

```
      C
            WRITE (6,40)
      40    FORMAT (' GENERATE TRANSIENT GRAPH  DATA?, 1-YES')
            READ (5,30) LGTGD
      C-----------------------------------------------
      C     CREATE INDIVIDUAL SPACIAL DATA FILES
      C-----------------------------------------------
      C     GENERATE CS GRAPH DATA?
            IF (LGCSGD.NE.1) GO TO 180
      C
      C     READ DATE AND TIME
            READ (7,50) IDATE,ITIME
      50    FORMAT (A6)
      C
      C     WRITE DATE AND TIME ON CS DATA FILES?
            DO 60 K=1,NCSDF
            KK=LFCS(K)
            WRITE (KK,50) IDATE,ITIME
      60    CONTINUE
      C
      70    CONTINUE
      C     INITIALIZE MINIMUMS AND MAXIMUMS
            DO 80 K=1,NCSDF
            XMIN(K)=1.0E20
            XMAX(K)=-1.0E20
      80    CONTINUE
      C
      C     READ CROSS SECTION
            READ (7,90,END=150) NT,TIME,NP
      90    FORMAT (I15,/,E15.8,/,I15)
            READ (7,100,END=150) (IBLANK,(W(J,K),K=1,NCSDF),J=1,NP)
      100   FORMAT (I15,/,(E15.8))
      C
      C     EVALUATE NET CHARGE, MINS AND MAXS
            DO 120 J=1,NP
            W(J,12)=W(J,4)-W(J,5)+W(J,3)
            DO 110 K=1,NCSDF
            XMIN=AMIN1(XMIN,X)
            XMAX=AMAX1(XMAX,X)
      110   CONTINUE
      120   CONTINUE
      C
            TNP=NP
      C
      C     WRITE NP, CS, TIME, MIN, AND MAX ON OUTPUT DF
            DO 140 K=1,NCSDF
            KK=LFCS(K)
            WRITE (KK,130) TNP,(W(J,K),J=1,NP),TIME,XMIN(K),XMAX(K)
      130   FORMAT (E15.8)
      140   CONTINUE
      C
      C     TRANSFER NEXT CROSS SECTION
            GO TO 70
      C
      150   CONTINUE
      C     EOF REACHED ON FILE 7., WRITE EOF ON FILES 20.-36.
            DO 160 K=1,NCSDF
```

Fig. B.26. (Continued) Listing for Program GDG

```
114             KK=LFCS(K)
115             END FILE KK
116       160   CONTINUE
117             WRITE (6,170)
118       170   FORMAT (' BREAKDOWN OF CROSS SECTION OF COMPLETED',/)
119       C
120       C-----------------------------------------------
121       C     CREATE INDIVIDUAL TEMPORAL DATA FILES
122       C-----------------------------------------------
123       180   CONTINUE
124             TIME=0.0
125       C     GENERATE TRANSIENT GRAPH DATA?
126             IF (LGTGD.NE.1) GO TO 320
127       C
128       C     READ DATE AND TIME
129             READ (8,50) IDATE,ITIME
130       C
131       C     WRITE DATE AND TIME ON TRANS. DATA FILES
132             DO 190 K=1,NTDF
133             KK=LFT(K)
134             WRITE (KK,50) IDATE,ITIME
135       190   CONTINUE
136       C
137       C     READ CROSS SECTION LABEL
138       200   CONTINUE
139             READ (8,210,END=290) NP
140       210   FORMAT (I15)
141       C
142       C     NUMBER OF TRANS. DATA PTS. .GT. 0?
143             IF (NP.GT.0) GO TO 230
144             WRITE (6,220)
145       220   FORMAT (' ZERO TRANS. DATA PTS., BREAKDOWN TRANS. DF SPEC.',/)
146             GO TO 320
147       230   CONTINUE
148             TNP=NP
149       C
150       C     INITIALIZE MINIMUMS AND MAXIMUMS
151             DO 240 K=1,NTDF
152             XMIN(K)=1.0E20
153             XMAX(K)=-1.0E20
154             KK=LFT(K)
155             WRITE(KK,270) TNP
156       240   CONTINUE
157       C
158             NPL=NP
159             NPC=0
160             NP=200
161       245   CONTINUE
162             NPC=NPC+200
163             IF(NPC.GT.NPL) NP=NPL+200-NPC
164       C
165       C     READ CROSS SECTION DATA
166             READ (8,250,END=290) (IBLANK,(W(J,K),K=1,NTDF),J=1,NP)
167       250   FORMAT (I15,/,(E15.8))
168       C
169             DO 260 J=1,NP
170             DO 260 K=1,NTDF
```

Fig. B.26. (Continued) Listing for Program GDG

```
171             XMIN=AMIN1(XMIN,X)
172             XMAX=AMAX1(XMAX,X)
173       260   CONTINUE
174       C
175       C     WRITE TRANSIENT DATA ON OUTPUT DATA FILE
176             DO 280 K=1,NTDF
177             KK=LFT(K)
178             WRITE (KK,270) (W(J,K),J=1,NP)
179       270   FORMAT (E15.8)
180       280   CONTINUE
181       C
182             IF(NPC.LT.NPL) GO TO 245
183       C
184             DO 285 K=1,NTDF
185             KK=LFT(K)
186             WRITE(KK,270) TIME,XMIN(K),XMAX(K)
187       285   CONTINUE
188       C
189       C     TRANSFER NEXT CROSS SECTION
190             GO TO 200
191       C
192       290   CONTINUE
193       C
194       C     EOF REACHED ON FILE 6., WRITE EOF ON FILES 37.-49.
195             DO 300 K=1,NTDF
196             KK=LFT(K)
197             END FILE KK
198       300   CONTINUE
199       C
200             WRITE (6,310)
201       310   FORMAT (' BREAKDOWN OF TRANS. DF COMPLETED',/)
202       C
203       320   CONTINUE
204       C
205       C     FREE DATA FILES
206             CALL ERTRAN (6,'@FREE 20. . ')   @ XXN
207             CALL ERTRAN (6,'@FREE 21. . ')   @ DXN
208             CALL ERTRAN (6,'@FREE 22. . ')   @ DOPN
209             CALL ERTRAN (6,'@FREE 23. . ')   @ HOL
210             CALL ERTRAN (6,'@FREE 24. . ')   @ ELE
211             CALL ERTRAN (6,'@FREE 25. . ')   @ E
212             CALL ERTRAN (6,'@FREE 26. . ')   @ V
213             CALL ERTRAN (6,'@FREE 27. . ')   @ TEMP
214             CALL ERTRAN (6,'@FREE 28. . ')   @ CURHOL
215             CALL ERTRAN (6,'@FREE 29. . ')   @ CURELE
216             CALL ERTRAN (6,'@FREE 30. . ')   @ CURDIS
217             CALL ERTRAN (6,'@FREE 31. . ')   @ Q
218             CALL ERTRAN (6,'@FREE 32. . ')   @ CI
219             CALL ERTRAN (6,'@FREE 33. . ')   @ GS
220             CALL ERTRAN (6,'@FREE 34. . ')   @ GI
221       C
222             CALL ERTRAN (6,'@FREE 37. . ')   @ TIME
223             CALL ERTRAN (6,'@FREE 38. . ')   @ DTIME
224             CALL ERTRAN (6,'@FREE 39. . ')   @ DHOLM
225             CALL ERTRAN (6,'@FREE 40. . ')   @ DELEM
226             CALL ERTRAN (6,'@FREE 41. . ')   @ DEM
227             CALL ERTRAN (6,'@FREE 42. . ')   @ DTEMPM
```

Fig. B.26. (Continued) Listing for Program GDG

```
228            CALL ERTRAN (6,'@FREE 43. . ')   @ PIBM
229            CALL ERTRAN (6,'@FREE 44. . ')   @ PIVMIN
230            CALL ERTRAN (6,'@FREE 45. . ')   @ TEMPM
231            CALL ERTRAN (6,'@FREE 46. . ')   @ CIM
232            CALL ERTRAN (6,'@FREE 47. . ')   @ GSGR
233            CALL ERTRAN (6,'@FREE 48. . ')   @ CDISM
234            CALL ERTRAN (6,'@FREE 49. . ')   @ VOBIAS
235      C
236            STOP
237            END
```

Fig. B.26. (Continued) Listing for Program GDG

which presents the electron and hole current profiles for several different points in time during a simulation, all on the same graph. On the other hand, graphs of this nature are not possible for the transient data, since the respective data files only contain one cross section, or profile. All graphs are plotted on a single set of coordinates, thus making some variable combinations undesirable.

The graph to be plotted may be specified either through a simple code word, or in terms of graph data file codes. For example, in the former case the code word JPNX would designate a graph of hole and electron current components versus position. In the latter case, the code word NEW would first be entered, causing the program to solicit the graph data file codes for the respective variables to be plotted. Four data file codes must be entered as data with the first representing the independent variable and the next three representing the dependent variables. If only one or two dependent variables are to be specified then the remaining positions, or position must be filled by zeros. For the above example 20, 28, 29, 0 would be entered. A list of the graph data file codes and the available graph codes is shown in Table B.3.

A flow chart for GRAPH is presented in Fig. B.27 and the source listing in Fig. B.28. GRAPH employs Tektronix Graphing II software [1,2], inaddition to the subroutines described below.

Subroutine NTAB$

NTAB$ is described in Appendix B.1.

TABLE B.3

GRAPH CODES FOR PROGRAM GRAPH

Graph	Graph	Graph Data File Number	Variable
Cross Section Graphs:			
PX	p*x	20	x_N
NX	n*x	21	Δx_N
PNX	p,n*x	22	N_I
EX	E*x	23	n
TX	T*x	24	p
JPX	J_p*x	25	E
JNX	J_n*x	26	V
JDX	J_D*x	27	T
JPNX	J_p,J_n*x	28	J_p
JPNDX	J_p,J_n,J_D*x	29	J_n
VX	V*x	30	J_D
DXX	Δx_N*x	31	Q
DOPX	N_I*x	32	N_i
QX	Q*x	33	G_{SRH}
CIX	N_i*x	34	G_I
GSX	G_{SRH}*x		
GIX	G_I*x		
GSIX	$(G_{SRH}+G_I)$*x		
Transient Graph:			
VT	V*t	37	t

TABLE B.3 (Continued)

Graph Code	Graph	Graph Data File Number	Variable
DTT	$\Delta t*t$	38	Δt
DPT	$\Delta p_{max}*t$	39	Δp_{max}
DNT	$\Delta n_{max}*t$	40	Δn_{max}
DPNT	$\Delta p_{max}, \Delta n_{max}*t$	41	ΔE_{max}
DET	$\Delta E_{max}*t$	42	ΔT_{max}
DTEMT	$\Delta T_{max}*t$	43	PIB_{max}
TEMT	$T_{max}*t$	44	PIV
QSGRT	QSGR*t	45	T_{max}
JDT	$J_{D_{max}}*t$	46	$N_{i_{max}}$
PIVT	PIV*t	47	GSGR
		48	$J_{D_{max}}$
		49	V

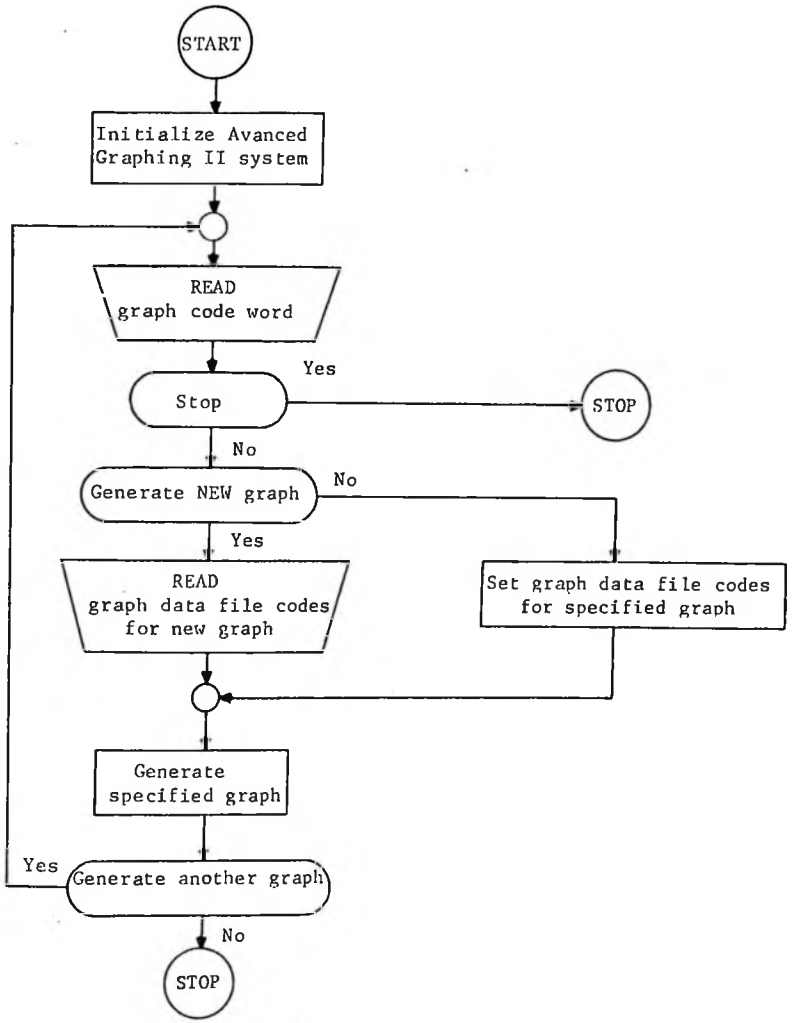


Fig. B.27. Flow Chart for Program GRAPH

```
      C********** GRAPH ***********
      C
      C INTERACTIVELY GRAPHS SIMULATION RESULTS ON A TEKTRONICS
      C GRAPHICS TERMINAL.  REQUIRES INDIVIDUAL GRAPH DATA FILES
      C GENERATED BY GDG (GRAPH DATA GENERATOR).
      C
            DIMENSION IRUN(3),KGC(12)
            DIMENSION KGCODE(29),NU(4,29)
            DIMENSION NSCS(35),CSTIME(35)
            COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
      C
            DATA KONE/'@@@@@1'/KSTOP/'STOP'/
            DATA IRUN(2)/'    '/KNEW/'NEW'/
            DATA NGC/15/
            DATA KGC/12*'      '/
      C
            DATA KGCODE/'PX','NX','PNX',
           1'EX','TX','JPX','JNX',
           2'JDX','JPNX','JPNDX',
           3'VX','VI','DXX','DOPX','QX',
           4'CIA','GSX','GIX','GSIX','DTT','JPT','DNT',
           5'DPNT','DET','DIENT','TEMT','QSGRT','JDT','PIVT'/
      C
            DATA NU/20,23,0,0,20,24,0,0,
           120,25,24,0,20,25,0,0,
           220,27,0,0,20,28,0,0,
           320,29,0,0,20,30,0,0,
           420,28,29,0,20,28,29,30,
           520,26,0,0,37,49,0,0,
           620,21,0,0,20,22,0,0,
           720,31,0,0,20,32,0,0,
           820,33,0,0,20,34,0,0,
           920,33,34,0,37,38,0,0,
           137,39,0,0,37,40,0,0,
           237,39,40,0,37,41,0,0,
           337,42,0,0,37,45,0,0,
           437,47,0,0,37,48,0,0,
           537,44,0,0/
      C
      C ASSIGN DATA FILES
            CALL ERTRAN (6,'@ASG,AX 20. . ') @ XXN
            CALL ERTRAN (6,'@ASG,AX 21. . ') @ DXN
            CALL ERTRAN (6,'@ASG,AX 22. . ') @ DOPN
            CALL ERTRAN (6,'@ASG,AX 23. . ') @ HOL
            CALL ERTRAN (6,'@ASG,AX 24. . ') @ ELE
            CALL ERTRAN (6,'@ASG,AX 25. . ') @ E
            CALL ERTRAN (6,'@ASG,AX 26. . ') @ V
            CALL ERTRAN (6,'@ASG,AX 27. . ') @ TEMP
            CALL ERTRAN (6,'@ASG,AX 28. . ') @ CURHOL
            CALL ERTRAN (6,'@ASG,AX 29. . ') @ CURELE
            CALL ERTRAN (6,'@ASG,AX 30. . ') @ CURDIS
            CALL ERTRAN (6,'@ASG,AX 31. . ') @ Q
            CALL ERTRAN (6,'@ASG,AX 32. . ') @ CI
            CALL ERTRAN (6,'@ASG,AX 33. . ') @ GS
            CALL ERTRAN (6,'@ASG,AX 34. . ') @ GI
      C
```

Fig. B.28. Listing for Program GRAPH

```
      CALL ERTRAN (6,'@ASG,AX 37. . ') @ TIME
      CALL ERTRAN (6,'@ASG,AX 38. . ') @ DTIME
      CALL ERTRAN (6,'@ASG,AX 39. . ') @ DHOLM
      CALL ERTRAN (6,'@ASG,AX 40. . ') @ DELEM
      CALL ERTRAN (6,'@ASG,AX 41. . ') @ DEM
      CALL ERTRAN (6,'@ASG,AX 42. . ') @ DTEMPM
      CALL ERTRAN (6,'@ASG,AX 43. . ') @ PIBM
      CALL ERTRAN (6,'@ASG,AX 44. . ') @ PIVMIN
      CALL ERTRAN (6,'@ASG,AX 45. . ') @ TEMPM
      CALL ERTRAN (6,'@ASG,AX 46. . ') @ CIM
      CALL ERTRAN (6,'@ASG,AX 47. . ') @ GSGR
      CALL ERTRAN (6,'@ASG,AX 48. . ') @ CDISM
      CALL ERTRAN (6,'@ASG,AX 49. . ') @ VDBIAS
C
C OBTAIN DATE AND TIME FROM DATA FILE 22
      READ(22,2) IRUN(1),IRUN(3)
2     FORMAT(A6)
      REWIND 22
C
C INITIALIZE ADVANCED GRAPHICS II SYSTEM
      CALL INITT(30)
C
5     CONTINUE
C
C SPECIFY WHICH GRAPH
      WRITE(6,10)
10    FORMAT(/,' WHICH GRAPH')
      READ(5,15) KWG
15    FORMAT(A6)
C
      DO 20 K=1,NGC
      IF(KWG.NE.KGCODE(K)) GO TO 20
C
      KGC(1)=KGCODE(K)
      NUX=NU(1,K)
      NUY1=NU(2,K)
      NUY2=NU(3,K)
      NUY3=NU(4,K)
      GO TO 100
C
20    CONTINUE
C
C DEFINE NEW GRAPH COMBINATION
      IF(KWG.NE.KNEW) GO TO 24
      WRITE(6,21)
21    FORMAT(' ENTER GRAPH TITLE')
      READ(5,30) KGC
30    FORMAT(12A6)
      WRITE(6,22)
22    FORMAT(' SPECIFY NUX,NUY1,NUY2,NUY3')
      READ(5,23) NUX,NUY1,NUY2,NUY3
23    FORMAT()
      GO TO 100
C
24    CONTINUE
C
C TERMINATE XQT
```

Fig. B.28. (Continued) Listing for Program GRAPH

```
114             IF(KWG.NE.KSTOP) GO TO 26
115             WRITE(6,27)
116       27    FORMAT(' ********** XQT TERMINATED **********')
117             GO TO 1000
118       C
119       C ERROR
120       26    CONTINUE
121             WRITE(6,25)
122       25    FORMAT(' ERROR: UNDEFINED GRAPH REQUESTED, TRY AGAIN')
123       C
124             GO TO 5
125       C
126       C********** GENERATE GRAPH *********
127       C
128       100   CONTINUE
129             IFLAG=0
130             INEGY=1
131       105   CONTINUE
132             CALL BINITT
133             WRITE(6,110) (KGC(J),J=1,11)
134       110   FORMAT(/,1X,11A6,/)
135             CALL GENCUR(IFLAG,INEGY,NUX,NUY1,NUY2,NUY3,NSCS,CSTIME)
136             CALL HEADER(150,775,KGC,NSCS,IRUN)
137             CALL TINPUT(KSIG)
138             CALL ERASE
139             IF(KSIG.EQ.KONE) GO TO 5
140             GO TO 105
141       C
142       1000  STOP
143             END
```

Fig. B.28. (Continued) Listing for Program GRAPH

Subroutine GENCUR

GENCUR supervises the generation of the graph specified by GRAPH. This procedure includes reading the appropriate data from the graph data files, determining minimums and maximums for the independent variable and dependent variable data, establishing the type of data plot for each axis (linear or log), establishing the graph boundaries, and displaying the resulting graph. Source listing for GENCUR is presented in Fig. B.29.

Subroutine LILOY

LILOY provides a linear or log dependent variable (y-axis) plot option. If the log plot is selected and the dependent variable data passes through zero a change of boundaries for the dependent variable axis is solicited; if unchanged, an absolute value plot of the dependent variable data is generated. LILOY source listing is presented in Fib. B.30.

Subroutine SELCS

SELCS solicits the number of cross sections and the numbers for the respective cross sections to be plotted. Source listing for SELCS is presented in Fig. B.30.

Subroutine SMIMA

SMIMA updates minimum and maximum values. Source listing for SMIMA is presented in Fig. B.31.

```
      SUBROUTINE GENCUR(IFLAG,INEGY,NUX,NUY1,NUY2,NUY3,NSCS,TIME)
C
C SUB GENCUR LOADS APPROPRIATE DATA FROM DATA FILES,
C INTERACTIVELY UPDATES MINS. AND MAXS. AND DISPLAYS
C THE SUBSEQUENT CURVES. A MAX OF THREE DEPENDENT
C VARIABLES CAN BE PLOTTED. INDEPENDENT AND RESPECTIVE
C DEPENDENT VARIABLES STORED IN SEPARATE DATA FILES
C AS SPECIFIED IN ARG. LIST.
C
      COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
      DIMENSION TIME(1),NSCS(1)
C
C SUPPRESS GRID LINES
      IG=2
      CALL XFRM(IG)
      CALL YFRM(IG)
C
C SELECT CROSS SECTIONS TO BE DISPLAYED
      CALL  SELCS(IFLAG,NSCS,NDEFCS)
C
C LOADING REQUIRED?
      IF(IFLAG.NE.0.AND.NDEFCS.EQ.0) GO TO 235
C
C LOAD SPECIFIED CROSS SECTIONS
C
C READ DATE AND TIME SUCH AS TO SKIP
      READ(NUX,213) IDATE,ITIME
      IF(NUY1.NE.0) READ(NUY1,213) IDATE,ITIME
      IF(NUY2.NE.0) READ(NUY2,213) IDATE,ITIME
      IF(NUY3.NE.0) READ(NUY3,213) IDATE,ITIME
213   FORMAT(A6)
C
C INITIALIZE MINS. AND MAXS.
      CALL  INMIMA(XMIN,XMAX,YMIN,YMAX)
C
C INITIALIZE NUMBER OF CROSS SECTION TIMES SAVED
      TIME(1)=NSCS(1)
C
      K=1
      JX=1
      DO 230 I=1,99
      IF(NSCS(K+1).NE.I) GO TO 225
C
C LOAD CROSS SECTION AND UPDATE MINS. AND MAXS.
      CALL  LOAD(INEGY,IEOF,NUX,X(JX),XTIME,TXMIN,TXMAX)
C
      IF(IEOF.EQ.0) GO TO 214
      NSCS(1)=K
      TIME(1)=K
      GO TO 233
214   CONTINUE
C
      CALL SMIMA(XMIN,TXMIN,XMAX,TXMAX)
      CALL  LOAD(INEGY,IEOF,NUY1,Y1(JX),Y1TIME,TYMIN,TYMAX)
      CALL SMIMA(YMIN,TYMIN,YMAX,TYMAX)
      IF(NUY2.NE.0) CALL LOAD(INEGY,IEOF,NUY2,Y2(JX),Y2TIME,TYMIN,TYMAX)
```

Fig. B.29. Listing for Subroutine GENCUR

```
      IF(NUY2.NE.0) CALL SMIMA(YMIN,TYMIN,YMAX,TYMAX)
      IF(NUY3.NE.0) CALL LOAD(INEGY,IEOF,NUY3,Y3(JX),Y3TIME,TYMIN,TYMAX)
      IF(NUY3.NE.0) CALL SMIMA(YMIN,TYMIN,YMAX,TYMAX)
C
C CHECK CROSS SECTION COMPONENT CORRESPONDENCE
      IF(XTIME.NE.Y1TIME) GO TO 217
      IF(NUY2.NE.0.AND.XTIME.NE.Y2TIME) GO TO 217
      IF(NUY3.NE.0.AND.XTIME.NE.Y3TIME) GO TO 217
         GO TO 220
217   WRITE(6,215) XTIME
215   FORMAT(' ERROR: XTIME=',E15.8,',  XTIME.NE.YTIME')
      STOP
C
220   CONTINUE
C
C SAVE CROSS SECTION TIME, TIME(1)=NSCS(1)
      TIME(K+1)=XTIME
C
C COMPUTE X AND Y POSITION OF NEXT CROSS SECTION
      JX=JX+X(JX)+1
C
C ALL  SPECIFIED CROSS SECTION LOADED?
      IF(K.EQ.NSCS(1)) GO TO 233
      K=K+1
      GO TO 230
225   CONTINUE
C
C SKIP NEXT CROSS SECTION
      CALL SKIP(NUX)
      CALL SKIP(NUY1)
      IF(NUY2.NE.0) CALL SKIP(NUY2)
      IF(NUY3.NE.0) CALL SKIP(NUY3)
230   CONTINUE
C
233   CONTINUE
      REWIND NUX
      REWIND NUY1
      IF(NUY2.NE.0) REWIND NUY2
      IF(NUY3.NE.0) REWIND NUY3
C
235   CONTINUE
C
C SPECIFIED CROSS SECTIONS LOADED!
C DEFINE MINS. AND MAXS., WITHOUT CHANGING
      CALL SPMIMA(XMIN,XMAX,YMIN,YMAX)
C LINEAR OR LOG Y-AXIS
      CALL LILOY(INEGY,YMIN,YMAX,NSCS(1),NUY1,NUY2,NUY3,ILLY)
C
C LINEAR OR LOG X - AXIS
      WRITE(6,237)
237   FORMAT(' 1-LINEAR, 2-LOG, X-AXIS SCALE')
      READ(5,238) ILL
238   FORMAT()
      CALL XTYPE(ILL)
      CALL YTYPE(ILLY)
C
C GENERATE GRAPH
```

Fig. B.29. Listing for Subroutine GENCUR

```
      C PLOT FIRST CROSS SECTION
            CALL ERASE
            CALL CHECK(X(1),Y1(1))
            CALL DSPLAY(X(1),Y1(1))
            IF(IG.LT.5) CALL FRAME
            IF(NUY2.NE.0) CALL LINE(34)
            IF(NUY2.NE.0) CALL CPLOT(X(1),Y2(1))
            IF(NUY3.NE.0) CALL LINE(52)
            IF(NUY3.NE.0) CALL CPLOT(X(1),Y3(1))
      C
            IF(NSCS(1).EQ.1) GO TO 245
      C
      C PLOT REMAINING CROSS SECTIONS
            KK=NSCS(1)
            JX=1
            DO 240 K=2,KK
            JX=JX+X(1)+1
            CALL LINE(1)
            CALL CPLOT(X(JX),Y1(JX))
            IF(NUY2.NE.0) CALL LINE(34)
            IF(NUY2.NE.0) CALL CPLOT(X(JX),Y2(JX))
            IF(NUY3.NE.0) CALL LINE(52)
            IF(NUY3.NE.0) CALL CPLOT(X(JX),Y3(JX))
      240   CONTINUE
      245   CONTINUE
      C
            IFLAG=1
      C
            RETURN
            END
```

Fig. B.29. (Continued) Listing for Subroutine GENCUR

```
      SUBROUTINE LILOY(INEGY,YMIN,YMAX,INCS,NUY1,NUY2,NUY3,ILLY)
C
C SUB. LILOY PROVIDES LINEAR OR LOG Y-AXIS OPTION
C IF LOG OPTION REQUESTED, Y-AXIS DATA IS CONDITIONED
C ACCORDING TO SIGNS ASSOCIATED WITH YMIN AND YMAX
C
      COMMON  X(1000),Y1(1000),Y2(1000),Y3(1000)
C LINEAR OR LOG Y-AXIS SCALE
      WRITE(6,5)
5     FORMAT(' 1-LINEAR, 2-LOG Y-AXIS SCALE')
      READ(5,10) I
10    FORMAT()
C
C ABSOLUTE Y-AXIS PLOT
      WRITE(6,11)
11    FORMAT(' 1-ABSOLUTE Y-AXIS PLOT')
      READ(5,10) IABS
      IF(IABS.NE.1) GO TO 14
C
9     CONTINUE
C GENERATE ABS VERSION OF DEPENDENT VARIABLE ARRAYS AND
C REEVALUATE YMIN AND YMAX
      YMIN=1.0D20
      YMAX=-1.0D20
      NP=Y1(1)+1.5
      DO 12 K=2,NP
      Y1(K)=ABS(Y1(K))
      YMIN=AMIN1(YMIN,Y1(K))
      YMAX=AMAX1(YMAX,Y1(K))
      IF(NUY2.LE.0) GO TO 12
      Y2(K)=ABS(Y2(K))
      YMIN=AMIN1(YMIN,Y2(K))
      YMAX=AMAX1(YMAX,Y2(K))
      IF(NUY3.LE.0) GO TO 12
      Y3(K)=ABS(Y3(K))
      YMIN=AMIN1(YMIN,Y3(K))
      YMAX=AMAX1(YMAX,Y3(K))
12    CONTINUE
C
C UPDATE USER SPECIFIED YMIN, AND YMAX
      CALL SMIMAY(YMIN,YMAX)
C
14    CONTINUE
C
      IF(I.EQ.2) GO TO 15
      IF(INEGY.LT.0) CALL NEGY(INEGY,INCS,NUY1,NUY2,NUY3)
      ILLY=1
      RETURN
C
15    CONTINUE
C RETRIVE SPECIFIED YMIN AND YMAX
      TYMIN=COMGET(IBASEY(11))
      TYMAX=COMGET(IBASEY(12))
C
      IF(TYMIN.GT.0) GO TO 30
      IF(TYMAX.LT.0) GO TO 25
```

Fig. B.30. Listing for Subroutine LILOY

```
57      C
58            WRITE(6,20)
59      20    FORMAT(' ERROR: LOG CURVE PASSES THROUGH ZERO',/,
60           1' 0 - REDEFINE Y-AXIS BOUNDARIES',/,
61           2' 1 - ABSOLUTE Y-AXIS PLOT')
62            READ(5,10) IYBND
63            IF(IYBND.EQ.1) GO TO 9
64            CALL SMIMAY(YMIN,YMAX)
65            GO TO 15
66      C
67      25    CONTINUE
68      C NEGATE Y-AXIS
69            IF(INEGY.GT.0) CALL NEGY(INEGY,INCS,NUY1,NUY2,NUY3)
70      C NEGATE YMIN AND YMAX
71            CALL DLIMY(-TYMAX,-TYMIN)
72      C
73            GO TO 35
74      30    CONTINUE
75            IF(INEGY.LT.0) CALL NEGY(INEGY,INCS,NUY1,NUY2,NUY3)
76      35    CONTINUE
77            ILLY=2
78      C
79            RETURN
80            END
```

Fig. B.30. (Continued) Listing for Subroutine LILOY

```
      SUBROUTINE SELCS(IFLAG,NSCS,NDEFCS)
C
C SUB. SELCS PROVIDES FOR SELECTION OF CROSS SECTIONS
C NDEFCS=0 - NSCS UNCHANGED - LOADING NOT REQUIRED!
C
      DIMENSION NSCS(1)
C
      IF(NSCS(1).LT.1.OR.IFLAG.EQ.0) GO TO 20
      KK=NSCS(1)+1
      WRITE(6,5) (NSCS(K),K=2,KK)
5     FORMAT(' SPECIFIED CROSS SECTIONS',//,
     11X,I2,30(',',I2))
C
      WRITE(6,10)
10    FORMAT(' 1 - REDEFINE CROSS SECTIONS')
      READ(5,15) NDEFCS
15    FORMAT()
C
      IF(NDEFCS.EQ.0) RETURN
C
20    CONTINUE
      NDEFCS=1
      WRITE(6,25)
25    FORMAT(' HOW MANY CROSS SECTIONS?')
C
      READ(5,15) NSCS(1)
      IF(NSCS(1).LT.1) GO TO 20
C
      WRITE(6,30)
30    FORMAT(' WHICH CROSS SECTIONS')
      KK=NSCS(1)+1
      READ(5,15) (NSCS(K),K=2,KK)
C
      RETURN
      END
```

(a) Listing for SELCS

```
      SUBROUTINE SMIMA(XMIN,TXMIN,XMAX,TXMAX)
C
C UPDATES MINIMUM AND MAXIMUM.
C
      XMIN=AMIN1(XMIN,TXMIN)
      XMAX=AMAX1(XMAX,TXMAX)
C
      RETURN
      END
```

(b) Listing for SMIMA

Fig. B.31. Listing for Subroutines SELCS and SMIMA

Subroutine HEADER

HEADER generates a ledger for each graph consisting of the graph title, the numbers of the cross sections plotted, and the run code designating the run that generated the data plotted. Source listing for HEADER is presented in Fig. B.32.

Subroutine LOAD

Data cross sections designated for display are read from the appropriate graph data files by LOAD. Source listing for LOAD is presented in Fig. B.33.

Subroutine INMIMA

INMIMA is used to initialize minimum and maximum variables. Source listing for INMIMA is presented in Fig. B.33.

Subroutine SPMIMA

SPMIMA outputs the minimum and maximum values for the dependent variable data to be plotted, and solicits the respective minimum and maximum values desired for the graph to be generated. Source listing for SPMIMA is presented in Fig. B.34.

Subroutine SKIP

SKIP is called to skip data cross sections not designated for display. Source listing for SKIP is presented in Fig. B.34.

Subroutine NEGY

NEGY negates the dependent variable arrays to be plotted. Source listing for NEGY is presented in Fig. B.35.

Subroutine SMIMAY

SMIMAY outputs the minimum and maximum values for the dependent variable data to be plotted, and solicits the respective minimum and maximum values desired for the graph to be generated. Source listing for SMIMAY is presented in Fig. B.35.

```
      SUBROUTINE HEADER(IX,IY,ITITLE,NSCS,IRUN)
C
C SUB HEADER GENERATES GRAPH TITLE, CS-CODE, RUN NO.
C
      DIMENSION NSCS(1),IRUN(1),ITITLE(12)
      DIMENSION ICS(33),IARRAY(15)
C
      DATA IFILL/32/
      DATA ICS/32,67,83,32,32,32,44,
     132,32,44,32,32,44,32,32,44,
     232,32,44,32,32,44,32,32,44,
     332,32,44,32,32,44,32,32/
C
      KK=NSCS(1)
      ICS(1)=2+3*KK
      DO 5 K=1,KK
      J=2+3*K
      FNUM=NSCS(K+1)
      CALL IFORM(FNUM,IWIDTH,IARRAY,IFILL)
      ICS(J)=32
      IF(IWIDTH.GE.2) ICS(J)=IARRAY(IWIDTH-1)
      ICS(J+1)=IARRAY(IWIDTH)
5     CONTINUE
C
      CALL MOVABS(IX,IY)
      DO 10 K=1,12
      CALL AOUTST(6,ITITLE(K))
10    CONTINUE
      CALL NOTATE(IX,IY-30,ICS(1),ICS(2))
      CALL MOVABS(IX,IY-55)
      CALL AOUTST(6,IRUN(1))
      CALL AOUTST(3,IRUN(2))
      CALL AOUTST(6,IRUN(3))
C
      RETURN
      END
```

Fig. B.32. Listing for Subroutine HEADER

```
      SUBROUTINE LOAD(INEGY,IEOF,NU,X,TIME,XMIN,XMAX)
C
C SUB 'LOAD' LOADS NEXT CROSS SECTION
C
      DIMENSION X(1)
C
C SET INEGY
      INEGY=1
      IEOF=0
C
C READ NUMBER OF DATA POINTS
      READ(NU,5,END=100) X(1)
5     FORMAT(E15.8)
C
C LOAD CROSS SECTION
      NP=X(1)+1
      DO 10 K=2,NP
      READ(NU,5) X(K)
10    CONTINUE
C
      READ(NU,5) TIME,XMIN,XMAX
C
      RETURN
C
100   CONTINUE
      IEOF=1
      RETURN
C
      END
```

(a) Listing for LOAD

```
      SUBROUTINE INMIMA(XMIN,XMAX,YMIN,YMAX)
C
C INITIALIZES MINIMUMS AND MAXIMUMS.
C
      XMIN= 1.0E20
      XMAX=-1.0E20
      YMIN= 1.0E20
      YMAX=-1.0E20
C
      RETURN
      END
```

(b) Listing for INMIMA

Fig. B.33. Listing for Subroutines LOAD and INMIMA

```
      SUBROUTINE SPMIMA(XMIN,XMAX,YMIN,YMAX)
C
C ALLOWS OPERATOR TO DEFINE BOTH Y-AXIS AND X-AXIS BOUNDS
C FOR GRAPH BEING GENERATED.
C
      WRITE(6,5) XMIN,XMAX
5     FORMAT(E11.4,' XMIN',/,E11.4,' XMAX')
      READ(5,10) TXMIN,TXMAX
10    FORMAT()
C
      WRITE(6,15) YMIN,YMAX
15    FORMAT(E11.4,' YMIN',/,E11.4,' YMAX')
      READ(5,10) TYMIN,TYMAX
C
C SET MINS. AND MAXS.
      CALL DLIMX(TXMIN,TXMAX)
      CALL DLIMY(TYMIN,TYMAX)
C
      RETURN
      END
```

(a) Listing for SPMIMA

```
      SUBROUTINE SKIP(NU)
C
C SUB. 'SKIP' SKIPS NEXT CROSS SECTION
C
C READ NUMBER OF DATA POINTS
      READ(NU,5,END=100) TNP
5     FORMAT(E15.8)
C
C READ CROSS SECTION
      NP=TNP
      DO 10 K=1,NP
      READ(NU,5) X
10    CONTINUE
C
C READ TIME,XMIN,XMAX
      READ(NU,5) X,X,X
C
      RETURN
C
100   CONTINUE
      WRITE(6,110) NU
110   FORMAT(' ERROR: UNEXPECTED EOF FOR SUB SKIP, NU=',
     1I13)
      END
```

(b) Listing for SKIP

Fig. B.34. Listing for Subroutines SPMIMA and SKIP

```
      SUBROUTINE NEGY(INEGY,INCS,NUY1,NUY2,NUY3)
C
C SUB. NEGY NEGATES Y-AXIS DATA VALUES
C
      COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
      INEGY=-INEGY
C
      N=0
      DO 5 K=1,INCS
      N=N+1
      NP=Y1(N)
      DO 5 J=1,NP
      N=N+1
      Y1(N)=-Y1(N)
      IF(NUY2.EQ.0) GO TO 5
      Y2(N)=-Y2(N)
      IF(NUY3.EQ.0) GO TO 5
      Y3(N)=-Y3(N)
5     CONTINUE
C
      RETURN
      END
```

(a) Listing for NEGY

```
      SUBROUTINE SMIMAY(YMIN,YMAX)
C
C ALLOWS OPERATOR TO DEFINE Y-AXIS BOUNDS FOR GRAPH
C BEING GENERATED.
C
      WRITE(6,15) YMIN,YMAX
15    FORMAT(E11.4,' YMIN'/,E11.4,' YMAX')
      READ(5,10) TYMIN,TYMAX
10    FORMAT()
C
C SET CYDMIN AND CYDMAX
      CALL DLIMY(TYMIN,TYMAX)
C
      RETURN
      END
```

(b) Listing for SMIMAY

Fig. B.35. Listing for Subroutines NEGY and SMIMAY

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APPENDIX B

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