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DETERMINATION OF SEMICONDUCTOR JUNCTION
VULNERABILITY TO SECOND BREAKDOWN

University of Alabama
University, Alabama

**U.S. ARMY
MISSILE
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June 1977

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Investigations with the numerical model have led 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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VULNERABILITY TO SECOND BREAKDOWN

by

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and

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Prepared For

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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 header.

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 led 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 sections and an appendix. Section 2 presents a description of thermal second breakdown in thin film silicon-on-sapphire diodes. The development of the numerical model is presented in Section 3. Section 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.

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 section 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 Busenstein 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 stroboscopically 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 nonuniform 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 widening. 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 recieves 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 random 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 feed-back 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.

3. DIODE MODEL

In this section 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 [3,4]. This procedure has also been used to investigate transient and permanent radiation effects in both diode and transistor structures [5], as well as for small signal analysis [6]. 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

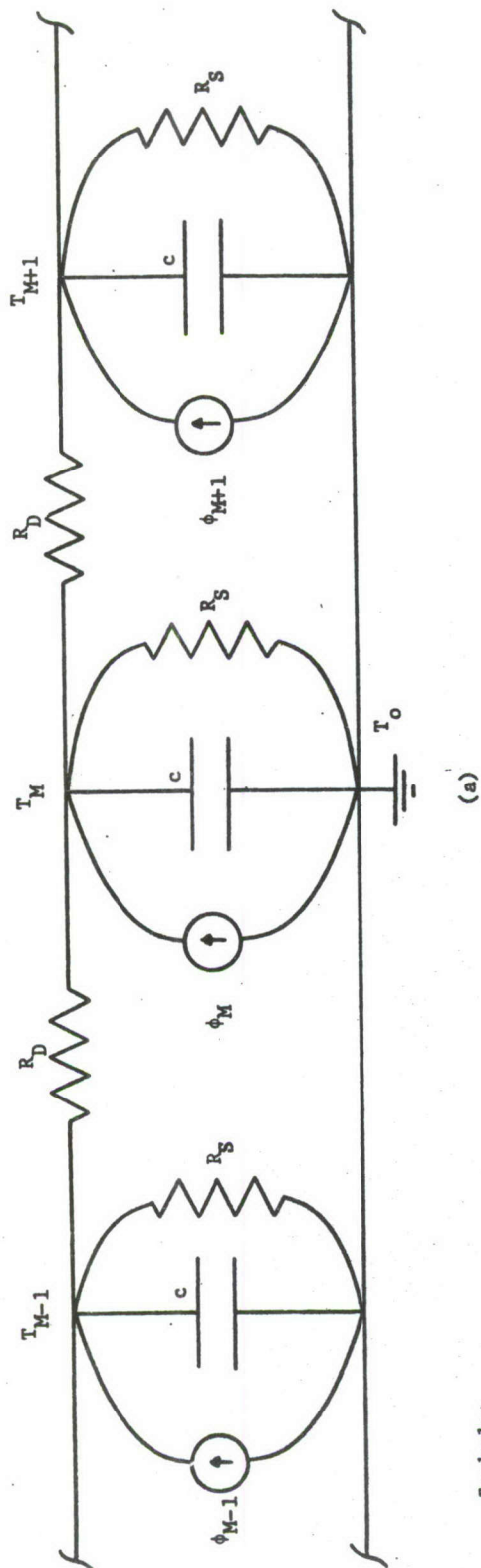
A comprehensive mathematical diode model capable of simulating thermal second breakdown is developed. The model features simplified two-dimensional thermal conduction along with thermally dependent semiconductor parameters and is characterized by four coupled nonlinear partial differential equations 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 header 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 longitudinal axis of the one-dimensional diode structure and perpendicular to this axis through the substrate into a constant temperature header which functions as an ideal 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 header. 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.

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

For this case the heat sink effect, associated with the header, enters equation (3.1) through the power density term, $\Phi(x,t)$. This term is



Symbols:

- ϕ - Heat generation
- T - Temperature
- T_0 - Header temperature
- ρ - Diode density
- c - Diode specific heat
- K_D - Diode thermal conductivity
- R_D - Diode thermal resistance
- K_S - Substrate thermal conductivity
- R_S - Substrate thermal resistance
- x - Position
- x_w - Diode and substrate width
- x_{DT} - Diode thickness
- x_{ST} - Substrate thickness
- Δx_M - Distance between adjacent M-nodes
- A_D - Diode cross sectional area
- A_S - Substrate cross sectional area

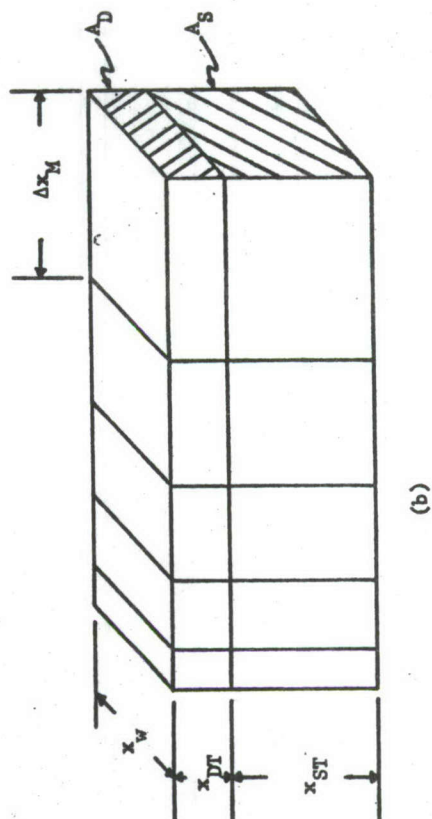


Fig. 3.1 (a) Electrical Analog of Thermal Model and (b) Diode Model Physical Design

defined as a net power density factor which accounts for both heat generation and heat lost by mechanisms other than conduction along the longitudinal axis of the diode model. From basic thermal conduction principles [7] 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

$$\Phi(x, t) = |E(x, t)| [|J_p(x, t)| + |J_n(x, t)|] - \frac{K_s(x, t)}{x_{DT} x_{ST}} [T(x, t) - T_o] \quad (3.2)$$

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

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

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

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

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

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

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

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

and

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

where

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

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

$$G_{gr}(x,t) = q \frac{n_i(x,t)^2 - p(x,t)n(x,t)}{[p(x,t)+n_i(x,t)]\tau_n + [n(x,t)+n_i(x,t)]\tau_p} + q \alpha_p(x,t) |J_p(x,t)| + q \alpha_n(x,t) |J_n(x,t)|, \quad (3.11)$$

and

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

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

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

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

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

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

and

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

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 [8]. 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

$$p(x,0), E(x,0), T(x,0) , \quad (3.18)$$

or

$$n(x,0), E(x,0), T(x,0) \quad (3.19)$$

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

Considerably more latitude exists 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 [9] for investigating this phenomenon, and readily facilitates the comparison of the numerical simulation with experimental data. For a current source driving function the boundary conditions are defined by:

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

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

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

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

and either

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

or

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

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

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) $J_p = J_T(t)$ $J_n = 0$ $E = 0$ $T = T_0$	$J_p = 0$ $J_n = J_T(t)$ (or, $E = 0$) $T = T_0$	Current	Direct	Iterative
2) $p = p_{po}$ $n = n_{po}$ $E = E(t)$ $T = T_0$	$p = p_{no}$ $n = n_{no}$ (or, $E = E(t)$) $T = T_0$	Ohmic	Indirect	Iterative
3) $J_p = J_T(t)$ $J_n = 0$ $E = 0$ $T = T_0$	$p = p_{no}$ $n = n_{no}$ ----- $T = T_0$	Hybrid	Direct	Iterative
4) $p = p_{po}$ $n = n_{po}$ ----- $T = T_0$	$J_p = 0$ $J_n = J_T(t)$ $E = 0$ $T = T_0$	Hybrid	Direct	Iterative

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

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

and

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

where for silicon

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

$$b_n = 3.26 \times 10^6 \text{ V cm}^{-1}, \quad \text{and} \quad T_o = 300^\circ \text{ K} . \quad (3.28)$$

The above description of the ionization coefficients was derived from Sze's [10] characterization of these coefficients and represents an empirical approximation of their thermal dependence. The ionization thermal coefficient β has units of $(1/K^0)$ 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 [4] as a function of net doping density N_I and electric field is given by

$$\mu(N_I, E) = \mu_0 \left[1 + \frac{N_I}{N_I/S+N} + \frac{(E/A)^2}{E/A+F} + \left(\frac{E}{B}\right)^2 \right] \quad (3.29)$$

where

	μ_0	N	S	A	F	B
Holes	480	4×10^{16}	81	6.1×10^3	1.6	2.5×10^4
Electrons	1400	3×10^{16}	350	3.5×10^3	8.8	7.4×10^3

(3.30)

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

$$\mu \propto T^{-\gamma} \quad (3.31)$$

where for silicon γ has been determined experimentally to be approximately equal to $5/2$ for both holes and electrons. Then with this result

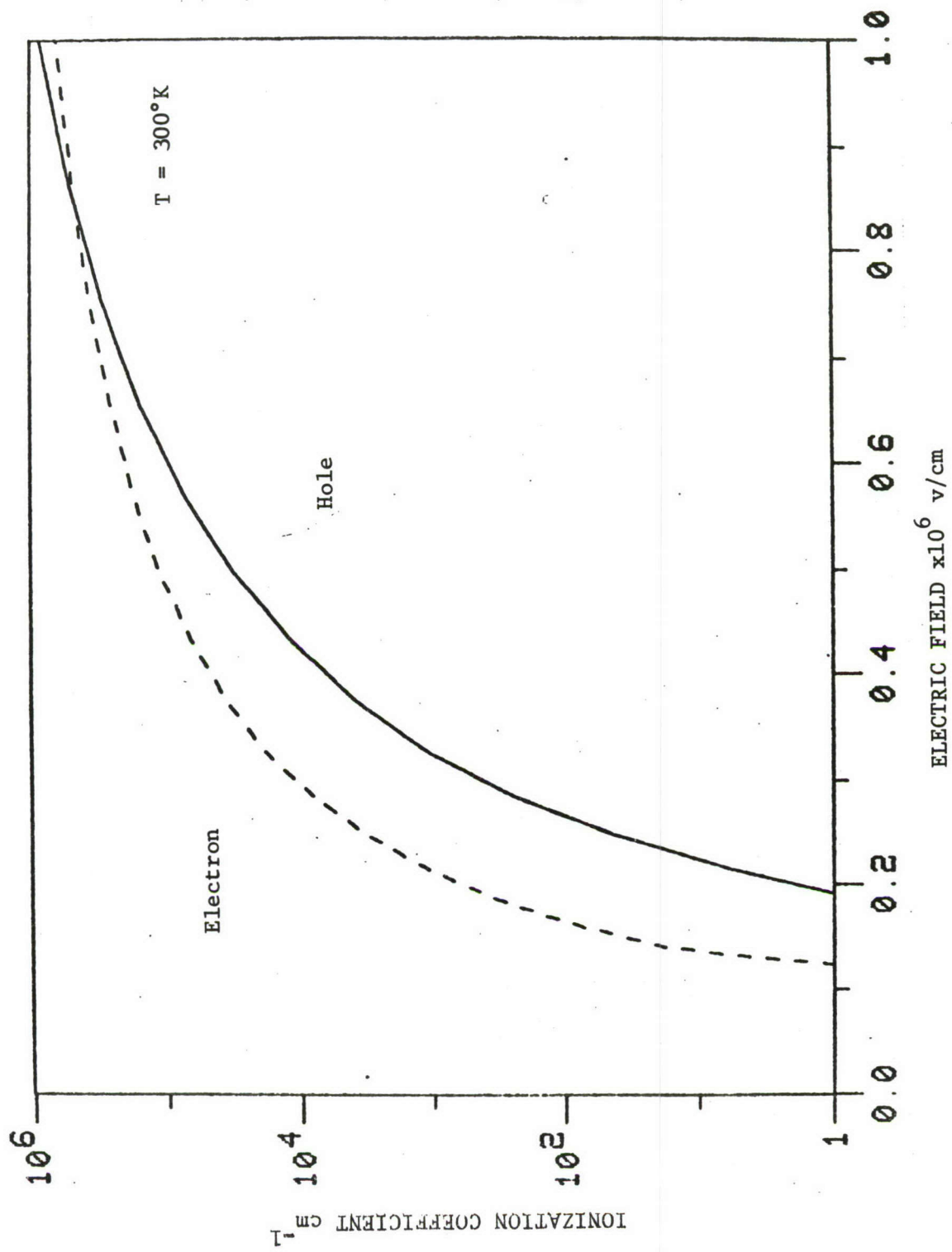


Fig. 3.2. Hole and Electron Ionization Coefficient Versus Electric Field

mobility thermal dependence can be conveniently added to equation (3.29) to yield

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

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 ionized impurities, semiconductor resistivity as a function of net impurity concentration, electric field, and temperature is given by

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

where

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

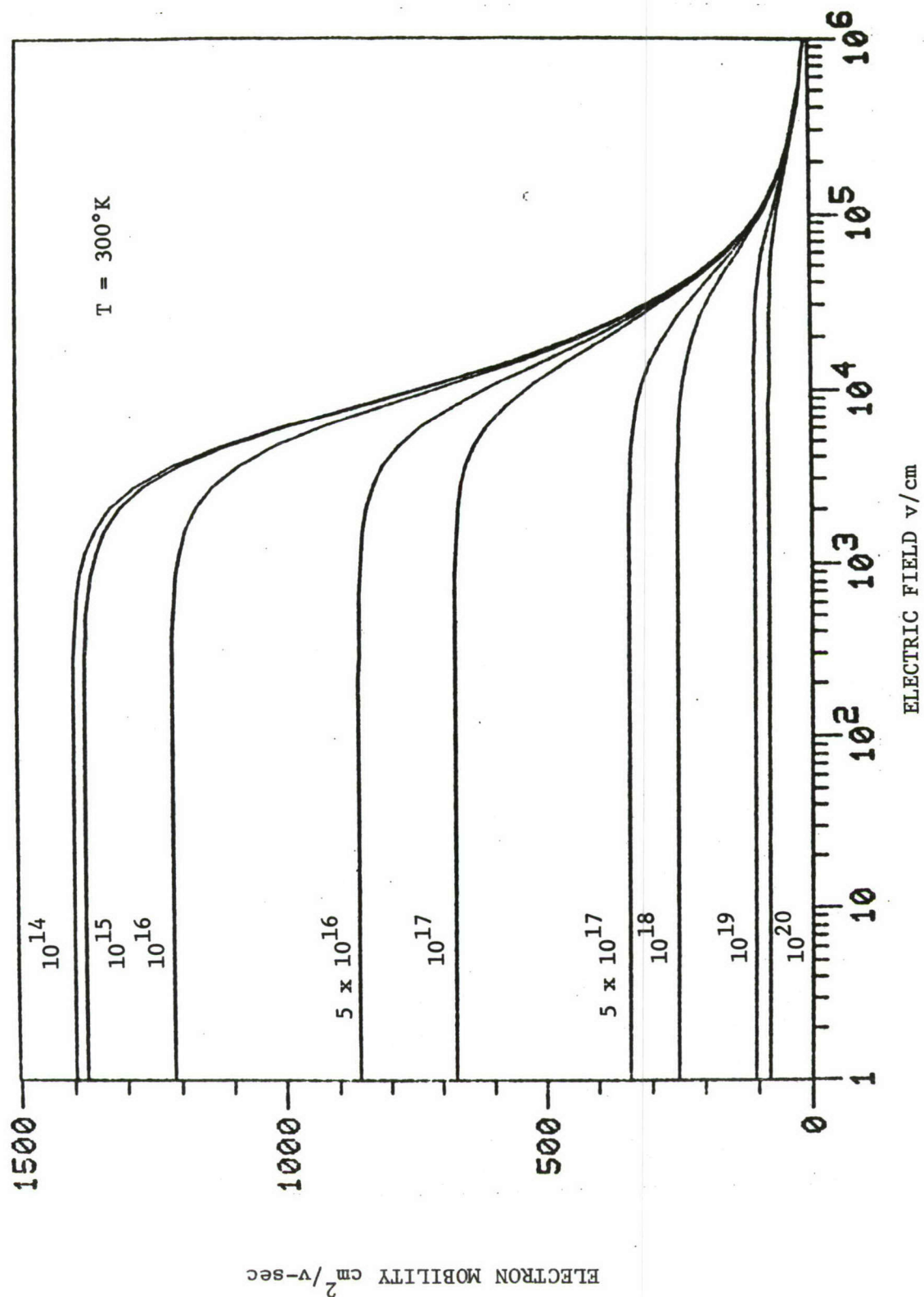


Fig. 3.3 Electron Mobility Versus Electric Field for Different Impurity Levels

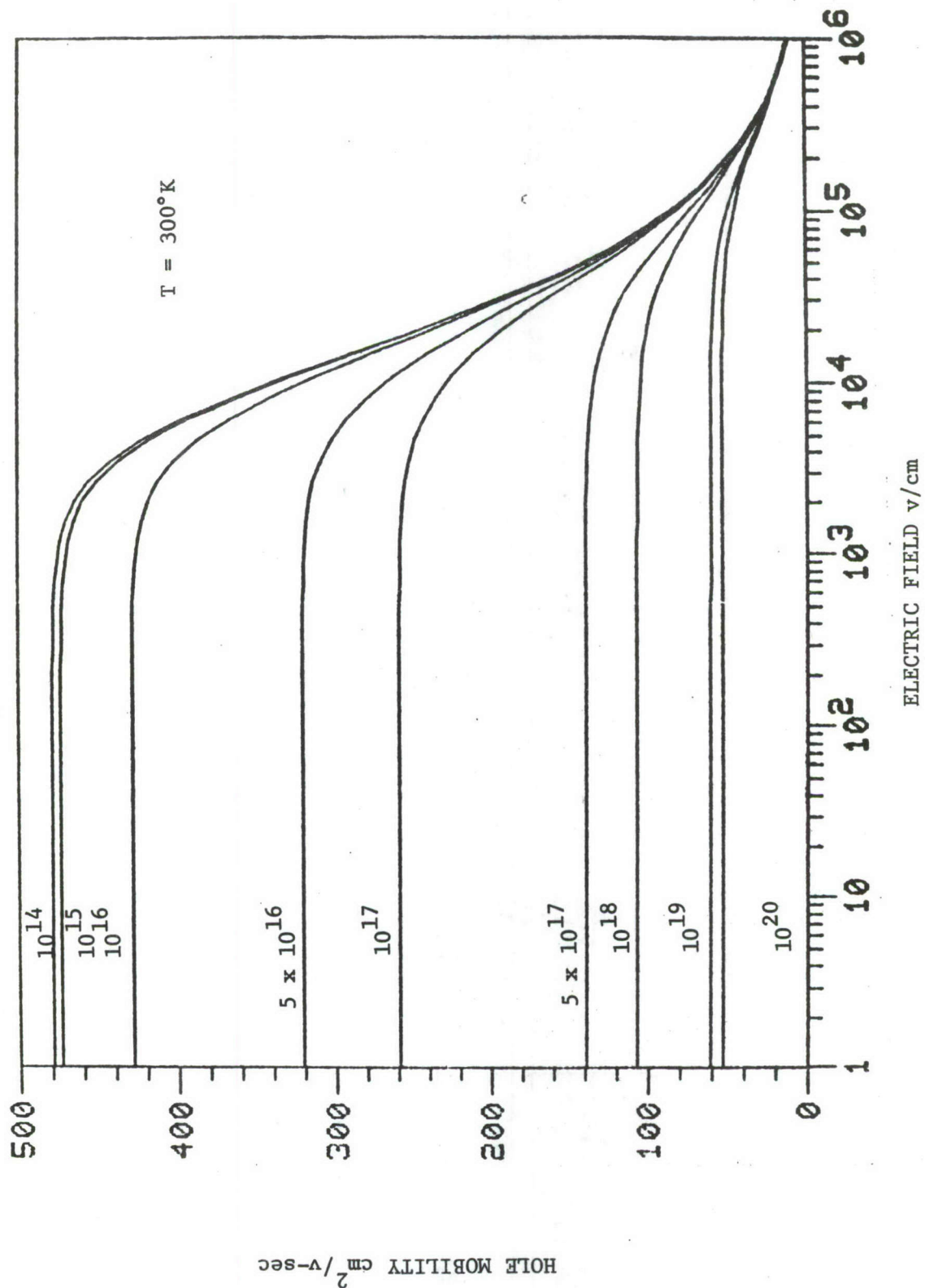


Fig. 3.4. Hole Mobility Versus Electric Field for Different Impurity Levels

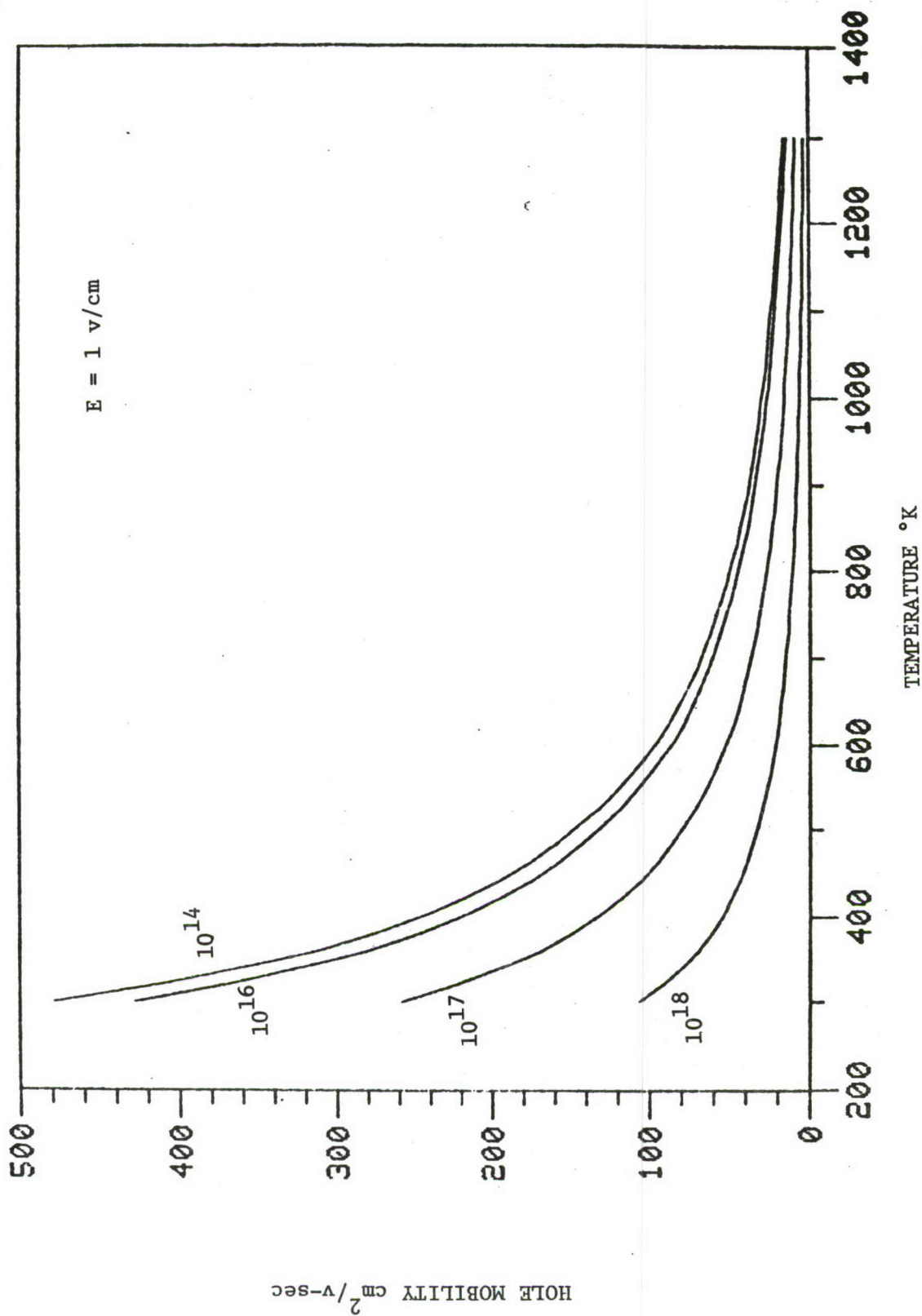


Fig. 3.5. Hole Mobility Versus Temperature for Different Impurity Levels

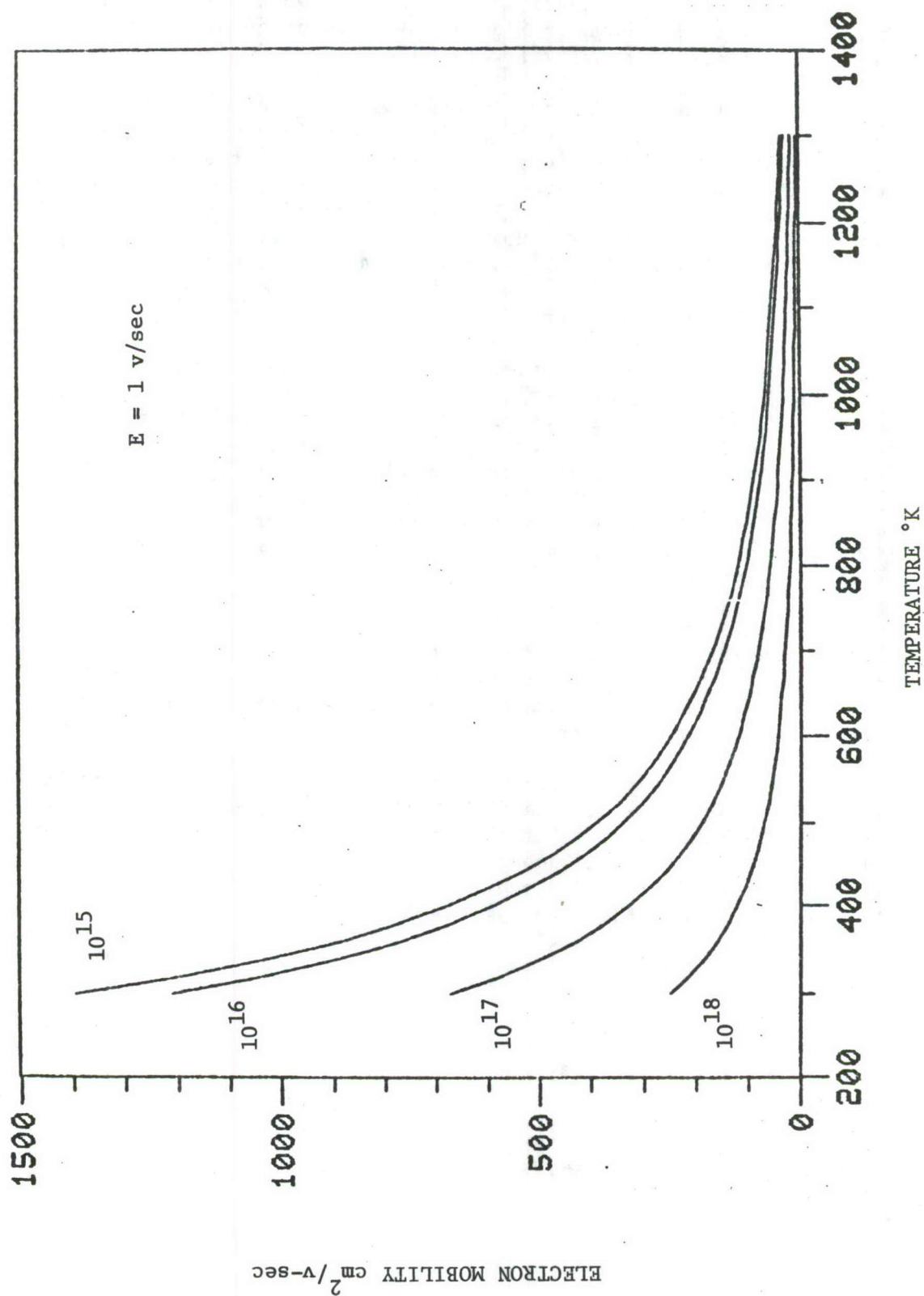


Fig. 3.6. Electron Mobility Versus Temperature for Different Impurity Levels

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 [12] 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 avalanche ionization relation for carrier generation.

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:

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

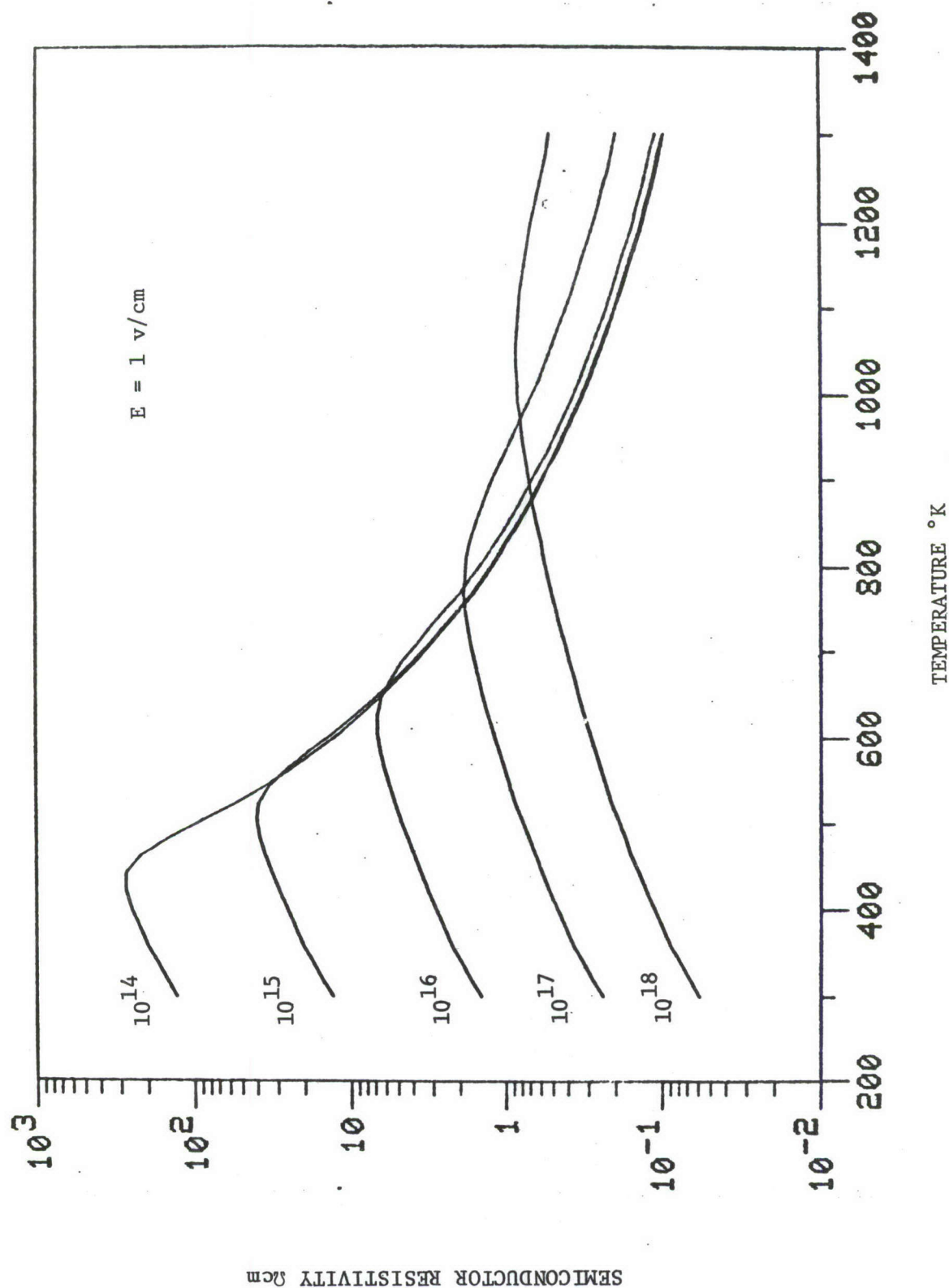


Fig. 3.7. Semiconductor Resistivity Versus Temperature for Different Impurity Levels

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	$L_D = \sqrt{\epsilon V_t / q n_i}$	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	$q D_o n_i / L_D$	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	$q n_i V_t / T_o \rho_o$	SPHN	4.20×10^3 J/gm-K°
Thermal conductivity	K_D, K_H	$q n_i V_t D_o / T_o$	TCONN	4.20×10^3 W/cm-K°

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

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

and

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

where

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

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

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

$$\Phi(x,t) = |E(x,t)| [|J_p(x,t)| + |J_n(x,t)|] - \frac{K_H(x,t)}{x_{DT} x_{DH}} [T(x,t) - T_0], \quad (3.41)$$

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

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

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

$$D_p(x,t) = \mu_p(x,t) T(x,t) , \quad (3.45)$$

and

$$D_n(x,t) = \mu_n(x,t) T(x,t) . \quad (3.46)$$

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-Nicholson 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 [4], 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. Figure 3.8 shows the grid structure to be used and one which has demonstrated utility for similar mathematical models through numerous applications [4,5,12]. 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.

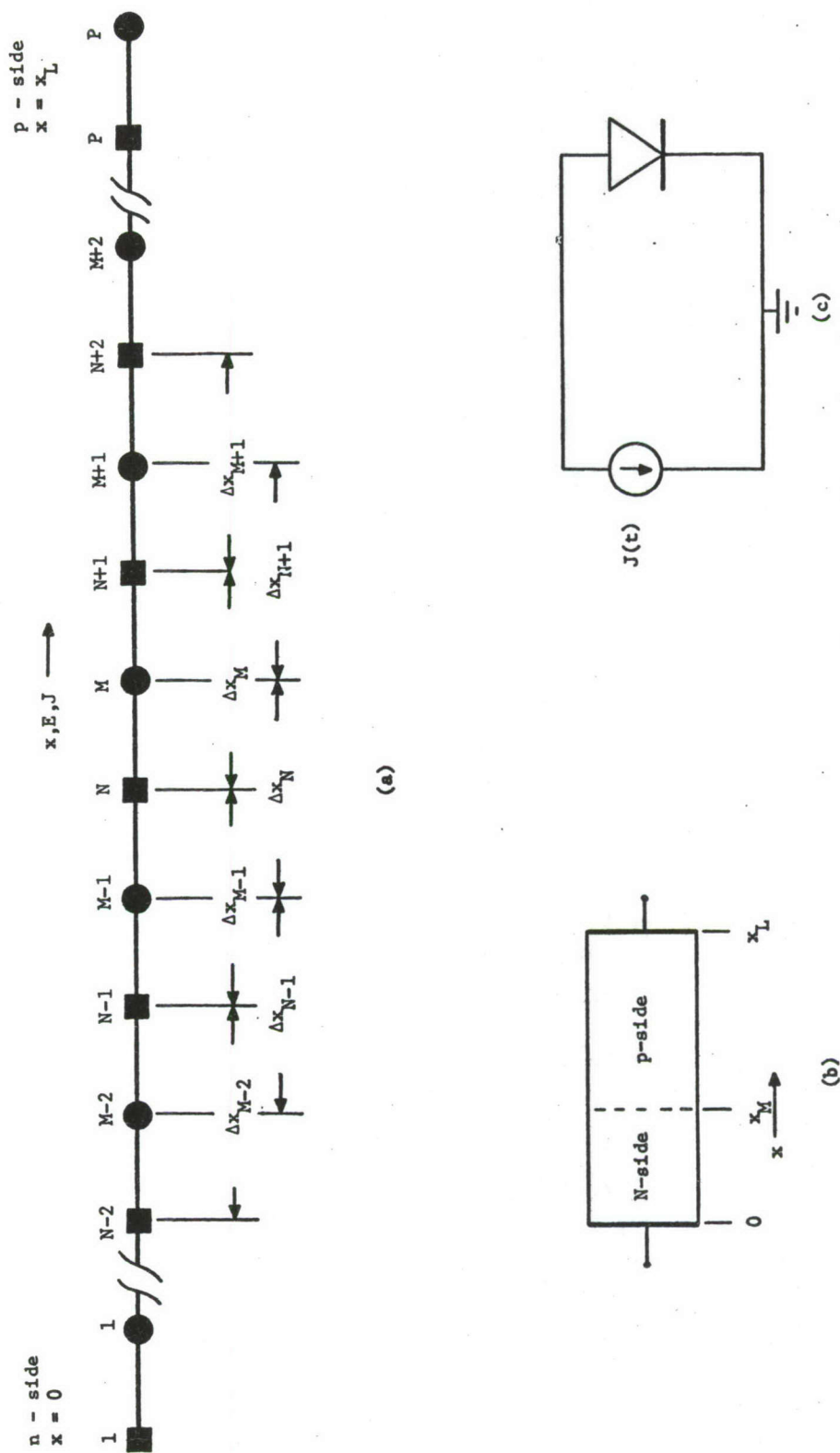


Fig. 3.8. (a) Numerical Diode Model Spatial Grid, (b) Physical Design and (c) External Circuit Configuration

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 [13] 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

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

and

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

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

$$\begin{aligned} \frac{[E(M,t) + \Delta E(M,t)] - [E(M-1,t) + \Delta E(M-1,t)]}{\Delta x(N)} &= [p(N,t) + \Delta p(N,t)] \\ &- [n(N,t) + \Delta n(N,t)] + N_I(N). \end{aligned} \quad (3.49)$$

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 [14]. Consider first the definition of the energy continuity equation which may be written as

$$\left[\begin{array}{c} \text{Rate of energy} \\ \text{storage in V} \end{array} \right] = \left[\begin{array}{c} \text{Rate of heat entering} \\ \text{V through its boundary} \\ \text{surfaces} \end{array} \right] + \left[\begin{array}{c} \text{Rate of heat} \\ \text{generation in} \\ \text{V} \end{array} \right] \quad (3.50)$$

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

$$\begin{aligned} \frac{\Delta T(M)}{\Delta t} &= \frac{-K_D(M,t)}{\rho c \Delta x(M)} \frac{T(M,t) - T(M-1,t)}{\Delta x(N)} \\ &+ \frac{K_D(M,t)}{\rho c \Delta x(M)} \frac{T(M+1,t) - T(M,t)}{\Delta x(N+1)} - \frac{K_H(M,t)}{x_{DT} \rho c} \frac{T(M,t) - T_0}{x_{HT}} \\ &+ \frac{1}{\rho c} |E(M,t)| [|J_p(M,t)| + |J_n(M,t)|] . \end{aligned} \quad (3.51)$$

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:

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

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

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

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

and

$$\frac{\Delta T(M,t)}{\Delta t} = F_T [T(M-1,t), p(N,t), n(N,t), E(M,t), T(M,t), p(N+1,t), n(N+1,t), T(M+1,t)] \quad (3.55)$$

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

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

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

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

and

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

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 [15] 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 [16], 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

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

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

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

and

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

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 occurrences 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

$$\begin{aligned} \frac{\Delta p(N,t)}{\Delta t} = & (1 - \theta) F_p(N,t) + \theta \{ F_p(N,t) + \Delta p(N-1,t) \frac{\partial F_p(N,t)}{\partial p(N-1,t)} \bigg|_t + \\ & \Delta E(M-1,t) \frac{\partial F_p(N,t)}{\partial E(M-1,t)} \bigg|_t + \text{-----} \} , \end{aligned} \quad (3.64)$$

which can be reduced directly to the simpler form

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

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:

$$\frac{1}{\theta \Delta t} \Delta p(N,t) = \frac{1}{\theta} F_p(N,t) + \Delta p(N-1,t) \frac{\partial F_p(N,t)}{\partial p(N-1,t)} \Big|_t + \text{-----} , \quad (3.66)$$

$$\frac{1}{\theta \Delta t} \Delta n(N,t) = \frac{1}{\theta} F_n(N,t) + \Delta n(N-1,t) \frac{\partial F_n(N,t)}{\partial n(N-1,t)} \Big|_t + \text{-----} , \quad (3.67)$$

$$- \Delta E(M-1,t) - \Delta x(N) \Delta p(N,t) + \Delta x(N) \Delta n(N,t) + \Delta E(M,t) = F_E(M,t) , \quad (3.68)$$

and

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

Or, in matrix form as:

$$\left\{ \frac{1}{\theta \Delta t} \begin{bmatrix} I \end{bmatrix} - \begin{bmatrix} \frac{\partial F_{ij}}{\partial Y_j} \end{bmatrix} \right\} \begin{bmatrix} \Delta Y_j \end{bmatrix} = \frac{1}{\theta} \begin{bmatrix} F_i \end{bmatrix} . \quad (3.70)$$

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 $2KT/q$ [6]. For most simulations, and especially reverse bias, an excessive number of grid points are required to overcome this instability.

An improved finite difference approximation [4] 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 mobility, current densities, temperature, and electric field between the N -node points constant and rewriting equation (3.38) as

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

and integrating between consecutive N -nodes to yield

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

where

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

Through a similar procedure the electron current becomes:

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

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 conditon 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 transcendental 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 conditons 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 is 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 concentration values for the above described current boundary conditions and for the np junction configuration adopted for the numerical model are as follows:

$$x = 0:$$

$$\nabla p(1,t) = \nabla p(2,t) + p(2,t) - p(1,t) , \quad (3.80)$$

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

$$x = x_L:$$

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

and

$$\Delta n(P,t) = \Delta n(P-1,t) + n(P-1,t) - n(P,t) . \quad (3.83)$$

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.

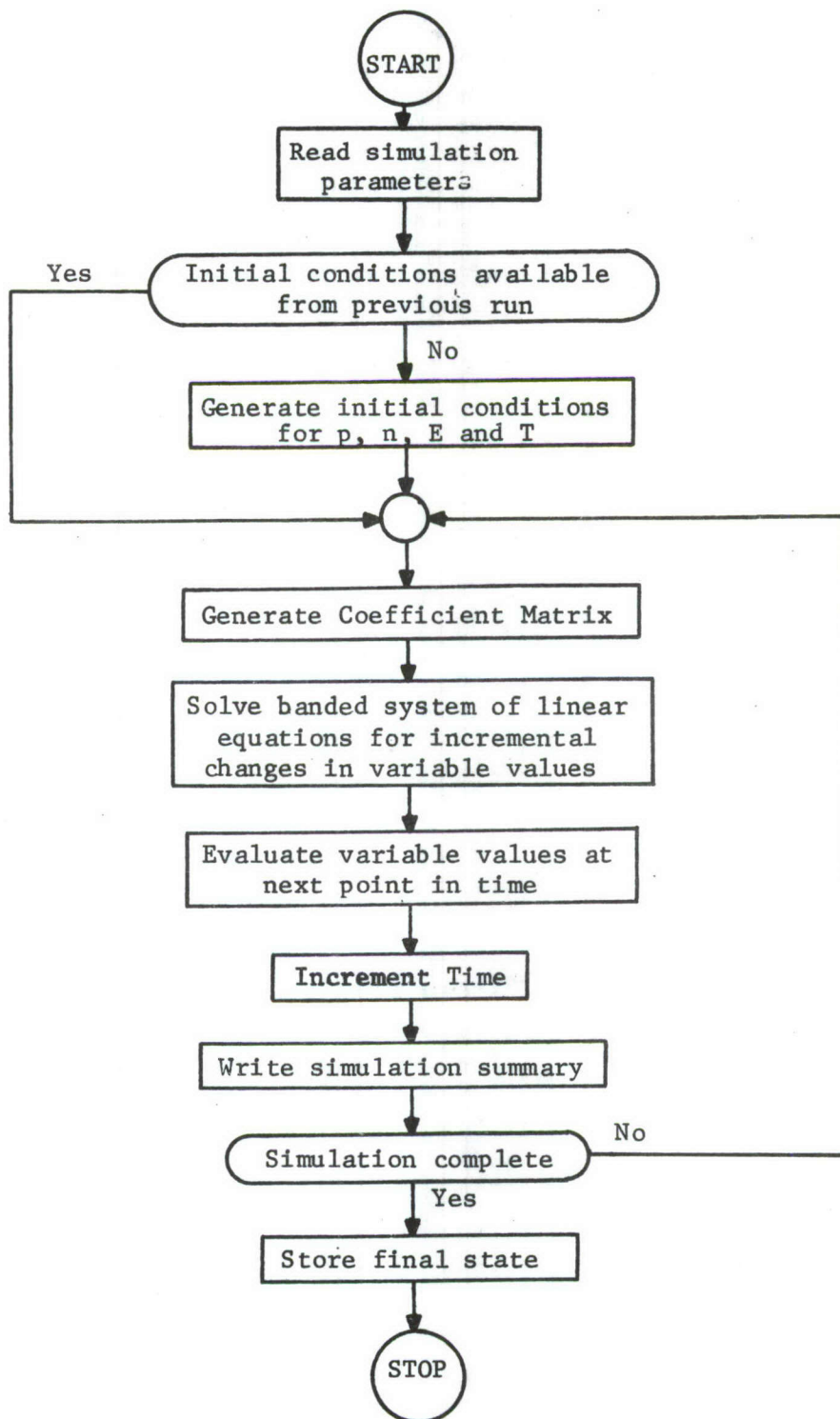


Fig. 3.10. Solution Procedure Flow Chart

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.

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 Section 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 grid points is limited to 101 or less. The 10 μm diode length is chosen to insure that several grid points fall within the depletion region on the high doped side of the junction. On the other hand, the relatively short bulk regions for this diode design make the diode model quite sensitive to mobile space charge induced depletion region widening 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 artificially 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/cm². The simulation is initiated by instantaneously increasing the reverse bias current to 10 amps/cm². Accordingly, the diode model undergoes a dynamic transient and terminates in a post second breakdown state.

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	$2.5 \times 10^{-3} \text{ 1/K}^\circ$
Thermal Conductivity	Semiconductor - $5 \times 10^{-7} \text{ watt/cm-K}^\circ$ Substrate - $5 \times 10^{-7} \text{ watt/cm-K}^\circ$
Semiconductor Specific Heat	0.7 J/gm-K°
Semiconductor Density	2.3 gm/cm ³
Constant Current Source Amplitude	10 amps/cm ²

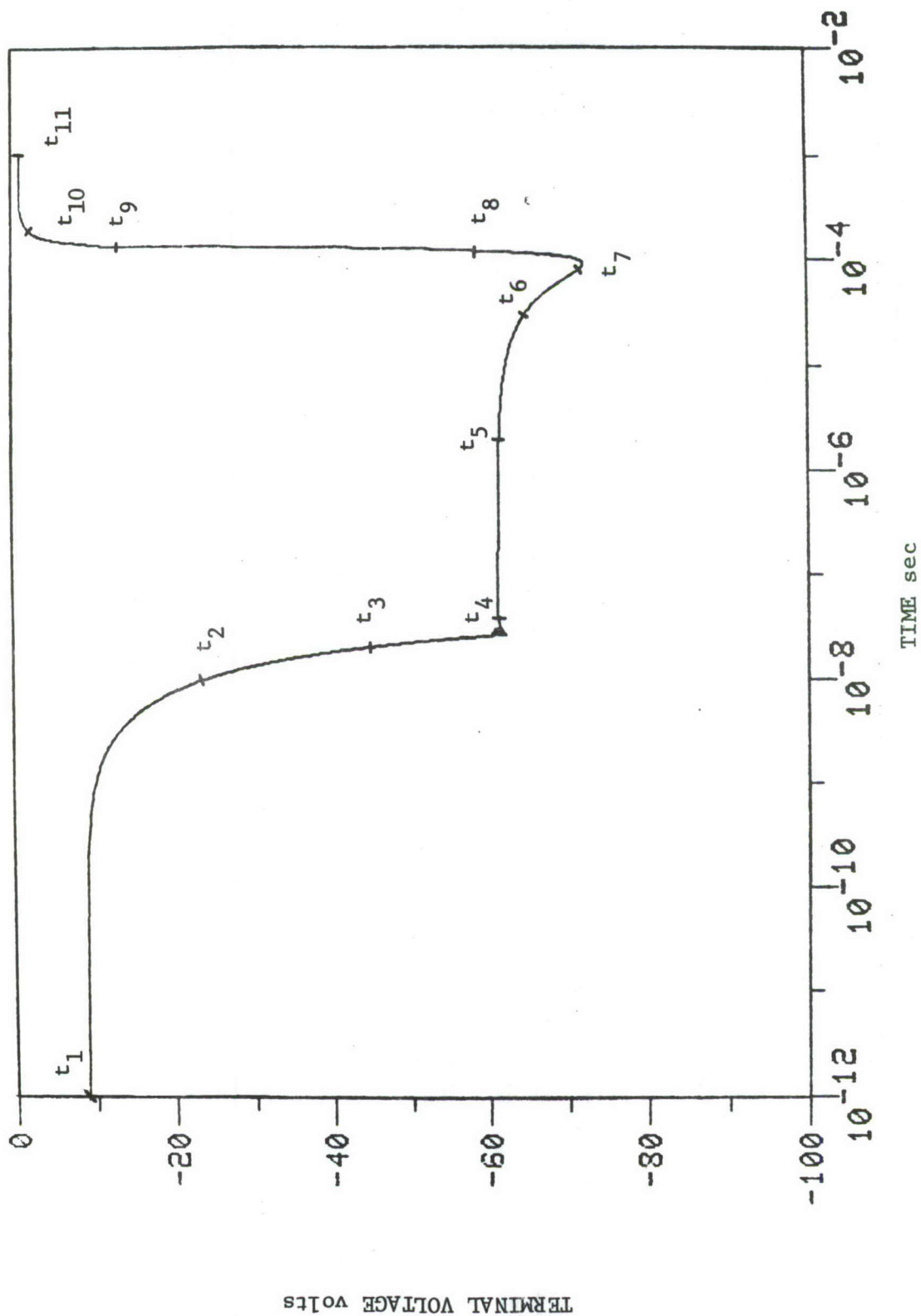


Fig. 4.1. Terminal Voltage as a Function of Time with Transient Reference Points at t_1 through t_{11} ($t_1=0.0$, $t_2=1.0 \times 10^{-8}$, $t_3=2.0 \times 10^{-8}$, $t_4=3.0 \times 10^{-8}$, $t_5=5.06 \times 10^{-8}$, $t_6=4.0 \times 10^{-6}$, $t_7=7.82 \times 10^{-5}$, $t_8=1.2 \times 10^{-4}$, $t_9=1.35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

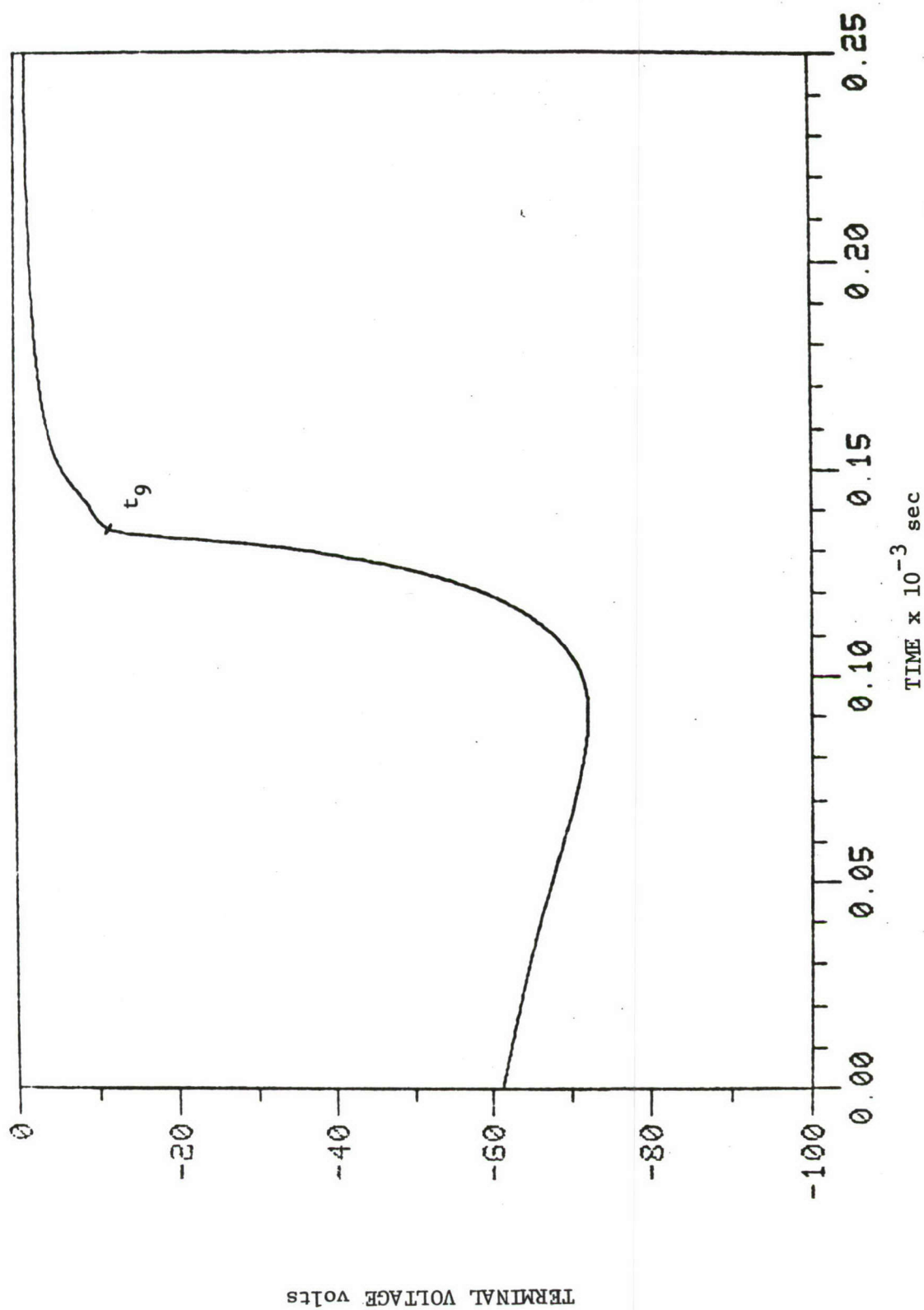


Fig. 4.2. Terminal Voltage as a Function of Time ($t_g = 1.35 \times 10^{-4}$ sec).

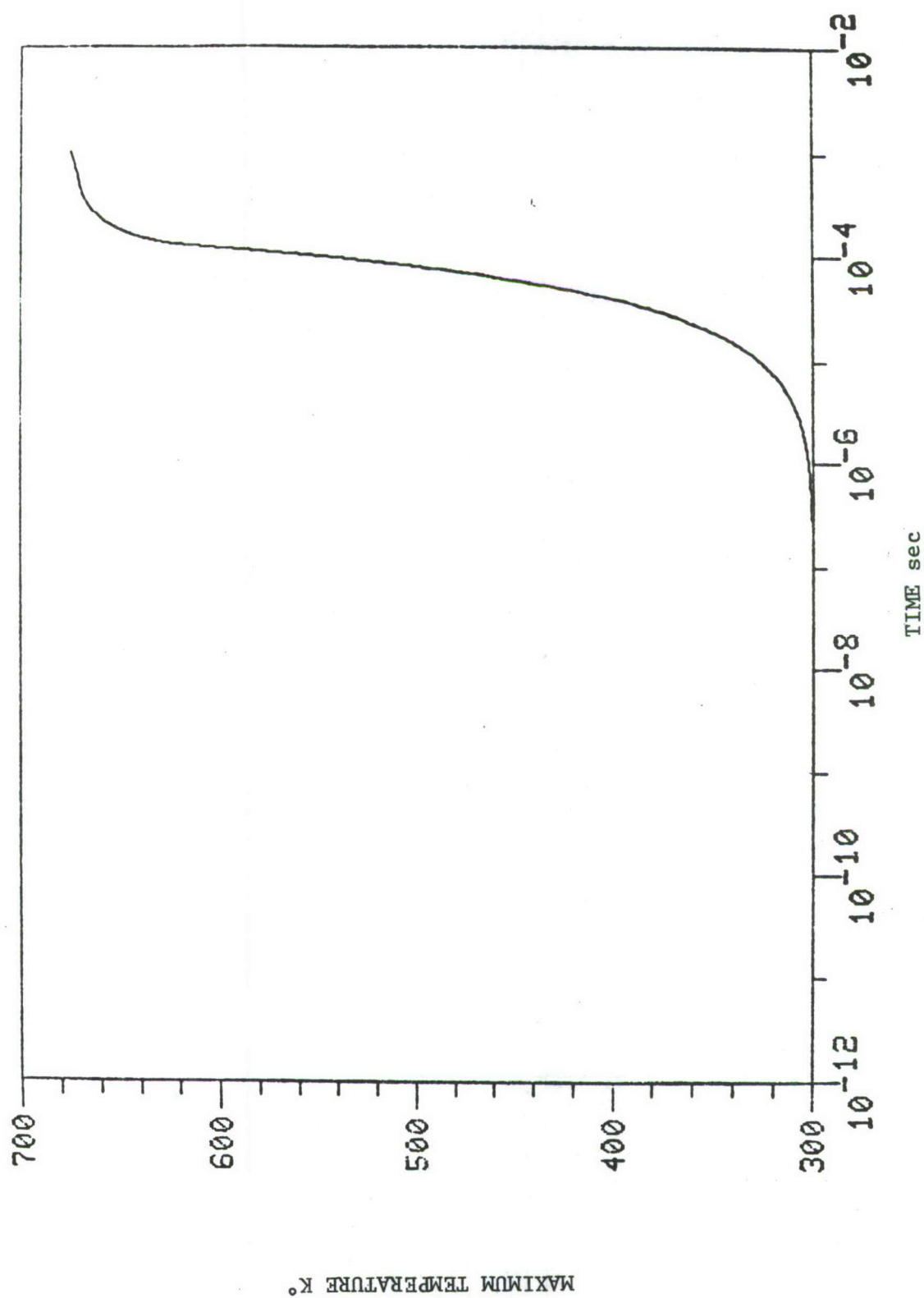


Fig. 4.3. Maximum Temperature as a Function of Time.

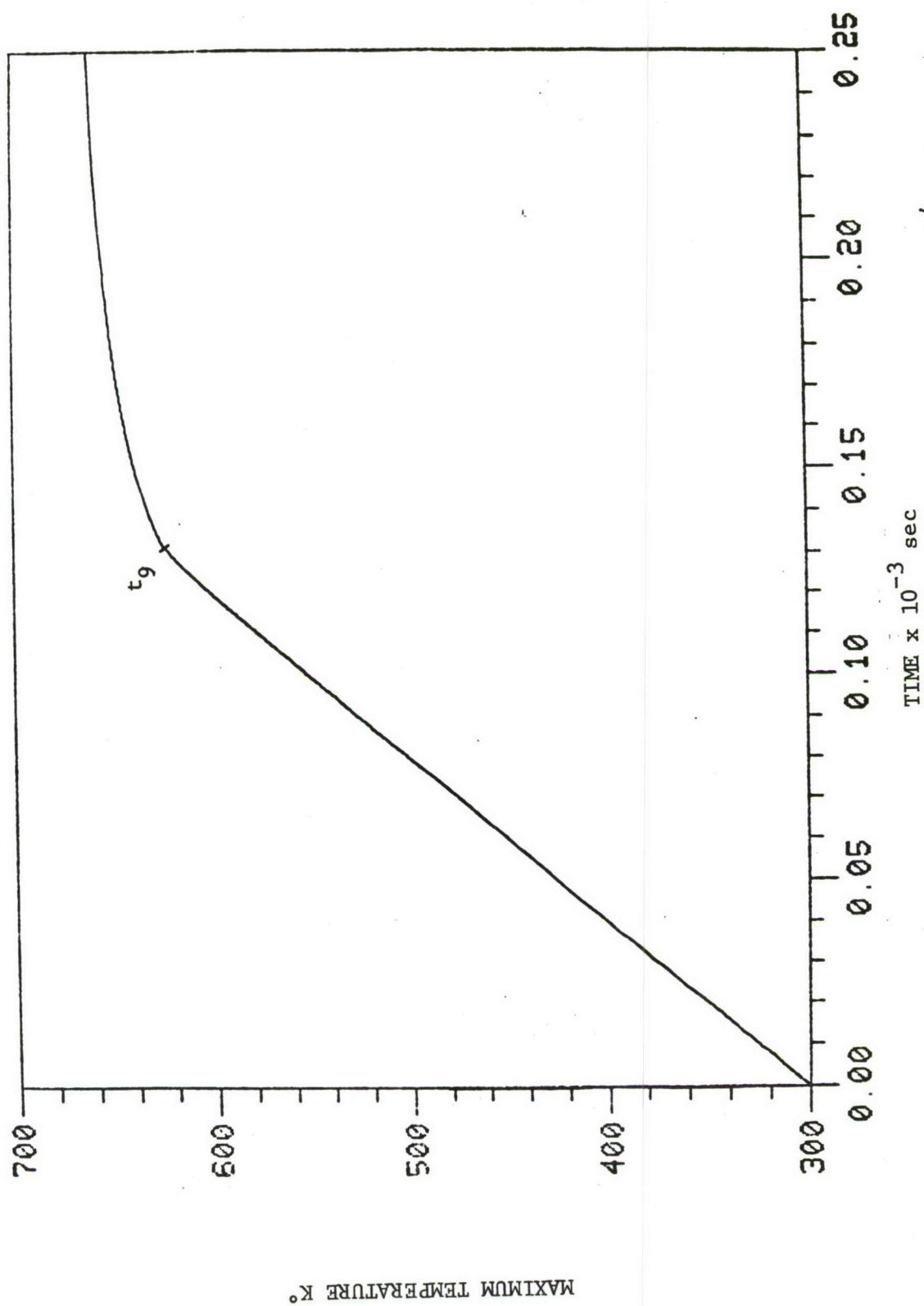


Fig. 4.4. Maximum Temperature as a Function of Time ($t_g = 1.35 \times 10^{-4}$ sec).

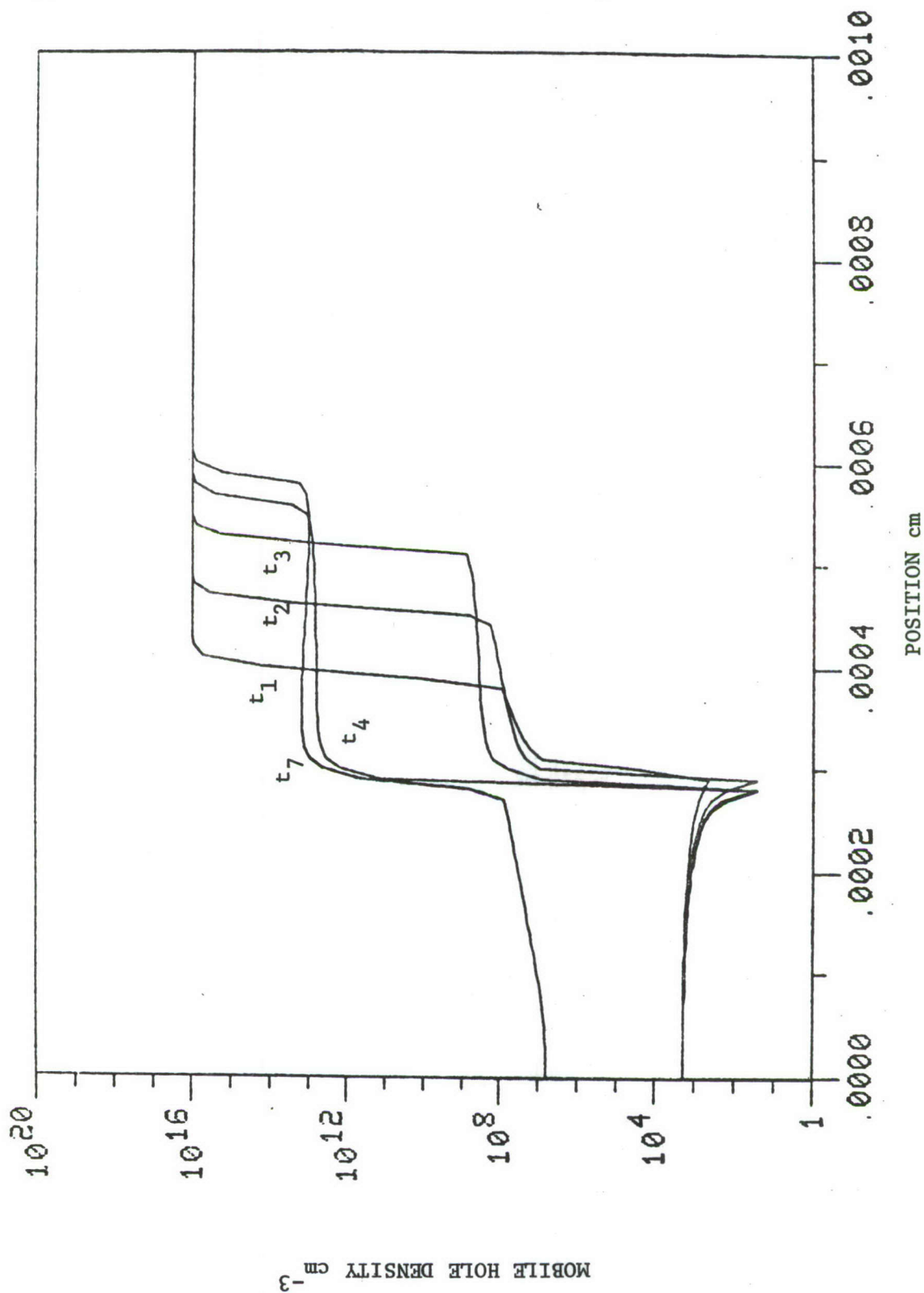


Fig. 4.5. Mobile Hole Density as a Function of Position at Various Instants of Time Prior to the Onset of Thermal Second Breakdown ($t_1=0.0$, $t_2=1.0 \times 10^{-8}$, $t_3=2.0 \times 10^{-8}$, $t_4=5.06 \times 10^{-8}$, $t_7=7.82 \times 10^{-5}$ sec).

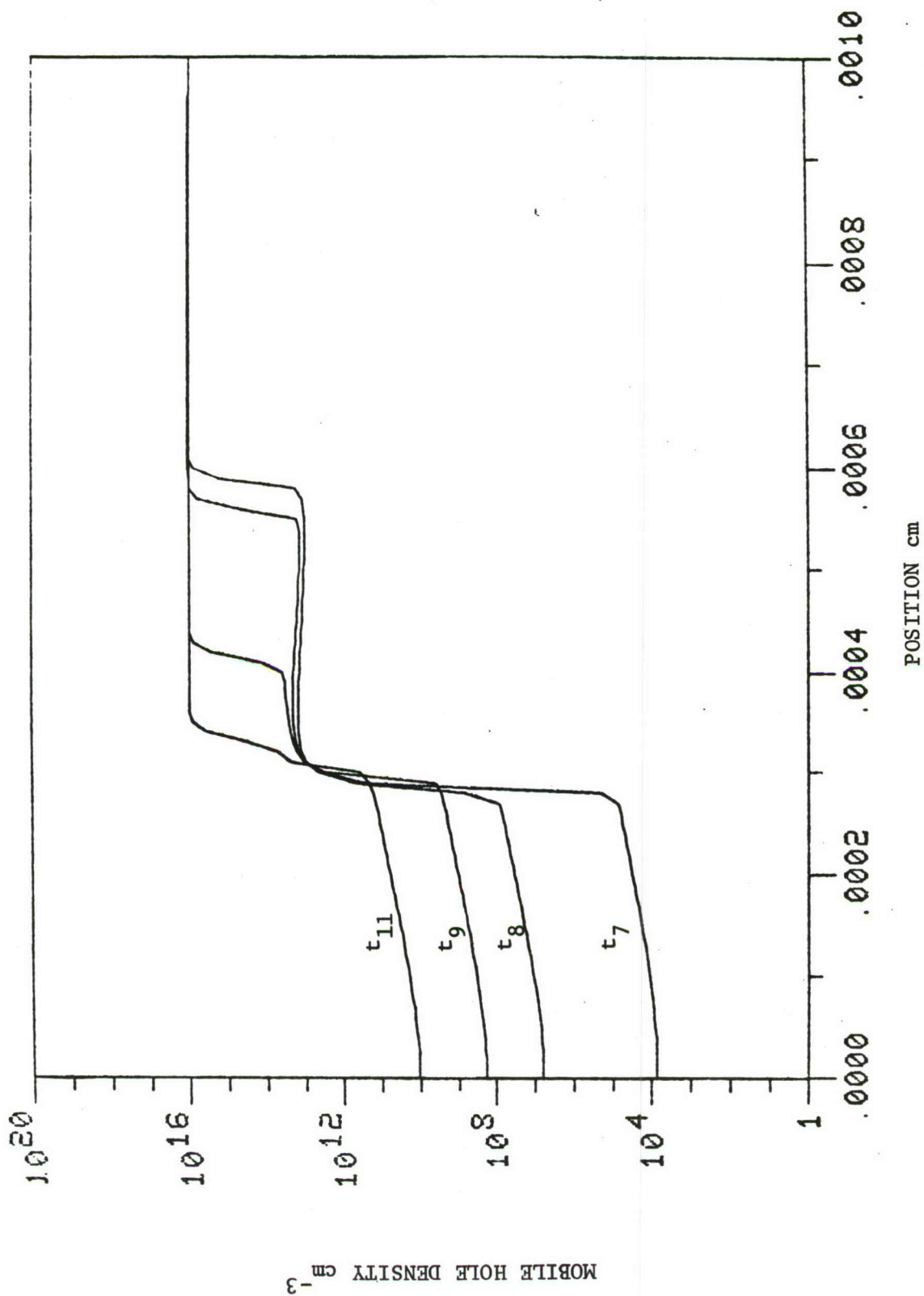


Fig. 4.6. Mobile Hole Density as a Function of Position at Various Instants of Time After the Onset of Thermal Second Breakdown ($t_7 = 7.82 \times 10^{-5}$, $t_8 = 1.2 \times 10^{-4}$, $t_9 = 1.35 \times 10^{-4}$, $t_{11} = 1.11 \times 10^{-3}$ - sec).

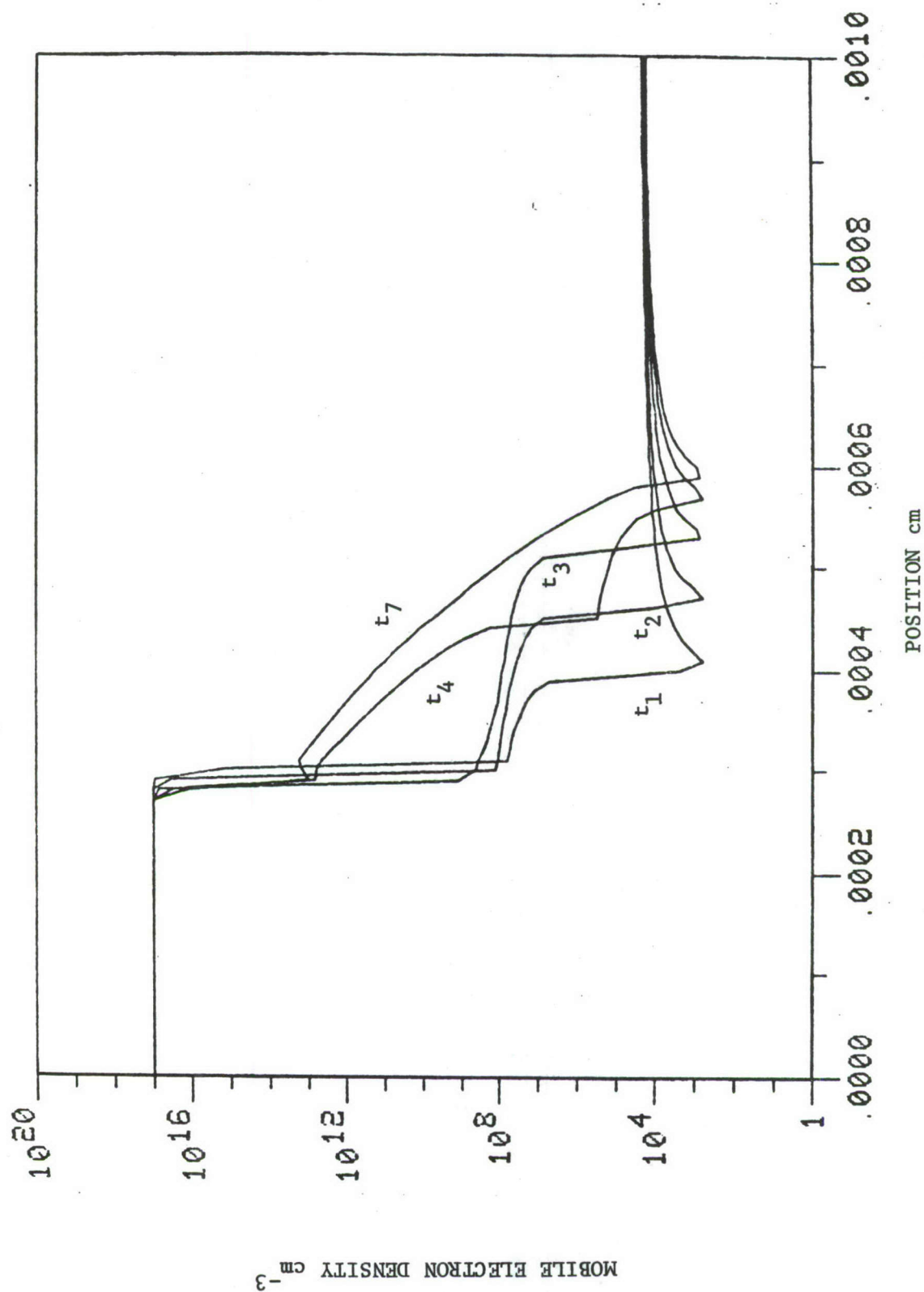


Fig. 4.7. Mobile Electron Density as a Function of Position at Various Instants of Time Prior to the Onset of Thermal Second Breakdown ($t_1=0.0$, $t_2=1.0 \times 10^{-8}$, $t_3=2.0 \times 10^{-8}$, $t_4=5.06 \times 10^{-8}$, $t_7=7.82 \times 10^{-5}$ - sec).

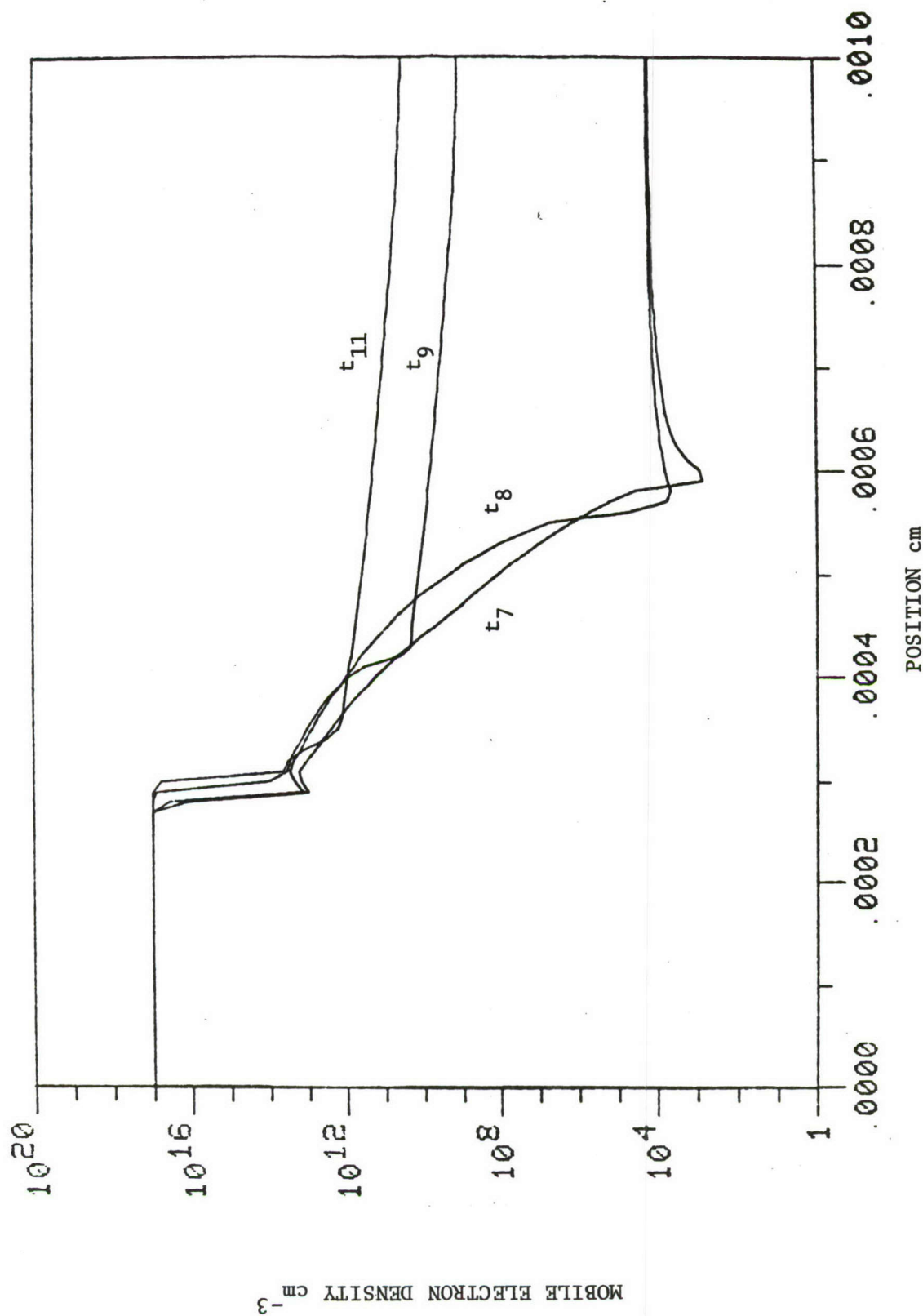


Fig. 4.8. Mobile Electron Density as a Function of Position at Various Instants of Time After the Onset of Thermal Second Breakdown ($t_7 = 7.82 \times 10^{-5}$, $t_8 = 1.2 \times 10^{-4}$, $t_9 = 1.35 \times 10^{-4}$, $t_{11} = 1.11 \times 10^{-3}$ - sec).

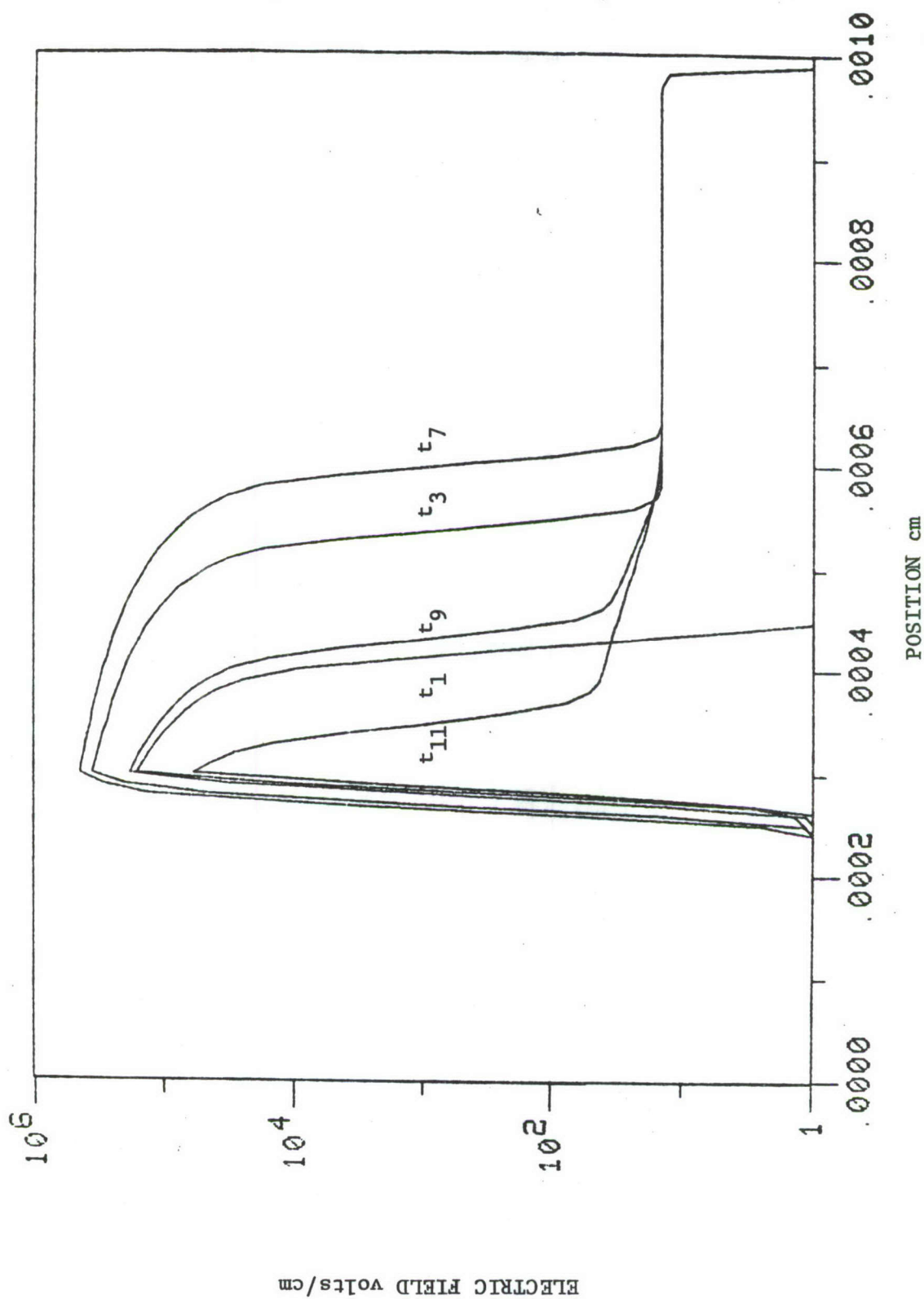


Fig. 4.9. Electric Field as a Function of Position at Various Instants of Time ($t_1=0.0$, $t_3=2.0 \times 10^{-8}$, $t_7=7.82 \times 10^{-5}$, $t_9=1.35 \times 10^{-4}$, $t_{11}=1.11 \times 10^{-3}$ - sec).

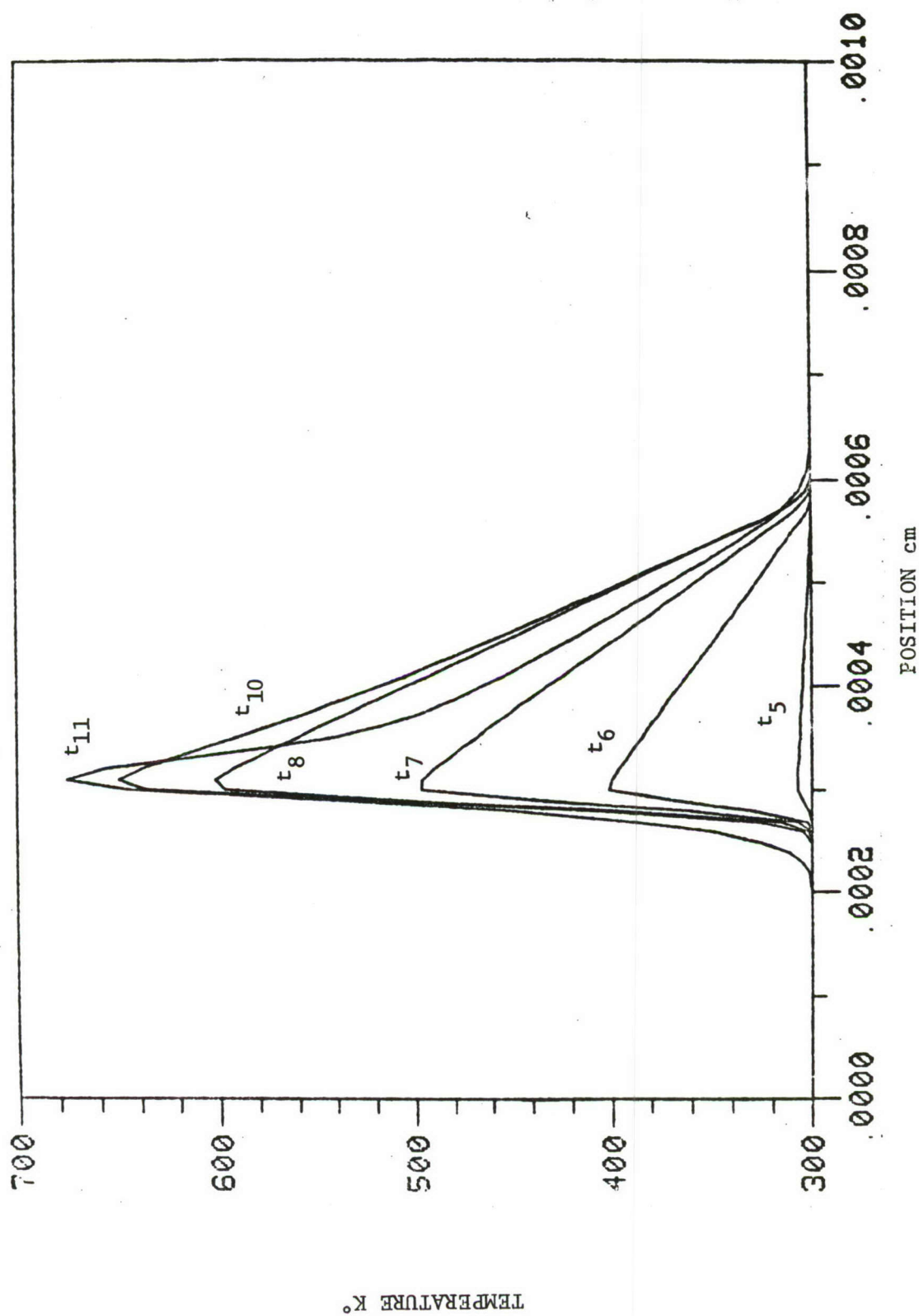


Fig. 4.10. Temperature as a Function of Position at Various Instants of Time ($t_5 = 3.0 \times 10^{-6}$, $t_6 = 4.0 \times 10^{-5}$, $t_7 = 7.82 \times 10^{-5}$, $t_8 = 1.2 \times 10^{-4}$, $t_{10} = 1.78 \times 10^{-4}$, $t_{11} = 1.11 \times 10^{-3}$ - sec).

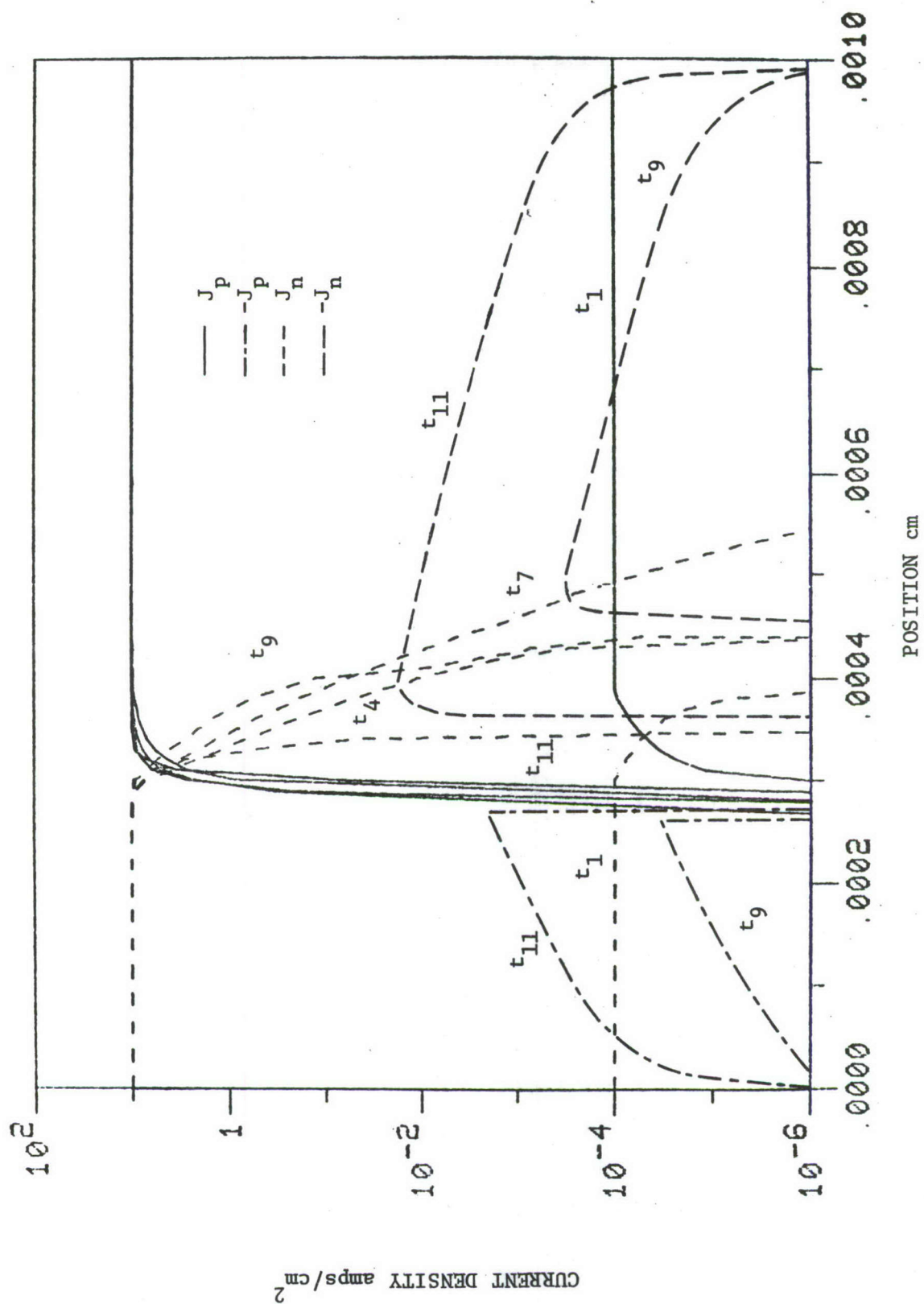
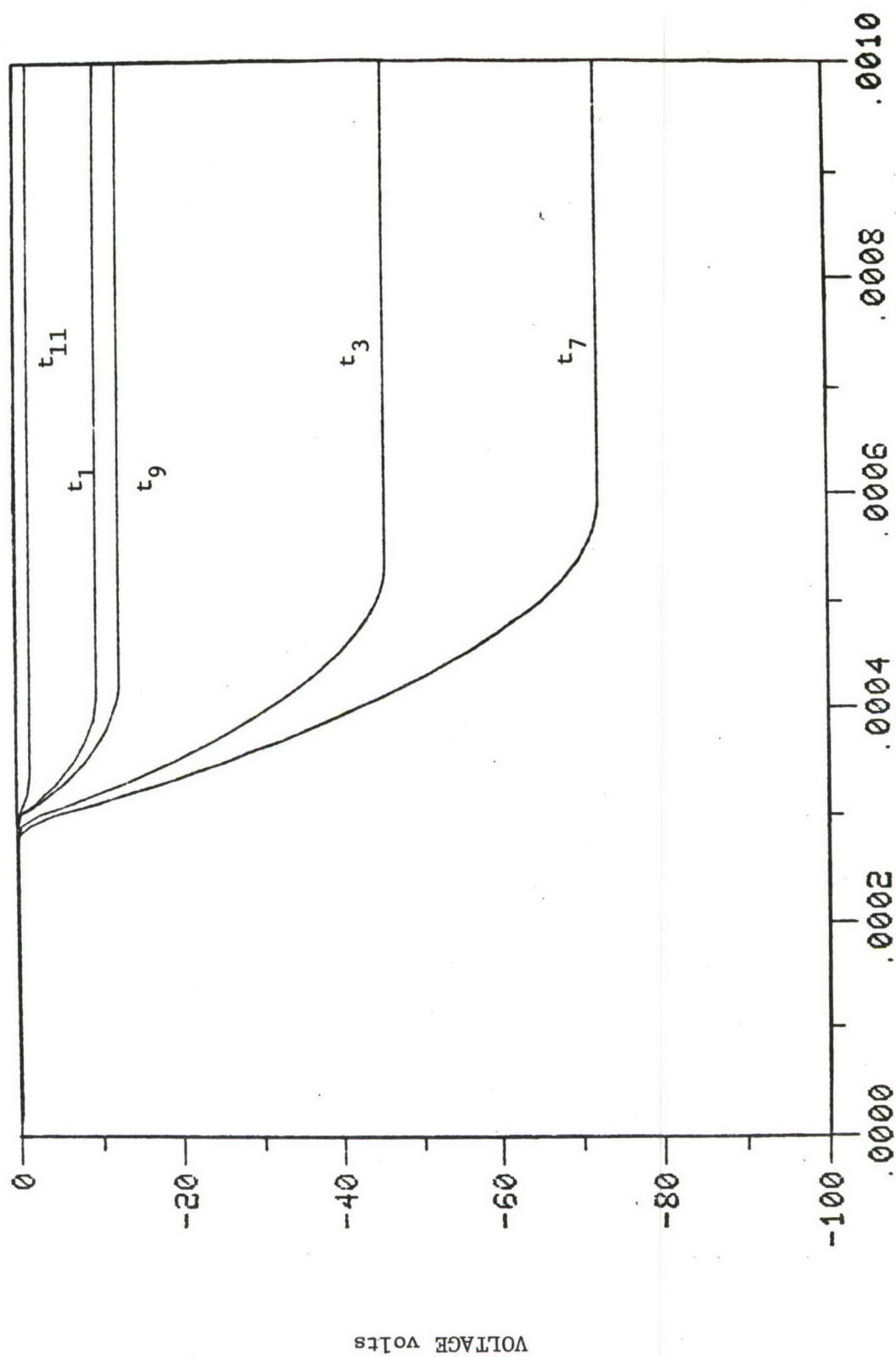


Fig. 4.11. Hole and Electron Current Densities as Functions of Position at Various Instants of Time ($t_1=0.0$, $t_4=5.06 \times 10^{-8}$, $t_7=7.82 \times 10^{-5}$, $t_9=1.35 \times 10^{-4}$, $t_{11}=1.11 \times 10^{-3}$ - sec).



POSITION cm

Fig. 4.12. Voltage as a Function of Position at Various Instants of Time ($t_1=0.0$, $t_3=2.0 \times 10^{-8}$, $t_7=7.82 \times 10^{-5}$, $t_9=1.35 \times 10^{-4}$, $t_{11}=1.11 \times 10^{-3}$ - sec).

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 logarithmic 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 heating, 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 Section 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 Section 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 widening 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 Section 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 advantage 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 $(4P-8) \times 12$. The formulation of the coefficients for this array and the required auxiliary 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

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

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

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

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

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

$$A(LT,6) = \frac{1}{\theta \Delta t} - \frac{\partial F_T(M)}{\partial T(M)} = \frac{1}{\theta \Delta t} - \sigma_1 - \sigma_2 - \sigma_3 \\ - \sigma_4 E(M) \left[\frac{\partial |J_p(M)|}{\partial T(M)} + \frac{\partial |J_n(M)|}{\partial T(M)} \right]$$

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

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

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

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

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

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

Where σ_1 , σ_2 , σ_3 , and σ_4 are defined in terms of the unnormalized parameters¹ K_D , K_H , ρ , c , x_{DT} , and x_{HT} as follows²:

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

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

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

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

VI. Hole and Electron Current and Subsequent Derivative Formulation

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

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

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

²Normalization 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. $\Delta x(M)E(M)/T(M) < \text{EXTCRI}$ (Current formulation switching variable).

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

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

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

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

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

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

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

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

$$\begin{aligned} \frac{\partial J_p(M)}{\partial E(M)} \approx & \frac{J_p(M)}{\mu_p(M)} \frac{\partial \mu_p(M)}{\partial E(M)} + \frac{\mu_p(M)T(M)}{\Delta x(M)} \left[p(N+1) \frac{\partial g(M)}{\partial E(M)} \right. \\ & \left. + p(N) \frac{\partial h(M)}{\partial E(M)} \right] \end{aligned}$$

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

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

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

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

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

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

VII. Avalanche Generation Factor and Subsequent Derivative Formulation

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

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

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

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

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

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

$$\begin{aligned} \frac{\partial G_I(N)}{\partial E(M-1)} = \lambda_m(N) & \left[|J_p(M-1)| \frac{\partial \alpha_p(M-1)}{\partial E(M-1)} + \alpha_p(M-1) \frac{\partial |J_p(M-1)|}{\partial E(M-1)} \right. \\ & \left. + |J_n(M-1)| \frac{\partial \alpha_n(M-1)}{\partial E(M-1)} + \alpha_n(M-1) \frac{\partial |J_n(M-1)|}{\partial E(M-1)} \right] \end{aligned}$$

$$\begin{aligned} \frac{\partial G_I(N)}{\partial T(M-1)} = \lambda_m(N) & \left[|J_p(M-1)| \frac{\partial \alpha_p(M-1)}{\partial T(M-1)} + \alpha_p(M-1) \frac{\partial |J_p(M-1)|}{\partial T(M-1)} \right. \\ & \left. + |J_n(M-1)| \frac{\partial \alpha_n(M-1)}{\partial T(M-1)} + \alpha_n(M-1) \frac{\partial |J_n(M-1)|}{\partial T(M-1)} \right] \end{aligned}$$

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

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

$$\begin{aligned} \frac{\partial G_I(N)}{\partial E(M)} = \lambda_p(N) & \left[|J_p(M)| \frac{\partial \alpha_p(M)}{\partial E(M)} + \alpha_p(M) \frac{\partial |J_p(M)|}{\partial E(M)} \right. \\ & \left. + |J_n(M)| \frac{\partial \alpha_n(M)}{\partial E(M)} + \alpha_n(M) \frac{\partial |J_n(M)|}{\partial E(M)} \right] \end{aligned}$$

$$\begin{aligned} \frac{\partial G_I(N)}{\partial T(M)} = \lambda_p(N) & \left[|J_p(M)| \frac{\partial \alpha_p(M)}{\partial T(M)} + \alpha_p(M) \frac{\partial |J_p(M)|}{\partial T(M)} \right. \\ & \left. + |J_n(M)| \frac{\partial \alpha_n(M)}{\partial T(M)} + \alpha_n(M) \frac{\partial |J_n(M)|}{\partial T(M)} \right] \end{aligned}$$

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

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

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

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

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

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

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

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

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

APPENDIX B

COMPUTER DIODE MODEL

This appendix reports the computer model developed to implement the numerical diode model formulated in Section 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, DGD (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 [17, 18].

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

TABLE B.1

SIMULATION STATE DATA FORMAT AND VARIABLE DEFINITIONS

<u>Position</u>	<u>Name</u>	<u>Type</u>	<u>Definition</u>
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

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

TABLE B.1 (Continued)

<u>Position</u>	<u>Name</u>	<u>Type</u>	<u>Definition</u>
17	NCS	I	Number of simulation cross sections in addition 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)

<u>Position</u>	<u>Name</u>	<u>Type</u>	<u>Definition</u>
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)

<u>Position</u>	<u>Name</u>	<u>Type</u>	<u>Definition</u>
65	XHT	R	Substrate thickness
66	THCONH	R	Semiconductor thermal conductivity
67	DBLANK	R	Dummy real variables to facilitate system expansion
:	:		
76	DBLANK		
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 in addition to the initial and final simulation times

by storing the various simulation final states on magnetic tape. Such a library is further enhanced by storing the simulation summary files 7 and 8 along with the corresponding final state so that subsequent graphic examinations of the simulations that produced the respective final states are possible without the necessity 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 spatially 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 succeeding 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 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

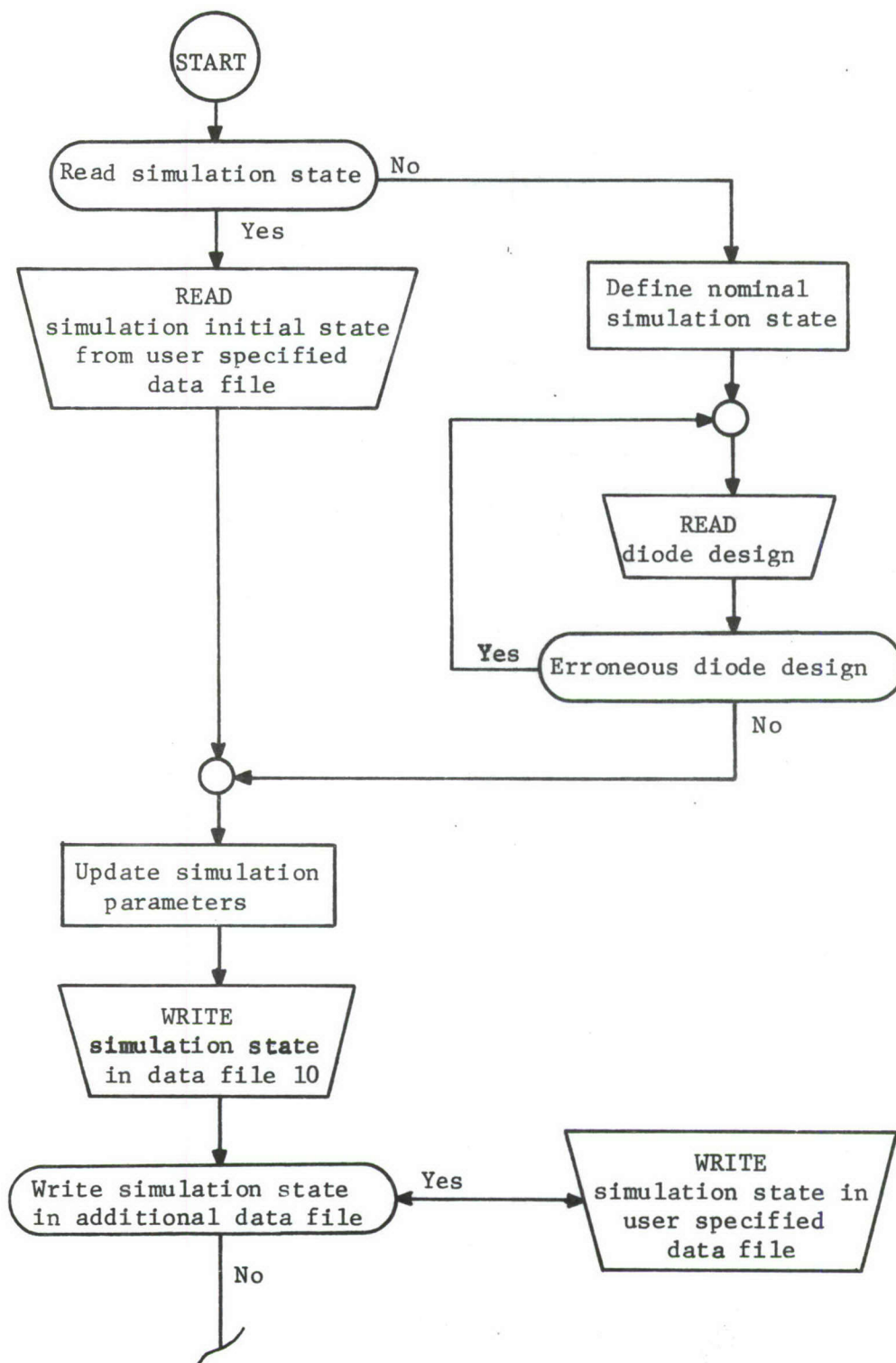


Fig. B.1. Flow Chart for Program DS

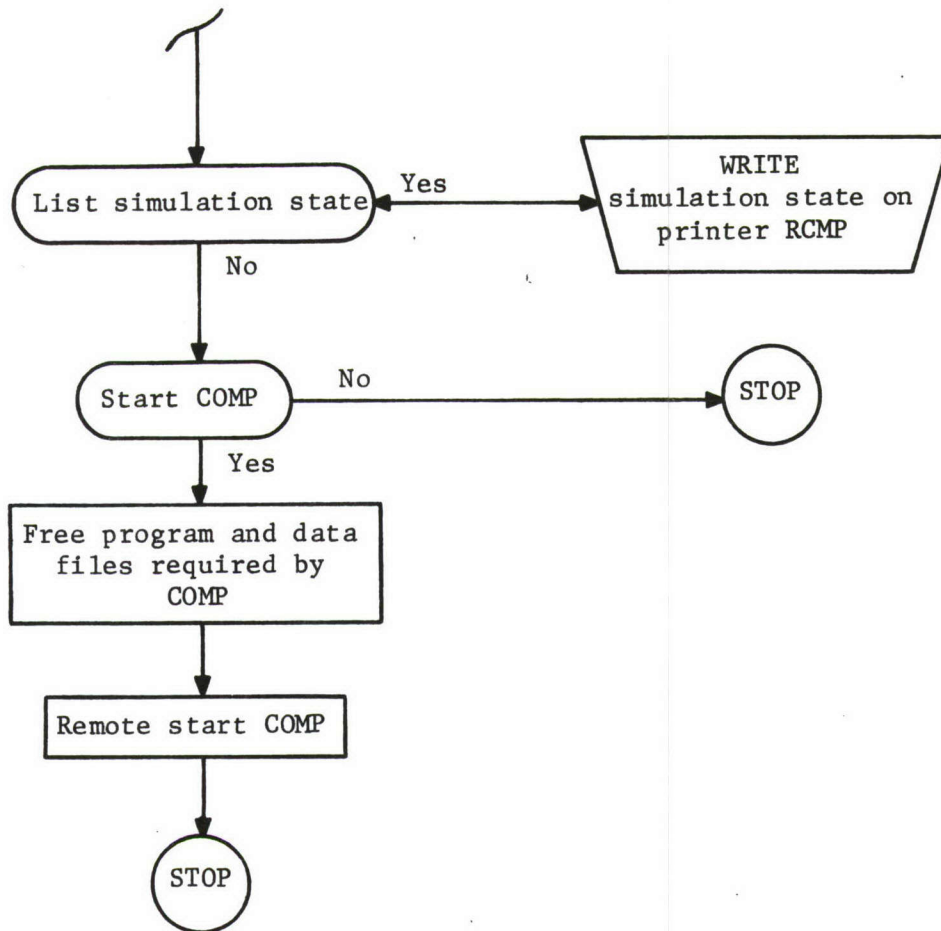


Fig. B.1. (Continued) Flow Chart for Program DS

```

1 C***** DS (DIODE SIMULATION) *****
2 C
3 C DS INTERACTIVELY GENERATES AND/OR UPDATES INITIAL
4 C STATES FOR THE DIODE SIMULATION PROGRAM COMP
5 C THROUGH THE FOLLOWING OPERATIONS:
6 C   1) UPDATING OF CONTROL AND MODEL PARAMETERS FOR AN
7 C      EXISTING STATE
8 C   2) GENERATION OF AN APPROXIMATE THERMAL EQUILIBRIUM
9 C      STATE THROUGH ANALYTIC FORMULATION
10 C   3) PRODUCE A STATE LISTING
11 C THE DESIGNATED INITIAL STATE IS TRANSFERRED TO COMP
12 C THROUGH DATA FILE 10. DS PROVIDES A REMOTE START
13 C OPTION FOR COMP, WHICH IS EXECUTED IN BATCH MODE.
14 C
15 C      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
16 C
17 C CONTROL PARAMETERS
18 C      INTEGER T,TMAX,RCMP,RCMPB,TLINC,TSINC
19 C
20 C DIODE STRUCTURE AND PHYSICAL PARAMETERS
21 C      INTEGER P
22 C      DIMENSION XXN(101), DXM(110), DOPN(101)
23 C
24 C INDEPENDENT VARIABLES
25 C      DIMENSION HOL(101), ELE(101), E(101), V(101), TEMP(101)
26 C
27 C SIMULATION PARAMETERS
28 C      DIMENSION CTIME(99)
29 C
30 C INITIAL STATE DATA
31 C
32 C ASSIGN DATA FILES
33 C      CALL ERTRAN (6,'QASG,AX 10. . ')
34 C      CALL ERTRAN (6,'QASG,AX 11. . ')
35 C      CALL ERTRAN (6,'QASG,AX 12. . ')
36 C      CALL ERTRAN (6,'QASG,AX 13. . ')
37 C
38 20 CONTINUE
39 C
40 C SPECIFY DATA FILE TO BE READ
41 C      LF=10
42 C      WRITE (6,30) LF
43 30 FORMAT (I11,' STATE FILE TO BE READ')
44 C
45 C      READ (5,40) LF
46 40 FORMAT (I11)
47 C
48 C THERMAL EQUILIBRIUM STATE GENERATION DEFAULT
49 C      LFREAD=LF
50 C      IF (LF.NE.0) GO TO 50
51 C
52 C DATA ASSIGNMENTS
53 C
54 C CONTROL PARAMETERS
55 C      NSF=13
56 C      T=0

```

Fig. B.2. Listing for Program DS


```

57      TMAX=100
58      TLINC=2
59      TSINC=1
60      RCMPB=136
61      LCSP1=2
62      LSCSP1=1
63      NTYBND=0
64      NTHDEP=1
65      NCS=0
66      LCS=1
67      LSCS=0
68      AITS=1.0D-4
69      C
70      C DIODE STRUCTURE AND PHYSICAL PARAMETERS
71      P=101                                @ NO. OF N NODES
72      DIEL=11.7D0                          @ SILICON
73      TEMPO=300.0D0                        @ DEG. KEL.
74      DONOR=1.0D16                         @ 1/CM**3
75      ACCEPT=1.0D16                       @ 1/CM**3
76      XMET=0.5D-4                          @ CM
77      XL=1.0D-4                            @ CM
78      CBEDS=2.8D19                         @ 1/CM**3
79      VBEDS=1.04D19                       @ 1/CM**3
80      ENGAP=1.082D0                        @ EV
81      XDT=1.0D-5                           @ CM
82      XHT=1.0D-5                           @ CM
83      C
84      C SIMULATION PARAMETERS
85      AREAD=1.0D-4                          @ CM**2
86      DT=1.0D-12                           @ SEC
87      TTIME=1.0D-0                          @ SEC
88      THETA=1.0D0                           @ CRANK-NICOLSON FACTOR
89      TIME=0.0D0                            @ SEC
90      TAUN=1.0D-9                           @ SEC
91      TAUP=1.0D-9                           @ SEC
92      THCOND=1.5D0                          @ WATT/CM/DEG. KEL.
93      THCONH=1.5D0                          @ WATT/CM/DEG. KEL.
94      SPHEAT=0.7D0                          @ JOULE/G/DEG. KEL.
95      DENSTY=2.33D0                         @ G/CM**3
96      FDTMUL=1.4D0
97      C
98      GO TO 90
99      50  CONTINUE
100     C
101     LFRTEM=LFRREAD
102     C
103     C READ INITIAL STATE FILE LF
104     C
105     INCLUDE RLF
106     C
107     INCLUDE LFFORM
108     C
109     LFRREAD=LFRTEM
110     C
111     I=1
112     WRITE (6,60) I
113     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=1
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      IDBIAN,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. BO
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,VOBISG,IDATE,ITIME,DIEL,CA
188 2RINT)
189 C
190 LFPREAD=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

```

228      LRP=1
229      INCLUDE DSIMP
230      INCLUDE DSIMPF
231  C
232  C
233      I=1
234      WRITE (6,220) I
235      READ (5,70) I
236      IF (I.EQ.1) GO TO 230
237  C
238  240  CONTINUE
239      I=1
240      WRITE (6,180) I
241      READ (5,70) I
242      IF (I.EQ.1) GO TO 190
243  C
244      I=1
245      WRITE (6,250) I
246  250  FORMAT (I11,' I=1, READ DIFF. STATE FILE')
247      READ (5,70) I
248      IF (I.EQ.1) GO TO 20
249  C
250      LF=11
251      WRITE (6,260) LF
252  260  FORMAT (I11,' LF, FILE FOR NEW ST., 0 - TRANSFER FILE ONLY')
253      READ (5,70) LF
254      LFSTOR=LF
255      IF (LF.EQ.0) GO TO 270
256  C
257  C WRITE VALUES INTO DATA FILE LF
258      INCLUDE WLF
259  C
260  270  CONTINUE
261  C
262  C WRITE STATE TRANSFER FILE 10 FOR COMP
263      LF=10
264      INCLUDE WLF
265      I=I
266  C
267  280  CONTINUE
268  C
269  C LIST INITIAL STATE PARAMETERS
270      I=1
271      WRITE (6,290) I
272  290  FORMAT (I11,' I=1, STATE PARAMETER LIST')
273      READ (5,70) I
274      IF (I.NE.1) GO TO 380
275  C
276  C ASSIGN OUTPUT SCRATCH DATA FILE 9.
277      CALL ERTRAN (6,'@BRKPT 9 . ')
278      CALL ERTRAN (6,'@FREE 9. . ')
279      CALL ERTRAN (6,'@CAT 9(+1). . ')
280      CALL ERTRAN (6,'@ASG,AX 9. . ')
281  C
282      RCMP=136
283      WRITE (6,300) RCMP
284  300  FORMAT (I11,' RCMP, SEL. PRINTER FOR STATE LISTING')

```

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


```

285      READ (5,70) RCMP
286      C
287      C WRITE DIODE SPEC., CONT.,AND SIM. PARS. ON UNIT 9
288      LF=9
289      LRP=0
290      C
291      WRITE (9,310) IDATE,ITIME
292      310  FORMAT ('1***** DS *****',T98,'DATE ',A6,3X,'TI
293      1ME ',A6,/)
294      C
295      INCLUDE DSPECP
296      INCLUDE DCONTP
297      INCLUDE DSIMP
298      I=1
299      C
300      C DEPENDENT VARIABLE LIST
301      C
302      I=1
303      WRITE (6,320) I
304      320  FORMAT (I11,' I=1, DEPENDENT VARIABLE LIST')
305      READ (5,70) I
306      IF (I.NE.1) GO TO 390
307      C
308      C WRITE STATE PROFILE
309      JJ=P-1
310      DO 330 J=1,JJ
311      DXM(J)=XXN(J+1)-XXN(J)
312      330  CONTINUE
313      DXM(P)=DXM(JJ)
314      C
315      IF(LPINT.LE.0)LPINT=1
316      I=1
317      K=51
318      340  CONTINUE
319      IF(1.GT.P)I=P
320      K=K+1
321      IF (K.LT.52) GO TO 360
322      K=1
323      WRITE (9,350) IDATE,ITIME
324      350  FORMAT ('1***** DS *****',T98,'DATE ',A6,3X,'T
325      1IME ',A6,/,/,T6,'I',T13,'XXN(I)',T25,'DXN(I)',T37,'DOPN(I)',T49,'H
326      20L(I)',T61,'ELE(I)',T73,'E(I)',T85,'V(I)',T97,'TEMP(I)',/)
327      360  WRITE (9,370) I,XXN(I),DXM(I),DOPN(I),HOL(I),ELE(I),E(I),V(I),TEMP
328      1(I)
329      370  FORMAT (T2,I5,T9,8E12.5)
330      IF (1.GE.P) GO TO 390
331      I=I+LPINT
332      GO TO 340
333      C
334      380  CONTINUE
335      C
336      IF (RCMP.EQ.0) GO TO 400
337      C
338      390  CONTINUE
339      C
340      C SEND STATE LISTING TO DESIGNATED PRINTER
341      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 DSA. . ')
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*DSA/J/V.SCOMPA,100 . '
370      1)
371      IF (RCMPB.EQ.101) CALL ERTRAN (6,'@START SB*DSA/J/V.SCOMPA,101 . '
372      1)
373      IF (RCMPB.EQ.102) CALL ERTRAN (6,'@START SB*DSA/J/V.SCOMPA,102 . '
374      1)
375      IF (RCMPB.EQ.136) CALL ERTRAN (6,'@START SB*DSA/J/V.SCOMPA,136 . '
376      1)
377  C
378      STOP
379      END

```

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

```

1  RLF  PROC
2  C
3      READ (LF,1410) NSF,T,TMAX,RCMPB,P,LNORC,TLINC,TSINC,LCS,LSCS,LSCSP
4      1I,LCSPI,LFREAD,LFSTOR,NTYBND,NTHDEP,NCS,IDATE,ITIME,IBLANK,IBLANK,
5      2IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK
6  C
7      READ (LF,1420) DIEL,TEMPO,CARINT,DONOR,ACCEPT,XMET,XL,TAUN,TAUP,AR
8      1EAD,DT,TTIME,TIME,THETA,VDBI,DX,DEPN,DEPP,DEPW,XDEPN,XDEPP,VDBIAN,
9      2VDBISG,CURTOT,EXTCRI,FDTMUL,VDCOMP,CBEDS,VBEDS,ENGAP,THCOND,SPHEAT
10     3,DENSTY,AITS,XDT,XHT,THCONH,DBLANK,DBLANK,DBLANK,DBLANK,DBLANK,DBL
11     4ANK,DBLANK,DBLANK,DBLANK,DBLANK
12  C
13     READ (LF,1420) (XXN(I),DOPN(I),HOL(I),ELE(I),E(I),V(I),TEMP(I),I=1
14     1,P)
15  C
16     IF (NCS.NE.0) READ (LF,1420) (CSTIME(I),I=1,NCS)
17  C
18     REWIND LF
19  C
20     END
21  C
22  WLF  PROC
23  C
24     WRITE (LF,1410) NSF,T,TMAX,RCMPB,P,LNORC,TLINC,TSINC,LCS,LSCS,LSCS
25     1PI,LCSPI,LFREAD,LFSTOR,NTYBND,NTHDEP,NCS,IDATE,ITIME,IBLANK,IBLANK
26     2,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK,IBLANK
27  C
28     WRITE (LF,1420) DIEL,TEMPO,CARINT,DONOR,ACCEPT,XMET,XL,TAUN,TAUP,A
29     1READ,DT,TTIME,TIME,THETA,VDBI,DX,DEPN,DEPP,DEPW,XDEPN,XDEPP,VDBIAN
30     2,VDBISG,CURTOT,EXTCRI,FDTMUL,VDCOMP,CBEDS,VBEDS,ENGAP,THCOND,SPHEA
31     3T,DENSTY,AITS,XDT,XHT,THCONH,DBLANK,DBLANK,DBLANK,DBLANK,DBLANK,DB
32     4LANK,DBLANK,DBLANK,DBLANK,DBLANK
33  C
34     WRITE (LF,1420) (XXN(I),DOPN(I),HOL(I),ELE(I),E(I),V(I),TEMP(I),I=
35     11,P)
36  C
37     IF (NCS.NE.0) WRITE (LF,1420) (CSTIME(I),I=1,NCS)
38  C
39     END FILE LF
40     REWIND LF
41  C
42     END
43  C
44  LFFORM PROC
45  C
46  C DATA FILE READ-WRITE FORMATS
47  1410 FORMAT (I30)
48  1420 FORMAT (D30.18)
49  C
50     END
51  C
52  DSPECP PROC
53  C
54     WRITE (LF,1430)
55     WRITE (LF,1440) DONOR
56     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.0.5D0) 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) LFPREAD
145      WRITE (LF,1760) LFPSTOR
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,' RCPMB, 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

```

171 1740 FORMAT (I11,' NCS, NO. OF ADDITIONAL CROSS SECTIONS')
172 1750 FORMAT (I11,' LFREAD, DATA FILE READ')
173 1760 FORMAT (I11,' LFSTOR, DATA FILE WRITTEN')
174 1770 FORMAT (I11,' LRPT, 1 - UPDATE CROSS SECTION TIMES')
175 1780 FORMAT (A11,' IDATE, STATE GENERATION DATE')
176 1790 FORMAT (A11,' ITIME, STATE GENERATION TIME')
177 1800 FORMAT (I11)
178 1810 FORMAT (D11.4)
179 C
180 END
181 C
182 DSIMP PROC
183 C
184 WRITE (LF,1820)
185 WRITE (LF,1830) CARINT
186 WRITE (LF,1840) AREAD
187 IF (LRP.EQ.1) READ (5,1970) AREAD
188 WRITE (LF,1850) XDT
189 IF (LRP.EQ.1) READ (5,1970) XDT
190 WRITE (LF,1860) XHT
191 IF (LRP.EQ.1) READ (5,1970) XHT
192 WRITE (LF,1870) TAUN
193 IF (LRP.EQ.1) READ (5,1970) TAUN
194 WRITE (LF,1880) TAUP
195 IF (LRP.EQ.1) READ (5,1970) TAUP
196 WRITE (LF,1890) AITS
197 IF (LRP.EQ.1) READ (5,1970) AITS
198 WRITE (LF,1900) THCOND
199 IF (LRP.EQ.1) READ (5,1970) THCOND
200 WRITE (LF,1910) THCONH
201 IF (LRP.EQ.1) READ (5,1970) THCONH
202 WRITE (LF,1920) SPHEAT
203 IF (LRP.EQ.1) READ (5,1970) SPHEAT
204 WRITE (LF,1930) DENSTY
205 IF (LRP.EQ.1) READ (5,1970) DENSTY
206 WRITE (LF,1940) LNORC
207 IF (LRP.EQ.1) READ (5,1980) LNORC
208 WRITE (LF,1950) VDBIAN,VDBISG,VDCOMP,VDBI
209 IF (LRP.EQ.1) READ (5,1960) VDBI
210 C
211 END
212 C
213 DSIMPF PROC
214 C
215 1820 FORMAT (/, ' DIODE MODEL PARAMETERS '/')
216 1830 FORMAT (D11.4,' CARINT, INTRINSIC CAR. CONC., 1/CM**3')
217 1840 FORMAT (D11.4,' AREAD, DIODE AREA, CM**2')
218 1850 FORMAT (D11.4,' XDT, DIODE THICKNESS, CM')
219 1860 FORMAT (D11.4,' XHT, HEADER THICKNESS, CM')
220 1870 FORMAT (D11.4,' TAUN, ELECTRON LIFETIME, SEC')
221 1880 FORMAT (D11.4,' TAUP, HOLE LIFETIME, SEC')
222 1890 FORMAT (D11.4,' AITS, IONIZATION TEMP COEFF.')
223 1900 FORMAT (D11.4,' THCOND, DIODE THERMAL COND., WATT/CM/DEG. KEL.')
224 1910 FORMAT (D11.4,' THCONH, HEADER THERMAL COND., WATT/CM/DEG. KEL.')
225 1920 FORMAT (D11.4,' SPHEAT, SPECIFIC HEAT, JOULE/G/DEG. KEL.')
226 1930 FORMAT (D11.4,' DENSTY, G/CM**3')
227 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 (I11)
234      C
235      END

```

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

```

1      SUBROUTINE DTMUL(NTRIS,TMIN,TMAX,DT,NMIN,NMAX,ALFA)
2      C
3      C EVALUATES OPTIMAL GEOMETRIC SERIES FACTOR, ALFA
4      C
5      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
6      C
7      N=NMAX-NMIN
8      TA=(TMAX-TMIN)/DT
9      DN=N
10     NN=1000000
11     IF(TA.LT.1000000) NN=TA
12     IF(N.LE.NN) GO TO 5
13     ALFAMA=0.500
14     ALFAMI=1.000
15     GO TO 9
16     5    CONTINUE
17     ALFAMA=1.500
18     ALFAMI=1.000
19     9    CONTINUE
20     C
21     DO 15 K=1,NTRIS
22     ALFA=(ALFAMA+ALFAMI)/2.000
23     DIF=(ALFA**DN-1.000)-TA*DLOG(ALFA)
24     C
25     IF(DIF.GT.0.000) GO TO 10
26     ALFAMI=ALFA
27     GO TO 15
28     10   CONTINUE
29     ALFAMA=ALFA
30     15   CONTINUE
31     C
32     RETURN
33     END

```

(a) Listing for DTMUL

```

1      SUBROUTINE CST(NCS,LF,LRP,CSTIME)
2      C
3      C INPUT/OUTPUT OF SIMULATION CROSS SECTION PRINT AND/OR
4      C STORAGE TIMES
5      C
6      DOUBLE PRECISION CSTIME(10)
7      C
8      C
9      DO 10 I=1,NCS
10     WRITE(LF,1457) CSTIME(I),I
11     1457 FORMAT(011.4,' CSTIME(',I2,') CROSS SECTION TIME, SEC')
12     IF(LRP.EQ.1) READ(5,1460) CSTIME(I)
13     1460 FORMAT(011.4)
14     10   CONTINUE
15     C
16     RETURN
17     END

```

(b) Listing for CST

```

1      NSTAB 50,1,1,1,1,1 6 1 5 4 9
2      END

```

(c) Listing for NTAB\$

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

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 spatial 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 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 Section 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

```

1      SUBROUTINE ISTG (NP,ACCEPT,DONOR,XMET,XL,X
2      1DEPN,XDEPP,TEMPO,XN,DXM,DOPN,HOL,ELE,E,V,TEMP,VDBISG,IDATE,ITIME,D
3      2IEL,CARINT)
4
5      C SUB ISTG GENERATES AN ANALYTIC THERMAL EQUILIBRIUM
6      C INITIAL STATE WITH UNIFORM GRID.
7
8      C      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
9
10     C      DIMENSION XN(1), DXM(1), DOPN(1), HOL(1), ELE(1), E(1), V(1), TEMP
11     1(1)
12
13     C SET IDATE AND ITIME
14     CALL ERTRAN (9,IDATE,ITIME)
15
16     C PHYSICAL CONSTANTS
17     Q=1.6D-19
18     BOZ=1.381D-23
19     PERM=8.854D-14
20     QKT=Q/BOZ/TEMPO
21
22     C EVALUATION OF THERMAL EQUILIBRIUM CARRIER CONC. VALUES
23     TDON=DONOR/CARINT
24     TACC=ACCEPT/CARINT
25
26     C TEMPERATURE DEPENDENCE FOR SUB. THEQCA CONVEYED
27     C THROUGH NORMALIZATION OF CARRIER CONCS. IMPURITIES
28     C ASSUMED FULLY IONIZED.
29     CALL THEQCA (TDON,TACC,HOLXO,ELEXO,HOLXL,ELEXL,VDBIAN)
30
31     C UNNORMALIZE CONCS.
32     HOLXO=HOLXO*CARINT
33     ELEXO=ELEXO*CARINT
34     HOLXL=HOLXL*CARINT
35     ELEXL=ELEXL*CARINT
36
37     C
38     C GENERATE LINEAR GRID AND ABRUPT IMPURITY PROFILE
39     NPM1=NP-1
40     XN(1)=0.0
41     DOPN(1)=DONOR
42     DXN=XL/NPM1
43     DO 40 K=2,NP
44     XN(K)=XN(K-1)+DXN
45     IF (XN(K).GT.XMET) GO TO 20
46     DOPN(K)=DONOR
47     GO TO 30
48     20 CONTINUE
49     DOPN(K)=-ACCEPT
50     30 CONTINUE
51     DXM(K-1)=XN(K)-XN(K-1)
52     40 CONTINUE
53     XN(NP)=XL
54
55     C GENERATE ANALYTIC ELECTRIC FIELD
56     TN=Q*DONOR/(PERM*DIEL)

```

Fig. B.5. Listing for Subroutine ISTG

```

57      TP=Q*ACCEPT/(PERM*DIEL)
58      EN=TN*(XMET-XDEPN)
59      C
60      DO 80 K=1,NP
61      IF (XN(K).GT.XDEPN) GO TO 50
62      C N-SIDE BULK REGION
63      E(K)=0.0
64      GO TO 80
65      50      CONTINUE
66      IF (XN(K).GT.XMET) GO TO 60
67      C N-SIDE DEPLETION REGION
68      E(K)=TN*(XN(K)-XDEPN)
69      GO TO 80
70      60      CONTINUE
71      IF (XN(K).GT.XDEPP) GO TO 70
72      C P-SIDE DEPLETION REGION
73      E(K)=EN-TP*(XN(K)-XMET)
74      GO TO 80
75      70      CONTINUE
76      C P-SIDE BULK REGION
77      E(K)=0.0
78      80      CONTINUE
79      C
80      C EVALUATE ANALYTICALLY: HOL, ELE, V, AND INITIALIZE TEMP
81      C
82      TA=(XDEPN**2)/2.0
83      TB=XMET+DONOR/ACCEPT*(XMET-XDEPN)
84      TC=TN*((1.0+ACCEPT/DONOR)*XMET**2-XDEPN**2)/2.0
85      C
86      DO 120 K=1,NP
87      TEMP(K)=TEMPO
88      IF (XN(K).GT.XDEPN) GO TO 90
89      C N-SIDE BULK REGION
90      DOPN(K)=DONOR
91      E(K)=0.0
92      V(K)=0.0
93      HOL(K)=HOLX0
94      ELE(K)=ELEX0
95      GO TO 120
96      90      CONTINUE
97      IF (XN(K).GT.XMET) GO TO 100
98      C N-SIDE DEPLETION REGION
99      DOPN(K)=DONOR
100     E(K)=TN*(XN(K)-XDEPN)
101     V(K)=TN*((XDEPN-XN(K)/2.0)*XN(K)-TA)
102     HOL(K)=HOLX0*DEXP(-QKT*V(K))
103     ELE(K)=ELEX0*DEXP(QKT*V(K))
104     GO TO 120
105     100     CONTINUE
106     IF (XN(K).GT.XDEPP) GO TO 110
107     C P-SIDE DEPLETION REGION
108     DOPN(K)=-ACCEPT
109     E(K)=EN-TP*(XN(K)-XMET)
110     V(K)=TP*(XN(K)/2.0-TB)*XN(K)+TC
111     HOL(K)=HOLX0*DEXP(-QKT*V(K))
112     ELE(K)=ELEX0*DEXP(QKT*V(K))
113     110     GO TO 120

```

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

```

114      110  CONTINUE
115      C P-SIDE BULK REGION
116          DOPN(K)=-ACCEPT
117          E(K)=0.0
118          V(K)=V(K-1)
119          HOL(K)=HOLXL
120          ELE(K)=ELEXL
121      120  CONTINUE
122      C
123          VDBISG=V(NP)
124      C
125          RETURN
126          END

```

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


```

1      SUBROUTINE THEQCA(DONOR,ACCEPT,HOLXO,ELEXO,HOLXL,
2      1ELEXL,VDBIAN)
3
4      C SUB. THEQCA GENERATES THERMAL EQUILIBRIUM HOLE AND
5      C ELECTRON CONCENTRATION FOR THE DONOR AND ACCEPTOR
6      C IMPURITY LEVELS RESPECTIVELY. THE CORRESPONDING BUILT-
7      C IN VOLTAGE IS ALSO EVALUATED. ALL ARGUMENTS ARE
8      C ASSUMED APPROPRIATELY NORMALIZED BY EITHER INTRINSIC
9      C CAR. CONC. OR THERMAL VOLT. CORRESPONDING TO SPECIFIED
10     C TEMPERATURE.
11
12     C      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
13
14     C FUNCTION 'ROOT' EVALUATES MAJORITY CAR. CONC.
15     C      DEFINE ROOT(TA)=DABS(TA)/2.0D0+DSQRT(TA*
16     C      1TA/4.0D0+1.0D0)
17
18     C EVALUATE MAJORITY CARRIER CONC. ON N-SIDE
19     C      ELEXO=ROOT(DONOR)
20
21     C EVALUATE MINORITY CARRIER CONC. ON N-SIDE
22     C      HOLXO=1.0D0/ELEXO
23
24     C EVALUATE MAJORITY CARRIER CONC. ON P-SIDE
25     C      HOLXL=ROOT(ACCEPT)
26
27     C EVALUATE MINORITY CARRIER CONC. ON P-SIDE
28     C      ELEXL=1.0D0/HOLXL
29
30     C EVALUATE DIODE BUILT-IN VOLTAGE
31     C      VDBIAN=-DLOG(ELEXO/ELEXL)
32
33     C      RETURN
34     C      END

```

(a) Listing for THEQCA

```

1      SUBROUTINE INTRI(CBEDS,VBEDS,ENGAP,TEMP,CARINT)
2
3      C SUB. INTRI COMPUTES INTRINSIC CAR. CONC.
4
5      C CBEDS - COND. BAND EFFECTIVE DENSITY OF STATES, 1/CM**3
6      C VBEDS - VALANCE BAND EFFECTIVE DENSITY OF STATES, 1/CM**3
7      C ENGAP - ENERGY GAP, EV
8      C TEMP - TEMPERATURE, DEG. KEL.
9      C CARINT - INTRINSIC CAR. CONC., 1/CM**3
10     C Q - UNIT CHARGE, COULOMBS
11     C BOZ - BOLTZMANN'S CONST., JOULES/DEG. KEL.
12
13     C      DOUBLE PRECISION CBEDS,VBEDS,ENGAP,TEMP,CARINT
14     C      DOUBLE PRECISION Q,BOZ
15
16     C      Q=1.6D-19
17     C      BOZ=1.381D-23
18     C      CARINT=DSQRT(CBEDS*VBEDS)*DEXP(-ENGAP*Q/(TEMP*BOZ*2.0D0))
19
20     C      RETURN
21     C      END

```

(b) Listing for INTRI

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

```

1      SUBROUTINE DEPL(L,ACCEPT,DONOR,CARINT,XMET,DEPN,DEPP,DEPW,XDEPN,
2      1XDEPP,VDBIAN,DIEL,TEMP)
3      C
4      C EVALUATES DEPLETION REGION CHARACTERISTICS THROUGH
5      C ANALYTIC FORMULATION FOR AN ABRUPT JUNCTION CONFIGURATION
6      C
7      DOUBLE PRECISION ACCEPT,DONOR,CARINT,XMET,DIEL,TEMP
8      DOUBLE PRECISION DEPN,DEPP,DEPW,XDEPN,XDEPP,VDBIAN
9      DOUBLE PRECISION Q,BOZ,PERM
10     DOUBLE PRECISION HOLXO,ELEXO,HOLXL,ELEXL
11     DOUBLE PRECISION TA,TB
12     C PHYSICAL CONSTANTS
13     Q=1.6D-19                                Q COULOMBS
14     BOZ=1.381D-23                             Q JOULES/DEG. KEL.
15     PERM=8.854D-14                             Q FARADS/CM, FREE SPACE PERM
16     C
17     C EVALUATE DIODE BUILT-IN VOLTAGE, VDBIAN
18     TA=ACCEPT/CARINT
19     TB=DONOR/CARINT
20     C
21     CALL THEQCA(TB,TA,HOLXO,ELEXO,HOLXL,ELEXL,VDBIAN)
22     C
23     VDBIAN=VDBIAN*BOZ*TEMP/Q
24     C
25     C EVALUATION OF DEPLETION REGION BOUNDARIES
26     TA=ACCEPT*DONOR
27     TB=ABS(2.0D0*DIEL*PERM*VDBIAN/Q)
28     DEPN=(TB*ACCEPT/(TA+DONOR*DONOR))*0.5
29     DEPP=(TB*DONOR/(TA+ACCEPT*ACCEPT))*0.5
30     DEPW=DEPN+DEPP
31     XDEPN=XMET-DEPN
32     XDEPP=XMET+DEPP
33     C
34     IF(L.NE.1) RETURN
35     C
36     WRITE(9,1001)
37     1001 FORMAT('1 ***** SUBROUTINE DEPL *****')
38     1' SUB. DATA')
39     WRITE(9,1002) ACCEPT
40     1002 FORMAT(T2,D15.4,' ACCEPT')
41     WRITE(9,1003) DONOR
42     1003 FORMAT(T2,D15.4,' DONOR')
43     WRITE(9,1004) CARINT
44     1004 FORMAT(T2,D15.4,' CARINT')
45     WRITE(9,1005) XMET
46     1005 FORMAT(T2,D15.4,' XMET')
47     WRITE(9,1006) DIEL
48     1006 FORMAT(T2,D15.4,' DIEL')
49     WRITE(9,1007) TEMP
50     1007 FORMAT(T2,D15.4,' TEMP')
51     WRITE(9,1008) Q
52     1008 FORMAT(T2,D15.4,' Q')
53     WRITE(9,1009) BOZ
54     1009 FORMAT(T2,D15.4,' BOZ')
55     WRITE(9,1010) PERM
56     1010 FORMAT(T2,D15.4,' PERM')

```

Fig. B.7. Listing for Subroutine DEPL

```

57      WRITE(9,1011)
58      1011 FORMAT(// ' SUB. OUTPUT'//)
59      WRITE(9,1012) VDBIAN
60      1012 FORMAT(T2,D15.4,' VDBIAN')
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) HOLX0,ELEX0,HOLXL,ELEXL
72      1018 FORMAT(4(T2,D30.16,/,))
73      C
74      C ERRONEOUS CALCULATION TO SUPPRESS DIAGNOSTICS IN
75      C RFOR
76      TA=HOLX0*ELEX0/HOLXL/ELEXL
77      C
78      RETURN
79      END

```

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

as long as the simulation state data format shown in Table B.1 is maintained. COMP is designed to facilitate an arbitrary impurity profile and a 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 Section 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 categories: 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 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.

***** COMP *****

DIODE STRUCTURE AND PHYSICAL PARAMETERS

.1000+018 DOI:OK, 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 XMEI, LOCATION OF MET. JUNCT., CM
101 P, NUMBER OF N-MODES
.2800+020 CBEUS, COND. BAND EFFECTIVE DEN. STATES, 1/CM**3
.1040+020 VBEUS, VAL. BAND EFFECTIVE DEN. STATES, 1/CM**3
.1082+001 ENIGAP, ENERGY GAP, EV
.3000+003 TENPO, INITIAL TEMP., DEG. KEL.
.1170+002 DIEL, DIELECTRIC CONSTANT

CONTROL PARAMETERS

12 NSF, NE* SI, FILE
.1000+003 CUNTOT, TERMINAL CURRENT DENSITY
0 NTHBND, TYPE BND. COND. X=XL, 0-CUR., 1-OHMIC
1 NTHDEP, THERMAL DEPENDENCE, 0-NO, 1-YES
136 RCMPPB, 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 FDMUL, FORWARD DT MULTIPLICATION FACTOR
2 TLINC, TIME STEP PRINT INC.
2 TSHNC, TIME STEP STORAGE INC.
1 LCS, 1-LIST CROSS SECTIONS
2 LCSP1, CROSS SECTION PRINT INTERVAL
0 LCS2, 1-STORE CROSS SECTIONS
0 LCS3, NO. OF ADDITIONAL CROSS SECTIONS
10 LFMHAD, DATA FILE READ
0 LFSIOR, DATA FILE WRITTEN
060675 IOATE, 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 XDI, DIODE THICKNESS, CM
.2500+004 XMI, HEADER THICKNESS, CM
.1000+009 TAUM, ELECTRON LIFETIME, SEC
.1000+009 TAUP, 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 DEVSIT, G/CM**3
0 LNMHC, 1 - LIST NORM CONSTANTS
- .81583346968295391+000 VDBIAN, ANALYTIC
- .803420613783595083+000 VDBISG, IN. ST .A PPROX.
.000000000000000000 VDCOMP, VDT FROM COMP

Fig. B.8. Simulation Summary Example

--.815833469868295391+000 VOB1, PARAMETER

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

DATE 061775

TIME 114554

TIME= .000

T= 0

HOL

DOFN

DXN

XAN

N

WJOLE CROSS SECTION,

E

ELE

V

TEMP

CURHOL

CURELE

CURDIS

PIB

CI

G5

GI

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

TIME= .229+02

DIQUE CROSS SECTION, Y= 100

N

X44

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	908-05	-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	236+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	741-13	-105+00	144+11	325+12	000
13	360-04	300-05	100+18	204+04	100+18	926-05	-301-09	300+03	152-11	100-03	741-13	-105+00	144+11	395+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	485+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	320-12	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	135-12	-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	280-10	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	119+14	000
43	126-03	300-05	100+18	887+03	100+18	291+01	-190-05	300+03	521-10	100-03	100-09	-105+00	144+11	150+14	000
45	132-03	300-05	100+18	580+03	997+17	152+03	-732-04	300+03	657-10	100-03	400-11	000	144+11	216+14	000
47	138-03	300-05	100+18	239+03	864+17	740+04	-379-02	300+03	893-10	100-03	102-12	-105+00	144+11	398+16	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	718+20	291+17
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	324+20	242+15
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	552+14	000
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	184+14	000
57	168-03	300-05	100+18	980+17	279+03	152+03	-207+01	300+03	100-03	116-09	109-11	-105+00	144+11	156+14	000
59	174-03	300-05	100+18	100+18	511+03	291+01	-207+01	300+03	100-03	100-09	105-10	000	144+11	135+14	000
61	180-03	300-05	100+18	100+18	719+03	557-01	-207+01	300+03	100-03	868-10	752-08	-105+00	144+11	117+14	000
63	186-03	300-05	100+18	100+18	899+03	109-02	-207+01	300+03	100-03	751-10	647-13	000	144+11	102+14	000
65	192-03	300-05	100+18	100+18	105+04	445-04	-207+01	300+03	100-03	650-10	283-13	000	144+11	885+13	000
67	198-03	300-05	100+18	100+18	119+04	245-04	-207+01	300+03	100-03	561-10	182-12	-105+00	144+11	769+13	000
69	204-03	300-05	100+18	100+18	130+04	241-04	-207+01	300+03	100-03	485-10	193-12	000	144+11	668+13	000
71	210-03	300-05	100+18	100+18	141+04	241-04	-207+01	300+03	100-03	419-10	191-12	000	144+11	582+13	000
73	216-03	300-05	100+18	100+18	157+04	241-04	-207+01	300+03	100-03	361-10	140-12	000	144+11	507+13	000
75	222-03	300-05	100+18	100+18	163+04	241-04	-207+01	300+03	100-03	310-10	295-13	-105+00	144+11	443+13	000
77	228-03	300-05	100+18	100+18	169+04	241-04	-207+01	300+03	100-03	266-10	165-12	000	144+11	388+13	000
79	234-03	300-05	100+18	100+18	173+04	241-04	-207+01	300+03	100-03	228-10	728-13	000	144+11	341+13	000
81	240-03	300-05	100+18	100+18	177+04	241-04	-207+01	300+03	100-03	194-10	115-12	-105+00	144+11	301+13	000
83	246-03	300-05	100+18	100+18	181+04	241-04	-207+01	300+03	100-03	164-10	115-12	-105+00	144+11	267+13	000
85	252-03	300-05	100+18	100+18	183+04	241-04	-207+01	300+03	100-03	138-10	148-12	000	144+11	239+13	000
87	258-03	300-05	100+18	100+18	186+04	241-04	-207+01	300+03	100-03	114-10	174-12	000	144+11	216+13	000
89	264-03	300-05	100+18	100+18	188+04	241-04	-207+01	300+03	100-03	92-11	166-12	-105+00	144+11	197+13	000
91	270-03	300-05	100+18	100+18	189+04	241-04	-207+01	300+03	100-03	73-11	883-13	000	144+11	182+13	000
93	276-03	300-05	100+18	100+18	189+04	241-04	-207+01	300+03	100-03	556-11	140-12	-105+00	144+11	171+13	000
95	282-03	300-05	100+18	100+18	190+04	241-04	-207+01	300+03	100-03	389-11	199-12	000	144+11	164+13	000
97	288-03	300-05	100+18	100+18	191+04	240-04	-207+01	300+03	100-03	230-11	559-13	000	144+11	160+13	000
99	294-03	300-05	100+18	100+18	191+04	208-04	-207+01	300+03	100-03	762-12	266-13	-105+00	144+11	159+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

DATE 061775

TIME 114554

TRANSIENT DATA

T	TIME	DTIME	DHOLM	DELEM	DEM	DTEMP	PIBM	PIVIN	TEMPM	CIM	QSGR	CDISM	VORIAS
0	0.000	100-07	.000	.000	.000	.000	-.619+17-	1.00+01	300+03	1.44+11	.000	.355+05	-.339190857-01
2	2.225-07	149-07	107+16	234+15	590+03	113-01	-.210+00	1.62-04	301+03	1.48+11	.116+02	.213+02	-.827784654-01
4	5.53-07	223-07	212+13	359+13	175+01	-.830-02	-.419+00	3.63-04	301+03	1.48+11	-.432+04	.184+03	-.828408063-01
6	1.05-06	333-07	317+13	354+13	262+01	118-01	314+00	5.12-04	301+03	1.48+11	-.182+04	.321-03	-.429086681-01
8	1.79-06	491-07	474+13	525+13	391+01	164-01	210+00	7.62-04	301+03	1.48+11	-.787+03	.632-03	-.430100011-01
10	2.69-06	743-07	709+13	777+13	584+01	220-01	210+00	1.14-03	301+03	1.48+11	-.341+03	.134-02	-.831613158-01
12	4.58-06	111-06	106+14	113+14	872+01	282-01	210+00	1.60-03	301+03	1.48+11	-.150+03	.295-02	-.833847252-01
14	7.01-06	167-06	159+14	169+14	130+02	373-01	210+00	2.03-03	300+03	1.47+11	-.650+02	.663-02	-.837247390-01
16	1.01-05	247-06	238+14	248+14	190+02	370-01	210+00	2.06-03	300+03	1.47+11	-.284+02	.150-01	-.442882063-01
18	1.62-05	369-06	357+14	366+14	290+02	370-01	210+00	2.06-03	300+03	1.47+11	-.124+02	.338-01	-.449820603-01
20	2.44-05	551-06	535+14	541+14	434+02	329-01	105+00	2.06-03	300+03	1.46+11	-.545+01	.759-01	-.461080107-01
22	3.66-05	823-06	802+14	805+14	647+02	266-01	314+00	2.11-03	300+03	1.46+11	-.240+01	.169+00	-.477918610-01
24	5.49-05	123-05	120+15	120+15	966+02	203-01	210+00	2.21-03	300+03	1.46+11	-.105+01	.375+00	-.503111957-01
26	8.22-05	164-05	181+15	180+15	144+03	158-01	210+00	2.33-03	300+03	1.45+11	-.452+00	.826+00	-.540826228-01
28	1.23-04	274-05	272+15	271+15	215+03	126-01	419+00	2.95-03	300+03	1.45+11	-.190+00	.181+01	-.597330183-01
30	1.64-04	409-05	410+15	410+15	321+03	103-01	314+00	2.95-03	300+03	1.45+11	-.751-01	.393+01	-.682093222-01
32	2.75-04	611-05	621+15	621+15	479+03	785-02	210+00	3.77-03	300+03	1.45+11	-.879-03	.176+02	-.809485801-01
34	4.11-04	913-05	946+15	946+15	712+03	407-02	524+00	5.63-03	300+03	1.45+11	-.243-01	.842+01	-.809485801-01
36	6.14-04	136-04	145+16	145+16	106+04	204-01	210+00	1.06-02	300+03	1.45+11	.116-01	.348-02	-.129111102+00
38	9.17-04	204-04	220+16	220+16	155+04	894-01	419+00	2.53-02	300+03	1.46+11	.201-01	.622+02	-.172734885+00
40	1.37-03	304-04	318+16	318+16	217+04	262+00	210+00	3.24-03	301+03	1.50+11	.269-01	.120+03	-.230633938+00
42	2.04-03	454-04	375+16	375+16	254+04	629-01	524+00	3.41-03	301+03	1.58+11	.273-01	.212+03	-.318444006+00
44	3.05-03	676-04	345+16	345+16	241+04	320-01	210+00	6.33-03	301+03	1.59+11	.411-03	.251+03	-.401622437+00
46	4.56-03	1.01-03	333+16	333+16	284+04	472+00	629+00	1.06-02	302+03	1.67+11	.783-02	.362+03	-.48505348+00
48	6.61-03	1.51-03	343+16	342+16	300+04	738+00	314+00	1.64-02	304+03	1.84+11	.707-02	.422+03	-.584977590+00
50	1.02-02	226-03	299+16	298+16	300+04	443+00	210+00	1.18-02	305+03	1.97+11	.273-02	.399+03	-.813785493+00
52	1.52-02	337-03	341+16	341+16	300+04	443+00	314+00	1.18-02	305+03	1.97+11	.273-02	.399+03	-.813785493+00
54	2.27-02	503-03	394+16	393+16	299+04	102+00	210+00	2.98+03	305+03	1.92+11	.157-02	.200+03	-.936778590+00
56	3.39-02	752-03	408+16	408+16	283+04	585+00	210+00	3.06+03	304+03	1.92+11	.157-02	.200+03	-.936778590+00
58	5.06-02	1.12-02	332+16	332+16	223+04	111+01	524+00	6.70+03	302+03	1.66+11	-.426-02	.133+03	-.116832100+01
60	7.55-02	1.68-02	176+16	177+16	120+04	843+00	419+00	1.34-02	300+03	1.48+11	-.704-02	.450+02	-.123563521+01
62	1.13-01	250-02	299+15	300+15	205+03	870-01	314+00	2.03-02	300+03	1.44+11	-.246-01	.142+01	-.125474149+01
64	1.68-01	374-02	500+13	500+13	344+01	327-03	210+00	2.27-02	300+03	1.44+11	-.666-03	.970-08	-.125561640+01
66	2.31-01	558-02	178+10	178+10	105-02	893-05	419+00	2.37-02	300+03	1.44+11	.666-03	.970-08	-.125561640+01
68	3.75-01	833-02	173+08	173+08	118-04	130-08	314+00	2.45-02	300+03	1.44+11	.666-03	.970-08	-.125561640+01
70	5.01-01	1.24-01	161+05	161+05	111-07	115-12	210+00	2.50-02	300+03	1.44+11	-.246-01	.142+01	-.125561640+01
72	8.37-01	1.56-01	149+03	149+03	242-09	517-15	210+00	2.53-02	300+03	1.44+11	-.666-03	.970-08	-.125561640+01
74	1.25+00	278-01	262+04	262+04	137-08	517-15	210+00	2.56-02	300+03	1.44+11	.151-13	.796-08	-.125561640+01
76	1.67+00	414-01	253+04	253+04	136-08	517-15	210+00	2.59-02	300+03	1.44+11	.101-13	.796-08	-.125561640+01
78	2.79+00	619-01	242+04	242+04	165-08	517-15	210+00	2.59-02	300+03	1.44+11	.101-13	.796-08	-.125561640+01
80	4.10+00	924-01	271+04	271+04	146-08	517-15	210+00	2.59-02	300+03	1.44+11	.678-14	.719-08	-.125561640+01
82	6.22+00	1.38+00	846+03	846+03	489-09	517-15	210+00	2.60-02	300+03	1.44+11	.454-14	.145-07	-.125561640+01
84	9.28+00	2.08+00	267+04	267+04	143-08	517-15	210+00	2.60-02	300+03	1.44+11	.454-14	.145-07	-.125561640+01
86	1.39+01	3.05+00	624+03	624+03	443-09	517-15	210+00	2.61-02	300+03	1.44+11	.204+14	.155-07	-.125561640+01
88	2.07+01	4.59+00	413+03	400+03	222-09	517-15	210+00	2.61-02	300+03	1.44+11	.136+14	.779-08	-.125561640+01
90	3.03+01	6.82+00	292+04	582+03	135-08	517-15	210+00	2.61-02	300+03	1.44+11	.914-15	.805-08	-.125561640+01
92	4.02+01	1.02+01	245+04	222+04	132-08	517-15	210+00	2.61-02	300+03	1.44+11	.612-15	.229-08	-.125561640+01
94	6.05+01	1.53+01	269+04	500+03	144-08	517-15	210+00	2.61-02	300+03	1.44+11	.410-15	.728-08	-.125561640+01
96	1.03+02	2.28+01	869+03	243+04	123-08	517-15	210+00	2.61-02	300+03	1.44+11	.274-15	.237-07	-.125561640+01
98	1.35+02	3.41+01	566+03	213+04	102-08	517-15	210+00	2.61-02	300+03	1.44+11	.184-15	.731-08	-.125561640+01
100	2.29+02	5.09+01	4.87+03	634+03	313-09	517-15	210+00	2.61-02	300+03	1.44+11	.123-15	.752-08	-.125561640+01

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

TABLE B.2

SYMBOL DEFINITIONS FOR SIMULATION SUMMARY

<u>Name</u>	<u>Definition</u>
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	Poisson 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)

<u>Name</u>	<u>Definition</u>
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

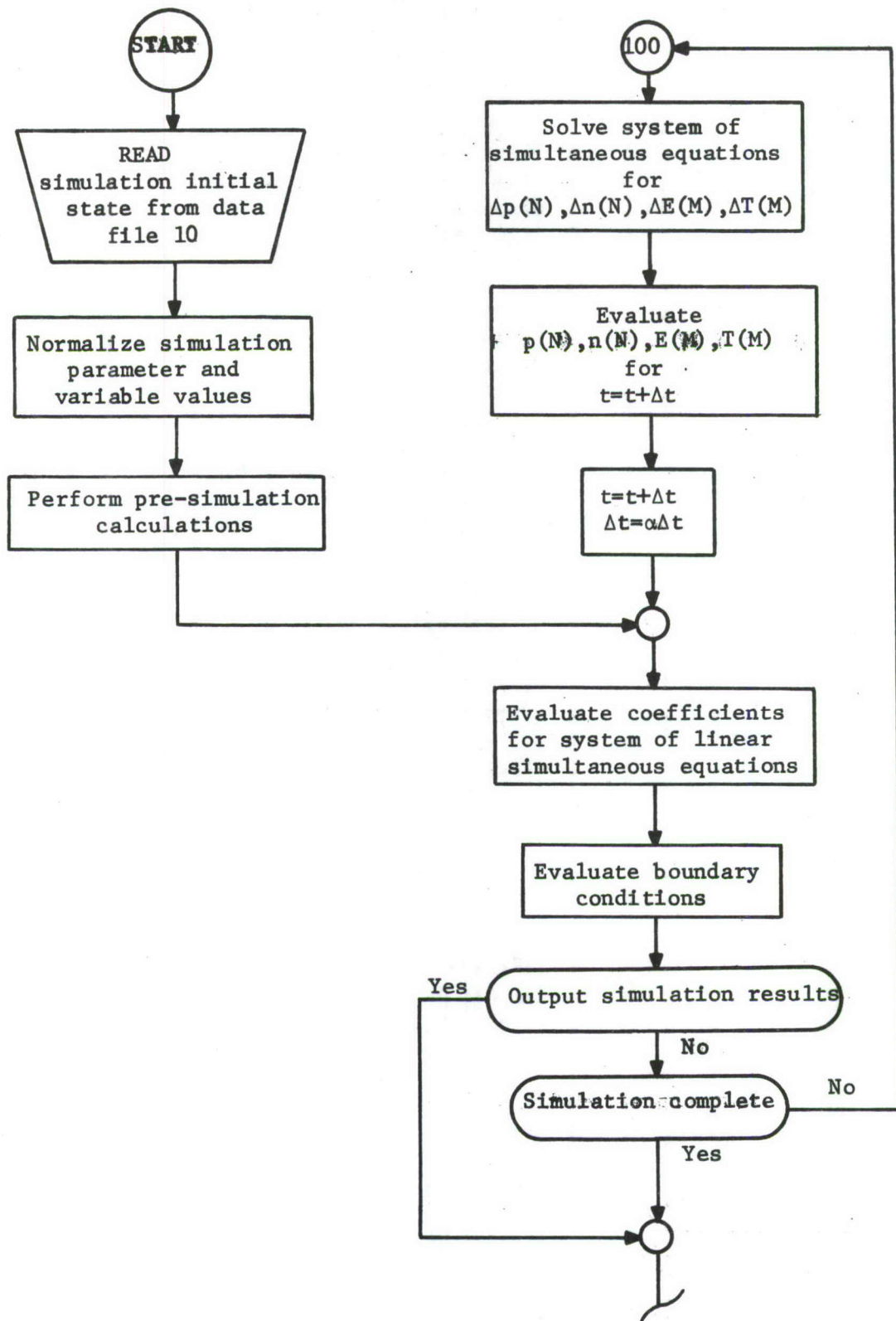


Fig. B.9. Flow Chart for Program COMP

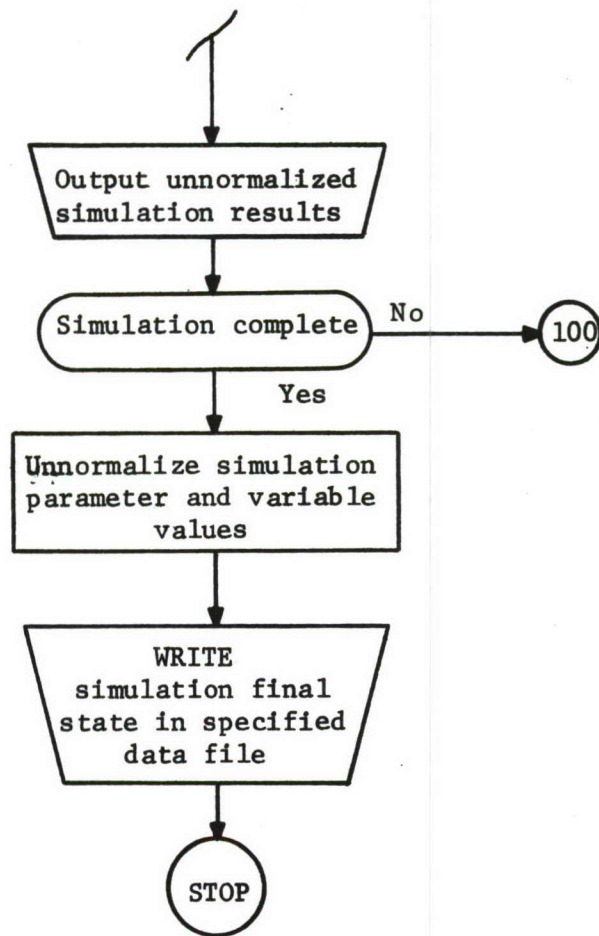


Fig. B.9. (Continued) Flow Chart for Program COMP

```

1 C***** COMP *****
2 C
3 C SIMULATES A ONE-DIMENSIONAL TWO CONTACT SEMICONDUCTOR
4 C DEVICE FOR CONSTANT CURRENT EXCITATION. IMPURITY
5 C PROFILE IS ARBITRARY EXCEPT FOR THE SPECIFIED TERMINAL
6 C MATERIAL TYPES (X=0, N-TYPE AND X=XL, P-TYPE) AND
7 C TEMPERATURE IS OPTIONALLY INCLUDED AS A DEPENDENT
8 C VARIABLE. MOBILITIES ARE IMPURITY, E-FIELD, AND
9 C TEMPERATURE DEPENDENT; WHEREAS, IONIZATION COEFFICIENTS
10 C ARE E-FIELD, AND TEMPERATURE DEPENDENT, BOTH BEING
11 C FORMULATED FOR SILICON.
12 C
13 C INITIAL STATE VALUES ARE READ FROM DATA FILE
14 C 10 WHICH CAN BE INTERACTIVELY GENERATED BY PROGRAM
15 C DS. COMP IS EXECUTED IN A BATCH MODE AND WRITES THE
16 C THE RESULTING STATE ON THE OUTPUT DATA FILE SPECIFIED
17 C IN DATA FILE 10. OPTIONALLY, ADDITIONAL DATA IS
18 C WRITTEN IN DATA FILES 7, AND 8.
19 C
20 C TECH: SINGLE ITERATION QUASILINEARIZATION
21 C UNKS: E-FIELD, HOLE AND ELECTRON CONCENTRATIONS, TEMPERATURE
22 C BND: X=0, N-SIDE
23 C 1) TERMINAL E-FIELD EQUAL ZERO
24 C 2) TERMINAL MAJ. CAR. DIFF. CUR. EQUAL TOTAL CUR.
25 C 3) TERMINAL TEMPERATURE EQUAL TEMPO
26 C X=XL, P-SIDE
27 C 1) TERMINAL TEMPERATURE EQUAL TEMPO
28 C 2) TERMINAL MAJ. CAR. DIFF. CUR. EQUAL TOTAL CUR.
29 C OR
30 C 2) THERMAL EQUILIBRIUM CAR. CONCS. (OHMIC CONTACT)
31 C TIME: GEOMETRIC IN 'FDTMUL'(FDTMUL=1, CONST. TIME STEP)
32 C
33 C
34 C IMPLICIT DOUBLE PRECISION (A-H,O-Z)
35 C INTEGER P,PM1,T,TMAX,RCMPB,P4,P4M8
36 C INTEGER TLINC,TSINC
37 C
38 C COMMON /INTRIN/ CBEDS,VBEDS,ENGAP
39 C COMMON /NORM/ XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
40 C COMMON /PHYCON/ Q,BOZ,PERM
41 C COMMON /GIONN/ GIPNMM,GINNMM,GIENM,GITNM,GINM,GIPN,GIN,GINN,GINP,G
42 C 1IPNPP,GINNPP,GIENP,GITNP
43 C COMMON /JPNP/ CPNP,CPNPM,CPNPP,CPENP,CPTNP
44 C COMMON /JNNP/ CNNP,CNNPM,CNNPP,CNENP,CNTNP
45 C COMMON /JPNM/ CPNM,CPNMM,CPNMP,CPENM,CPTNM
46 C COMMON /JNNM/ CNNM,CNNMM,CNNMP,CNENM,CNTNM
47 C COMMON /TDATA/TIME,DT,DHOLM,DELEM,DEM,DTM,PIBM,PIVMIN,
48 C 1TEMPM,CIM,QSGR,CDISM,VDBIAS
49 C COMMON /VAR/XXN(101),DXN(101),DOPN(101),HOL(101),ELE(101),E(101),
50 C 1V(101),TEMP(101)
51 C COMMON /CURR/CURHOL(101),CURELE(101),CURDIS(101)
52 C COMMON /PARM/PIB(101),CI(101),GS(101),GI(101)
53 C
54 C DOUBLE PRECISION DXM(101)
55 C DOUBLE PRECISION HMOB(101),EMOB(101)
56 C DOUBLE PRECISION ALFAP(101),ALFAN(101)

```

Fig. B.10. Listing for Program COMP

```

57      DOUBLE PRECISION A(404,12),DELT(404)
58      DOUBLE PRECISION CTIME(99)
59      C
60      C      DOUBLE PRECISION B(404,12),ERROR(404)
61      C
62      C
63      DATA PERM,B0Z,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 (A6)
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

```

114 C WRITE-READ SIM. PARS.
115 C
116 C INCLUDE DSIMP
117 C INCLUDE DSIMPF
118 C I=I
119 C
120 C*****
121 C PRELIMINARY COMPUTATIONS
122 C*****
123 C
124 C SET NEW DATE AND TIME
125 C IDATE=IDATET
126 C ITIME=ITIMET
127 C
128 C GENERATE NORMALIZATION CONSTANTS
129 C CALL INTRI (CBEDS,VBEDS,ENGAP,TEMPO,CARINT)
130 C CALL NOR2 (LNORC,DIEL,TEMPO,CARINT,XN,TN,CARN,EN,CURN,VN,REC,N,MOB
131 C 1N,DIFN,TEMPN)
132 C
133 C NORMALIZE REQUIRED VALUES
134 C
135 C ARRAY NORMALIZATION
136 C DO 30 I=1,P
137 C XXN(I)=XXN(I)/XN
138 C DOPN(I)=DOPN(I)/CARN
139 C ELE(I)=ELE(I)/CARN
140 C HOL(I)=HOL(I)/CARN
141 C E(I)=E(I)/EN
142 C V(I)=V(I)/VN
143 C TEMP(I)=TEMP(I)/TEMPN
144 C 30 CONTINUE
145 C
146 C PARAMETER NORMALIZATION
147 C TAUN=TAUN/TN
148 C TAUP=TAUP/TN
149 C VAPP=VAPP/VN
150 C VDBI=VDBI/VN
151 C DT=DT/TN
152 C DX=DX/XN
153 C TTIME=TTIME/TN
154 C TIME=TIME/TN
155 C HOLMO=HOLMO/RMOH,N
156 C ELEMO=ELEMO/RMOH,N
157 C CURTOT=CURTOT/CURN
158 C ACCEPT=ACCEPT/CARN
159 C DONOR=DONOR/CARN
160 C XMET=XMET/XN
161 C TEMPO=TEMPO/TEMPN
162 C
163 C DO 40 I=1,NCS
164 C CTIME(I)=CTIME(I)/TN
165 C 40 CONTINUE
166 C
167 C PROGRAM CONSTANTS
168 C NNCS=1
169 C P4=P*4
170 C P4M8=P4-8

```

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


```

171      PM1=P-1
172      RTHETA=1.000/THETA
173      RTHEDT=RTHETA/DT
174      TEMPNM=TEMPO
175      TEMPNP=TEMPO
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)=0.5DU*(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*XXN*XXN)
199      EB3=TN*THCONH/(XDT*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 (P4MB,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)=0.000
222      DELT(2)=DELT(6)+BNDB
223      DELT(3)=0.000
224      DELT(4)=0.000
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(LP)=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. PARAMETER SUBS.
272  C
273      V(1)=0.000
274      CALL CUK (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,0.500,0.500,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      QGR=0.000
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=1.000/DXM(N)
294      TA=DXM(NM1)+DXM(N)
295      DXRNM=DXM(NM1)/TA
296      DXRNP=DXM(N)/TA
297      DOPM=(DOPN(N)+DOPN(NP1))/2.000
298      C
299      IF(NTHDEP.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)=0.000
325      A(LP,2)=-RDXN*CPPNMM-GIPNMM
326      A(LP,3)=-GINNMM
327      A(LP,4)=-RDXN*CPENM-GIENM
328      A(LP,5)=-GSTNM-GITNM-RDXN*CPTNM
329      A(LP,6)=-GSPN-RDXN*(CPPHMP-CPPNPM)-GIPN
330      A(LP,7)=-GSNN-GINN
331      A(LP,8)=+RDXN*CPENP-GIENP
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*CNNNMM-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)=0.000
349      A(LN,12)=GSN+RDXN*(CNNP-CNNM)+GIN
350
351      C
352      C COEFFS. FOR POISSON'S EQN. AT MAJOR NODE NO. N
353      A(LE,1)=0.000
354      A(LE,2)=-1.000
355      A(LE,3)=0.000
356      A(LE,4)=-DXN(N)
357      A(LE,5)=DXN(N)
358      A(LE,6)=1.000
359      A(LE,7)=0.000
360      A(LE,8)=0.000
361      A(LE,9)=0.000
362      A(LE,10)=0.000
363      A(LE,11)=0.000
364      A(LE,12)=E(NM1)-E(N)+DXN(N)*(HOL(N)-ELE(N)+DOPN(N))
365
366      C
367      C FINAL UPDATE OF ENERGY BALANCE EQUATION PARAMETERS
368      TA=EB1T/UXM(N)
369      EB1=TA/UXN(N)
370      EB2=TA/UXN(N+1)
371
372      C
373      C COEFFS. FOR ENERGY BALANCES EQN. AT MAJOR NODE (M)
374      TA=EB4*DABS(E(N))
375      A(LT,6)=EB1+EB2+EB3-TA*(ABSDER(CPNP,CPTNP)+ABSDER(CNNP,CNTNP))
376      IF(NTHDEP.NE.1) GO TO 158
377
378      C
379      A(LT,1)=0.000
380      A(LT,2)=-EB1
381      A(LT,3)=-TA*ABSDER(CPNP,CPNPM)
382      A(LT,4)=-TA*ABSDER(CNNP,CNNPM)
383      TB=DABS(CPNP)+DABS(CNNP)
384      A(LT,5)=-EB4*TB*ABSDER(E(N),1.000)-TA*(ABSDER(CPNP,CPENP)+ABSDER(C
385      1NNP,CNENP))
386      A(LT,7)=-TA*ABSDER(CPNP,CPNPP)
387      A(LT,8)=-TA*ABSDER(CNNP,CNNPP)
388      A(LT,9)=0.000
389      A(LT,10)=-EB2
390      A(LT,11)=0.000
391      A(LT,12)=EB1*(TEMP(NM1)-TEMP(N))+EB2*(TEMP(NP1)-TEMP(N))+EB3*(TEMP
392      10-TEMP(N))+TA*TB
393
394      C
395      C PARTIAL EVALUATION OF HEAT STORAGE AND GENERATION RATES
396      QSR=QSR+UXM(N)*DELT(LT+4)
397      QGR=QGR+UXM(N)*DABS(E(N))*TB
398      GO TO 159
399
400      C
401      158 CONTINUE
402      A(LT,1)=0.000
403      A(LT,2)=0.000
404      A(LT,3)=0.000

```

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

```

456 C
457 C ELECTRON CONTINUITY EQN.
458 A(2,5)=A(2,5)+A(2,1)
459 A(2,6)=A(2,6)+A(2,2)
460 A(2,12)=A(2,12)-A(2,2)*BNDB
461 C
462 C X=XL, P-SIDE CONTACT
463 C NTYBND=0 - CURRENT BND. COND., NTYBND=1 - OHMIC BND. COND.
464 IF (NTYBND.EQ.1) GO TO 180
465 C
466 LP=4*P-11
467 LN=LP+1
468 LE=LN+1
469 LT=LE+1
470 BNDC=-DXM(PM1)/HMOB(PM1)*CURTOT/TEMP(PM1)+(-HOL(P)+HOL(PM1))
471 C
472 C HOLE CONTINUITY EQN.
473 A(LP,6)=A(LP,6)+A(LP,10)
474 A(LP,7)=A(LP,7)+A(LP,11)
475 A(LP,12)=A(LP,12)-A(LP,10)*BNDC
476 C
477 C ELECTRON CONTINUITY EQN.
478 A(LN,5)=A(LN,5)+A(LN,9)
479 A(LN,6)=A(LN,6)+A(LN,10)
480 A(LN,12)=A(LN,12)-A(LN,9)*BNDC
481 C
482 C ENERGY BALANCE EQN.
483 A(LT,3)=A(LT,3)+A(LT,7)
484 A(LT,4)=A(LT,4)+A(LT,8)
485 A(LT,12)=A(LT,12)-A(LT,7)*BNDC
486 C
487 180 CONTINUE
488 C
489 C EVALUATION OF DIODE BIAS VOLTAGE
490 VDBIAS=v(P)-VDBI
491 C
492 C EVALUATE HEAT STORAGE / GENERATION RATIO
493 IF (NTHDEP.EQ.1) QSGR=QSR/QGR/EB4/DT
494 C
495 C*****
496 C DATA OUTPUT
497 C*****
498 C
499 IF (T.GE.TMAX.OR.TIME.GE.TTIME.OR.LIPEST.EQ.1) GO TO 185
500 IF (NCS.EQ.0.OR.NNCS.GT.NCS) GO TO 190
501 IF (TIME.LT.CSTIME(NNCS).OR.LCS.EQ.0.AND.LSCS.EQ.0) GO TO 190
502 NNCS=NNCS+1
503 C
504 185 CONTINUE
505 NCSYES=1
506 GO TO 200
507 190 CONTINUE
508 C
509 IF (T/TLINC*TLINC-T.EQ.0) GO TO 200
510 IF (T/TSINC*TSINC-T.NE.0.OR.LSCS.EQ.0) GO TO 100
511 C
512 200 CONTINUE

```

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

```

513 C
514 C DETERMINE MAXIMUM 'DELT' FOR HOL, ELE, E, TEMP
515     DHOLM=0.000
516     DELEM=0.000
517     DEM=0.000
518     DTM=0.000
519     DO 210 N=1,P
520     LP=1+4*(N-1)
521     LN=LP+1
522     LE=LN+1
523     LT=LE+1
524     IF (DABS(DELT(LP)).GT.DABS(DHOLM)) DHOLM=DELT(LP)
525     IF (DABS(DELT(LN)).GT.DABS(DELEM)) DELEM=DELT(LN)
526     IF (DABS(DELT(LE)).GT.DABS(DEM)) DEM=DELT(LE)
527     IF (DABS(DELT(LT)).GT.DABS(DTM)) DTM=DELT(LT)
528 210 CONTINUE
529 C
530 C EVALUATE POISSON EQN. IMBALANCE AND DISPLACEMENT CURRENT
531     PIBM=0.000
532     TEMPM=0.000
533     CIM=0.000
534     CURDIS(1)=CURTOT-CURHOL(1)-CURELE(1)
535     CDISM=CURDIS(1)
536     DO 230 N=2,PM1
537     PIB(N)=(E(N)-E(N-1))/DXN(N)-HOL(N)+ELE(N)-DOPN(N)
538     IF (DABS(PIB(N)).GT.DABS(PIRM)) PIRM=PIB(N)
539     CURDIS(N)=CURTOT-CURHOL(N)-CURELE(N)
540     IF (DABS(CURDIS(N)).GT.DABS(CDISM)) CDISM=CURDIS(N)
541     IF(TEMP(N).GT.TEMPM) TEMPM=TEMP(N)
542     IF(CI(N).GT.CIM) CIM=CI(N)
543 230 CONTINUE
544     CURDIS(P)=CURDIS(PM1)
545 C
546     IF (NCSYES.NE.1) GO TO 250
547 C
548 C WRITE AND/OR STORE DIODE CROSS SECTIONS
549     CALL CSOP(ITIME,T,TIME,LCS,LCSP1,LSCS,LSCSPI,P)
550 C
551 250 CONTINUE
552 C
553 C BIAS MINIMUM PIVOT VALUE
554     PIVMIN=PIVMIN-1.000
555 C
556 C WRITE AND/OR STORE TRANSIENT DATA
557     CALL TNDAP(T,TMAX,1TIME,TLINC,TSINC,LSCS,NCSYES)
558 C
559     LIPEST=0
560     NCSYES=0
561 C
562     IF(T.LT.TMAX.AND.TIME.LT.TTIME) GO TO 100
563 C
564 C*****
565 C SIMULATION COMPLETED
566 C*****
567 C
568 C WRITE EOF'S ON DATA FILES 7 AND 8
569     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 330 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      330 CONTINUE
584      C
585      C PARAMETER UNNORMALIZATION
586      TAUN=TAUN*TN
587      TAUP=TAUP*TN
588      VAPP=VAPP*VN
589      VDBI=VDBI*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

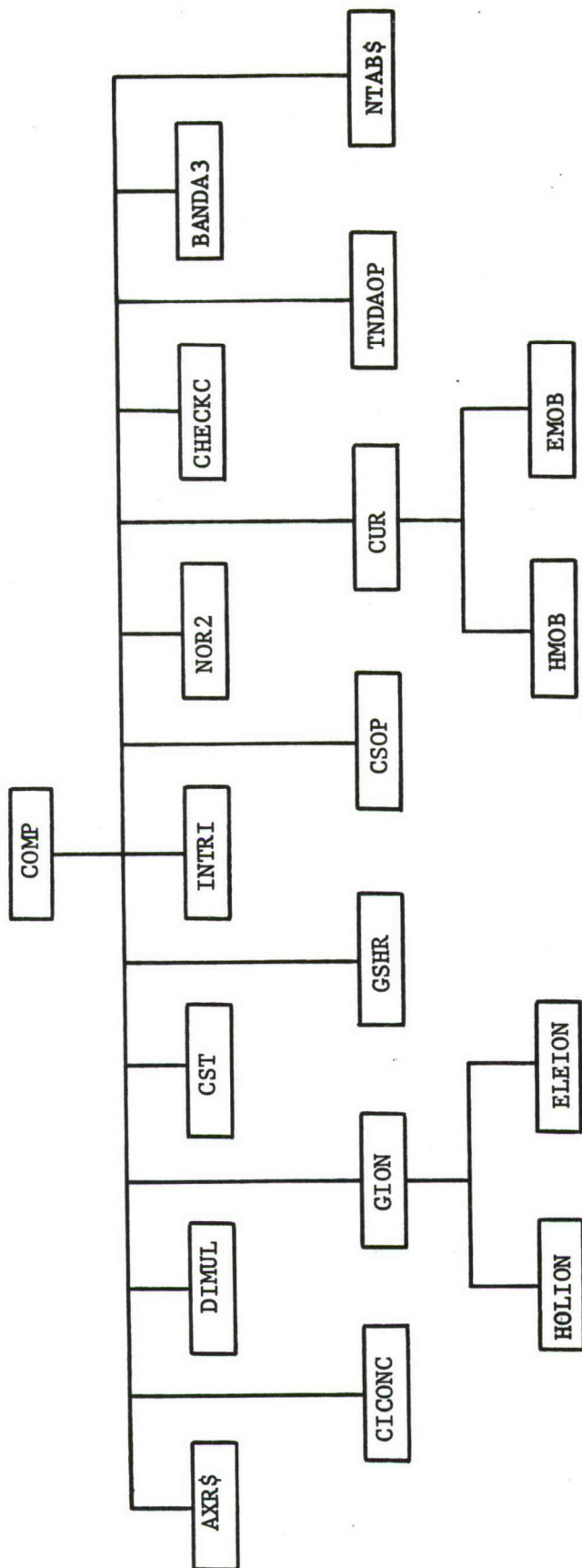


Fig. B.11. Subroutine Hierarchy for Program COMP

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.

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 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.

```

1      SUBROUTINE NOR2(L,DIEL,TEMPO,CARINT,XN,TN,CARN,EN,CURN,
2      1VN,RECN,MOBN,DIFN,TEMPN)
3      C
4      C EVALUATION OF NORMALIZATION CONSTANTS
5      C L.EQ.1, LISTING OF NORMALIZATION CONSTANTS IS GENERATED
6      C
7      C NORMALIZATION CONSTANT CODE
8      C XN=SPACIAL
9      C TN=TIME
10     C CARN=CARRIER
11     C EN=ELECTRIC FIELD
12     C CURN=CURRENT
13     C VN-VOLTAGE
14     C RECN=RECOMBINATION
15     C MOBN=MOBILITY
16     C DIFN=DIFFUSION
17     C TEMPN=TEMPERATURE
18     C
19     REAL*8 MOBN
20     DOUBLE PRECISION XN,TN,CARN,EN,CURN,VN,RECN,DIFN,TEMPN
21     DOUBLE PRECISION PERM,DIEL,BOZ,TEMPO,Q,TA,CARINT
22     C
23     C DIEL=DIELECTRIC CONSTANT
24     C TEMP=DEGREES KELVIN
25     C CARINT=INTRINSIC CARRIER CONC., 1/CM**3
26     C
27     PERM=8.854D-14          @ FARADS/CM, FREE SPACE PERM.
28     BOZ=1.381D-23          @ JOULS/DEGREE KELVIN, BOLTZ.
29     Q=1.6D-19              @ COULOMBS
30     C
31     DIFN=1.0D0              @ CM**2/SEC
32     CARN=CARINT             @ 1/CM**3
33     VN=BOZ*TEMPO/Q          @ VOLTS
34     MOBN=1.0D0/VN          @ CM**2/SEC/VOLT
35     TA=(PERM*DIEL*VN/Q/CARN) @ CM**2, TA=LD**2
36     TN=TA                   @ SEC, TN=LD**2/DO
37     XN=TA**0.5              @ CM, XN=LD
38     EN=VN/XN                @ VOLTS/CM
39     CURN=Q*CARN/XN          @ COULS/SEC/CM**2
40     RECN=CARN/TA            @ 1/SEC/CM**3
41     TEMPN=TEMPO             @ DEG. KEL.
42     C
43     IF(L.LT.1.0) GO TO 10
44     C
45     WRITE(6,5) PERM,BOZ,DIEL,TEMPO,CARINT
46     5 FORMAT('1 PROGRAM CONSTANTS'/
47     15X,'FREE SPACE PERMITTIVITY,',T35,'PERM=',T41,D23.18,' FARADS/CM'
48     2/,5X,'BOLTZMANN CONSTANT,',T35,'BOZ=',T41,D23.18,' JOULES/DEGREE
49     3KELVIN',//
50     4' PROGRAM PARAMETERS',/
51     55X,'DIELECTRIC CONSTANT,',T35,'DIEL=',T41,D23.18,' FOR SILICON'/
52     65X,'TEMPERATURE,',T35,'TEMPO=',T41,D23.18,' DEGREES KELVIN'/
53     75X,'INTRINSIC CARRIER CONC.',T35,'CARINT=',T41,D23.18,' 1/CM**3')
54     C
55     WRITE(6,8) XN,TN,CARN,EN,CURN,VN,RECN,MOBN,DIFN,TEMPN
56     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.')
```

C

```

67      10 RETURN
68      END
69
```

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


```

1      SUBROUTINE HOLION(AITS,E1,TEMP,AIPM,AIPEM,AIPTM)
2      C
3      C AITS - IONIZATION COEFF. THERMAL DEPENDENCE, 1/DEG. KEL.
4      C AIPM - HOLE IONIZATION COEFF. AT NODE (M)
5      C AIPEM - DERIVATIVE OF AIP WITH RESPECT TO E-FIELD
6      C AIPTM - DERIVATIVE OF AIP WITH RESPECT TO TEMPERATURE
7      C
8      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
9      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,REC,N,ROBN,DIFN,TEMPN
10     DATA HA,HB/2.25D7,3.26D6/
11     C
12     E=DABS(E1)
13     IF(E.LT.2.7D4) GO TO 15
14     IF(IFIT.NE.0) GO TO 10
15     A=XN*HA*(1.0D0+AITS*300.D0)
16     B=HB/EN
17     C=XN*HA*AITS*TEMPN
18     C
19     10  CONTINUE
20     TEXP=DEXP(-B/E)
21     AIPM=(A-C*TEMP)*TEXP
22     AIPEM=AIPM*B/E/E
23     AIPTM=-C*TEXP
24     C
25     IFIT=1
26     RETURN
27     C
28     15  CONTINUE
29     C
30     AIPM=0.0D0
31     AIPEM=0.0D0
32     AIPTM=0.0D0
33     C
34     RETURN
35     END

```

Fig. B.13. Listing for Subroutine HOLION

```

1      SUBROUTINE ELEION(AITS,E1,TEMP,AINM,AINEM,AINTM)
2      C
3      C AITS - IONIZATION COEFF. THERMAL DEPENDENCE, 1/DEG. KEL.
4      C AINM - ELECTRON IONIZATION COEFF. AT NODE (M)
5      C AINEM - DERIVATIVE OF AINM WITH RESPECT TO E-FIELD
6      C AINTM - DERIVATIVE OF AINM WITH RESPECT TO TEMPERATURE
7      C
8      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
9      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
10     DATA EA,EB/3.8D6,1.75D6/
11     C
12     E=DABS(E1)
13     IF(E.LT.1.7D4) GO TO 15
14     IF(IFIT.NE.0) GO TO 10
15     A=XN*EA*(1.0D0+AITS*300.D0)
16     B=EB/EN
17     C=XN*EA*AITS*TEMPN
18     C
19     10  CONTINUE
20     TEXP=DEXP(-B/E)
21     AINM=(A-C*TEMP)*TEXP
22     AINEM=AINM*B/E/E
23     AINTM=-C*TEXP
24     C
25     IFIT=1
26     RETURN
27     C
28     15  CONTINUE
29     C
30     AINM=0.0D0
31     AINEM=0.0D0
32     AINTM=0.0D0
33     C
34     RETURN
35     END

```

Fig. B.14. Listing for Subroutine ELEION

```

1      SUBROUTINE HMOB(DOP1,E1,TEMP,HMO,HMOE,HMOT)
2      C
3      C EVALUATES HOLE MOBILITY, E-FIELD DERIVATIVE AND
4      C TEMPERATURE DERIVATIVE AT NODE M
5      C
6      C IMPLICIT DOUBLE PRECISION (A-H,O-Z)
7      C COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
8      C
9      DATA HMOO,HN,HS,HA,HF,HB,ALFA/480.0D0,4.0D16,81.0D0,6.1D3,
10     11.6D0,2.5D4,2.3D0/
11      C
12      E=DABS(E1)
13      DOP=DABS(DOP1)
14      IF(IFIT.NE.0) GO TO 10
15      TA=RMOBN/HMOO*(TEMPN/300.0D0)**ALFA
16      TB=1.0D0/HS
17      TC=HN/CARN
18      TD=HA/EN
19      TE=HF*TD*TD
20      TF=(EN/HB)**2
21      C
22      10  CONTINUE
23      G=TA*TEMP**ALFA
24      GT=ALFA*G/TEMP
25      C
26      TG=1.0D0/(TD*E+TE)
27      ETE=E*E
28      H=1.0D0+DOP/(TB*DOP+TC)+(TG+TF)*ETE
29      HE=2.0D0*(TG+TF)*E-TG*TG*ETE*TD
30      C
31      HMO=1.0D0/(G*DSQRT(H))
32      HMOT=-GT*HMO/G
33      HMOE=-HE/(2.0D0*G*H**1.5D0)
34      C
35      IFIT=1
36      RETURN
37      END

```

Fig. B.15. Listing for Subroutine HMOB

```

1      SUBROUTINE EMOB(DOP1,E1,TEMP,EMO,EMOE,EMOT)
2      C
3      C EVALUATES ELECTRON MOBILITY, E-FIELD DERIVATIVE AND
4      C TEMPERATURE DERIVATIVE AT NODE M
5      C
6      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
7      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
8      C
9      DATA EM00,ENN,ES,EA,EF,EB,ALFA/1400.0D0,3.0D16,350.0D0,
10     13.5D3,8.8D0,7.4D3,2.5D0/
11     C
12     E=DABS(E1)
13     DOP=DABS(DOP1)
14     IF(IFIT.NE.0) GO TO 10
15     TA=RMOBN/EM00*(TEMPN/300.0D0)**ALFA
16     TB=1.0D0/ES
17     TC=ENN/CARN
18     TD=EA/EN
19     TE=EF*TD*TD
20     TF=(EN/EB)**2
21     C
22     10 CONTINUE
23     G=TA*TEMP**ALFA
24     GT=ALFA*G/TEMP
25     C
26     TG=1.0D0/(TD*E+TE)
27     ETE=E*E
28     H=1.0D0+DOP/(TB*DOP+TC)+(TG+TF)*ETE
29     HE=2.0D0*(TG+TF)*E-TG*TG*ETE*TD
30     C
31     EM0=1.0D0/(G*DSQRT(H))
32     EMOT=-GT*EM0/G
33     EMOE=-HE/(2.0D0*G*H**1.5D0)
34     C
35     IFIT=1
36     RETURN
37     END

```

Fig. B.16. Listing for Subroutine EMOB


```

1      SUBROUTINE TNDAOP(T,TMAX,ITIME,TLINC,TSINC,LSCS,NCSYES)
2
3      C
4      C   OUTPUTS TRANSIENT DATA ON UNIT 6 (PRINTER) AND ON
5      C   UNIT 8 (DATA FILE).  DATE IS WRITTEN ON UNIT 6 IN
6      C   BLOCKS OF 51/50 LINES THROUGH TEMPORARY ARRAY STORAGE.
7      C   OUTPUT INTERVALS ARE TLINC AND TSINC, RESPECTIVELY.
8      C
9      C   IMPLICIT DOUBLE PRECISION (A-H,O-Z)
10     COMMON /NORM/ XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
11     COMMON /TDATA/TIME,DT,DHOLM,DELEM,DEM,DTM,PIBM,PIVMIN,
12     1TEMPM,CIM,QSGR,CDISM,VDBIAS
13     INTEGER T,TMAX,TLINC,TSINC,TL(51)
14     REAL DL(51,13),D(13)
15
16     C
17     DATA NLLIM/51/
18
19     C
20     MS=TSINC
21     ML=TLINC
22     IF(MS.LE.0) MS=1000000
23     IF(ML.LE.0) ML=1000000
24
25     C
26     IS=T/MS*MS-T
27     IL=T/ML*ML-T
28
29     C
30     C   OUTPUT LINE OF DATA?
31     IF(IS.NE.0.OR.LSCS.EQ.0.AND.IL.NE.0.AND.NCSYES.NE.1) RETURN
32
33     C
34     C   UNNORMALIZED TRANSIENT DATA
35     D(1)=TIME*TN
36     D(2)=DT*TN
37     D(3)=DHOLM*CARN
38     D(4)=DELEM*CARN
39     D(5)=DEM*EN
40     D(6)=DTM*TEMPN
41     D(7)=PIBM*CARN
42     D(8)=PIVMIN
43     D(9)=TEMPM*TEMPN
44     D(10)=CIM*CARN
45     D(11)=QSGR
46     D(12)=CDISM*CURN
47     D(13)=VDBIAS*VN
48
49     C
50     C   WRITE DATA ON UNIT 8?
51     IF(IS.NE.0.AND.NCSYES.NE.1.OR.LSCS.NE.1) GO TO 15
52     WRITE(8,10) T,D
53     10   FORMAT(I15,13(/,E15.8))
54
55     C
56     15   CONTINUE
57
58     C
59     C   STORE DATA TO BE WRITTEN ON UNIT 6?
60     IF(IL.NE.0.AND.NCSYES.NE.1) RETURN
61     NL=NL+1
62
63     C
64     C   TRANSFER DATA TO TEMPORARY ARRAY STORAGE.
65     TL(NL)=T
66     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,'T',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

```

1      SUBROUTINE CSOP(ITIME,T,TIME,LCS,LCSPI,LSCS,LSCSPI,P)
2
3      C
4      C OUTPUTS DIODE CROSS SECTIONS ON UNIT 6 (PRINTER) AND
5      C ON UNIT 7 (DATA FILE). OUTPUT INTERVALS ARE LCSPI
6      C AND LSCSPI, RESPECTIVELY.
7      C
8      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
9      INTEGER T,P
10     COMMON /NORM/ XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
11     COMMON /VAR/XXN(101),DXN(101),DOPN(101),HOL(101),ELE(101),E(101),
12     1V(101),TEMP(101)
13     COMMON /CURR/CURHOL(101),CURELE(101),CURDIS(101)
14     COMMON /PARM/PIB(101),CI(101),GS(101),GI(101)
15
16     C
17     REAL UNTIME,D(15)
18
19     C
20     ML=LCSPI
21     MS=LSCSPI
22     IF(ML.LE.0) ML=1000000
23     IF(MS.LE.0) MS=1000000
24
25     C
26     C WRITE DATA FILE HEADER ON UNIT 7
27     UNTIME=TIME*TN
28     IF(LSCS.EQ.1) WRITE(7,10) T,UNTIME,P
29     10  FORMAT(I15/E15.8/I15)
30
31     C
32     TA=CARN/TN
33     K=0
34     KL=51
35     15  CONTINUE
36     K=K+1
37     IS=(K-1)/MS*MS-(K-1)
38     IL=(K-1)/ML*ML-(K-1)
39
40     C
41     C WRITE OR SKIP LINE OF DATA?
42     IF(IS.NE.0.AND.IL.NE.0.AND.K.LT.P) GO TO 15
43
44     C
45     C UNNORMALIZE AND WRITE DATA ON APPROPRIATE UNIT.
46     D(1)=XXN(K)*XN
47     D(2)=DXN(K)*XN
48     D(3)=DOPN(K)*CARN
49     D(4)=HOL(K)*CARN
50     D(5)=ELE(K)*CARN
51     D(6)=E(K)*EN
52     D(7)=V(K)*VN
53     D(8)=TEMP(K)*TEMPN
54     D(9)=CURHOL(K)*CURN
55     D(10)=CURELE(K)*CURN
56     D(11)=CURDIS(K)*CURN
57     D(12)=PIB(K)*CARN
58     D(13)=CI(K)*CARN
59     D(14)=GS(K)*TA
60     D(15)=GI(K)*TA
61
62     C
63     C WRITE DATA ON UNIT 7?
64     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


```

1      SUBROUTINE CICONC(DXRNM,DXRNP,TEMPMM,TEMPM,CIN,
2      1CITNM,CITNP)
3
4      C EVALUATES INTRINSIC CARRIER CONC. AT NODE N AND
5      C TEMPERATURE DERIVATIVE AT NODES M-1 AND M
6      C
7      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
8      COMMON /INTRIN/CBEDS,VBEDS,ENGAP
9      COMMON /NORM/XN,TN,CARN,EN,CURN,VN,RECN,RMOBN,DIFN,TEMPN
10     COMMON /PHYCON/Q,BOZ,PERM
11
12     C
13     IF(IFIT.NE.0) GO TO 10
14     A=1.0D0/CARN*DSQRT(CBEDS*VBEDS*(TEMPN/300.0D0)**3)
15     B=ENGAP*Q/(2.0D0*BOZ*TEMPN)
16
17     C
18     10 CONTINUE
19     CINM=A*TEMPMM**1.5*DEXP(-B/TEMPMM)
20     CINP=A*TEMPM**1.5*DEXP(-B/TEMPM)
21     TA=DXRNM*CINM
22     TB=DXRNP*CINP
23     CIN=TA+TB
24     CITNM=TA/TEMPMM*(1.5D0+B/TEMPMM)
25     CITNP=TB/TEMPM*(1.5D0+B/TEMPM)
26
27     C
28     IFIT=1
29     RETURN
30     END

```

Fig. B.19. Listing for Subroutine CICONC

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 1×10^{-6} direct evaluation is used, and if it is less than 1×10^{-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 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 diagonal system of linear equations which characterizes the numerical model developed in Section 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.

```

1      SUBROUTINE CUR(EXTCRI,DXMNP,DOPNP,HOLNN,HOLNP,ELENN,ELENP,
2      1ENP,TEMPNP,VNN,VNP,HMONP,EMONP)
3      C
4      C EVALUATION OF CURRENT COMPONENTS, CURRENT COMPONENT
5      C DERIVATIVES, AND DIODE VOLTAGE ABOUT NODE (N)
6      C SUB. MUST BE REF. FOR NODE N=1 TO INITIALIZE SYSTEM:
7      C DESIRED VALUES ARE THEN AVAILABLE ON SUBSEQUENT REFS.
8      C FOR N.GE.2
9      C
10     IMPLICIT DOUBLE PRECISION (A-H,O-Z)
11     COMMON /JPNP/CPNP,CPNPM,CPNPP,CPENP,CPTNP
12     COMMON /JNNP/CNNP,CNNPM,CNNPP,CNENP,CNTNP
13     COMMON /JPNM/CPNM,CPNMM,CPNMP,CPENM,CPTNM
14     COMMON /JNNM/CNNM,CNNMM,CNNMP,CNENM,CNTNM
15     C
16     C GENERATE NEW (M) MOBILITY COMPONENTS
17     C
18     CALL HMOB(DOPNP,ENP,TEMPNP,HMONP,HMOENP,HMOTNP)
19     CALL EMOB(DOPNP,ENP,TEMPNP,EMONP,EMOENP,EMOTNP)
20     C
21     C SHIFT CURRENT COMPONENTS: C(M-1)=C(M)
22     C
23     CPNM=CPNP
24     CPNMM=CPNPM
25     CPNMP=CPNPP
26     CPENM=CPENP
27     CPTNM=CPTNP
28     CNNM=CNNP
29     CNNMM=CNNPM
30     CNNMP=CNNPP
31     CNENM=CNENP
32     CNTNM=CNTNP
33     C
34     C GENERATE NEW (M) CURRENT COMPONENTS
35     C
36     TA=DXMNP*ENP
37     VNP=VNN-TA
38     TA=TA/TEMPNP
39     IF(DABS(TA).LT.EXTCRI) GO TO 10
40     C
41     C DIRECT EVALUATIONS
42     C
43     TA=DEXP(TA)
44     TB=1.0D0-1.0D0/TA
45     TA=1.0D0-TA
46     TC=HMONP*ENP
47     CPPNPP=TC/TA
48     CPPNPM=TC/TB
49     TC=EMONP*ENP
50     CNNNPP=TC/TB
51     CNNNPM=TC/TA
52     CPNP=CPPNPP*HOLNP+CPPNPM*HOLNN
53     CNNP=CNNNPP*ELENP+CNNNPM*ELENN
54     TA=DXMNP/TEMPNP
55     TB=TA*(HOLNP-HOLNN)/
56     1(1.0D0/CPNPM+1.0D0/CPNPP)

```

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=CNPN/ENP+TC+CNPN/EMONP*EMOENP
62      TD=ENP/TEMPNP
63      CPTNP=CPNP/HMONP*HMOTNP+TB*TD
64      CNTNP=CNPN/EMONP*EMOTNP-TB*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      CNPN=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=CNPN/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=CNPN/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

```

1      SUBROUTINE GION(AITS,DXRNM,DXRNP,ENP,TEMPNP,AIPNP,AINNP)
2      C
3      C GENERATION OF AVALANCHE IONIZATION FACTORS ABOUT NODE
4      C (N). WEIGHTING FACTORS DXRNM AND DXRNP HAVE BEEN
5      C INCORPORATED TO FACILITATE A NONUNIFORM SPACIAL GRID.
6      C SUB. MUST BE REF. FOR NODE N=1 TO INITIALIZE SYSTEM:
7      C DESIRED VALUES ARE THEN AVAILABLE ON SUBSEQUENT REFS.
8      C FOR N.GE.2
9      C
10     IMPLICIT DOUBLE PRECISION (A-H,O-Z)
11     COMMON /JPNP/CPNP,CPNPM,CPNPP,CPENP,CPTNP
12     COMMON /JNNP/CNNP,CNNPM,CNNPP,CNENP,CNTNP
13     COMMON /GIONN/GIPNMM,GINNMM,GIENM,GITNM,
14     1GINM,GIPN,GIN,GINN,GINP,GIPNP,
15     2GINNPP,GIENP,GITNP
16     C
17     ABSDER(F,DERF)=DSIGN(1.0D0,F)*DERF
18     C
19     IF(IFIT.EQ.0) TDXRNP=0.5D0
20     C
21     C GENERATE NEW (M) IONIZATION COEFFS.
22     C
23     CALL HOLION(AITS,ENP,TEMPNP,AIPNP,AIPEN,AIPTNP)
24     CALL ELEION(AITS,ENP,TEMPNP,AINNP,AINEN,AINTNP)
25     C
26     C SHIFT AND WEIGHT AVALANCHE FACTORS: GI(M-1)=GI(M)
27     C MODIFY WEIGHT FACTOR TO COMPENSATE FOR PREVIOUS WEIGHTING.
28     C
29     TDXRNM=DXRNM/TDXRNP
30     GINM=GINP*TDXRNM
31     GIPNMM=GIPNPM*TDXRNM
32     GIPNMP=GIPNPP*TDXRNM
33     GINNMM=GINNPM*TDXRNM
34     GINNMP=GINNPP*TDXRNM
35     GIENM=GIENP*TDXRNM
36     GITNM=GITNP*TDXRNM
37     C
38     C GENERATE NEW (NP) AVALANCHE FACTORS:
39     C
40     ABCPNP=DABS(CPNP)
41     ABCNNP=DABS(CNNP)
42     C
43     GINP=DXRNP*(AIPNP*ABCPNP+AINNP*ABCNNP)
44     GIPNPM=DXRNP*AIPNP*ABSDER(CPNP,CPNPM)
45     GIPNPP=DXRNP*AIPNP*ABSDER(CPNP,CPNPP)
46     GINNPM=DXRNP*AINNP*ABSDER(CNNP,CNNPM)
47     GINNPP=DXRNP*AINNP*ABSDER(CNNP,CNNPP)
48     GIENP=DXRNP*(ABCPNP*AIPENP+
49     1AIPNP*ABSDER(CPNP,CPENP)+ABCNNP*AINENP+
50     2AINNP*ABSDER(CNNP,CNENP))
51     GITNP=DXRNP*(ABCPNP*AIPNP+
52     1AIPNP*ABSDER(CPNP,CPTNP)+ABCNNP*AINNP+
53     2AINNP*ABSDER(CNNP,CNTNP))
54     C
55     GIN=GINM+GINP
56     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

```

1      SUBROUTINE GSHR(TAUP,TAUN,HOL,ELE,
2      1TEMPMM,TEMPM,CIN,CITNM,CITNP,
3      2G,GP,GN,GTNM,GTNP)
4      C
5      C EVALUATION OF SHOCKLEY-HALL-READ GENERATION-RECOMBINATION
6      C THROUGH MID-ENERGY-BAND-GAP GEN.-RECOMB. CENTERS, AND
7      C HOLE AND ELECTRON DERIVATIVES AT NODE (N) AND TEMPERATURE
8      C DERIVATIVES AT NODES (M-1) AND (M)
9      C
10     IMPLICIT DOUBLE PRECISION (A-H,O-Z)
11     C
12     TA=CIN+ELE
13     TB=CIN+HOL
14     TC=TAUN*TB+TAUP*TA
15     TD=TC*TC
16     TE=CIN*CIN-HOL*ELE
17     TF=(2.0D0*CIN*TC-(TAUP+TAUN)*TE)/TD
18     C
19     G=TE/TC
20     GP=-(TAUN*CIN+TAUP*ELE)*TA/TD
21     GN=-(TAUP*CIN+TAUN*HOL)*TB/TD
22     GTNM=TF*CITNM
23     GTNP=TF*CITNP
24     C
25     RETURN
26     END

```

Fig. B.22. Listing for Subroutine GSHR


```

1      SUBROUTINE BANDA3(LRMAX,NCD,NHD,LROW,LCOL,A,X,NBNDTX,PIVMIN)
2
3      C SUB. 'BANDAG' EVALUATES THE SOLUTION OF A BANDED
4      C (OR DIAGONAL) SYSTEM OF (LRMAX) LINEAR SIMULTANEOUS
5      C EQUATIONS THROUGH THE GAUSSIAN ELIMINATION TECHNIQUE.
6      C RESULTING 'A' ARRAY OF NO USE TO USER!
7
8      C P      - SOLUTION ARRAY LENGTH, INCLUDES UNKNOWN AND
9      C          BOUNDARY VALUES
10     C NCD    - COLUMN NUMBER OF CENTRAL DIAGONAL IN 'A'
11     C NHD    - COLUMN NUMBER FOR EQUATION CONSTANTS IN 'A'
12     C A      - COEFFICIENT AND CONSTANT ARRAY
13     C X      - SOLUTION ARRAY
14     C NBNDTX - NUMBER OF POSITIONS RESERVED FOR BND. VALUES AT TOP OF 'X' ARRAY
15     C LRMAX  - NUMBER OF EQUATIONS TO BE SOLVED SIMULTANEOUSLY
16     C NDB    - NUMBER OF COEFFICIENT DIAGONALS BELOW CENTRAL
17     C          (OR MAIN) DIAGONAL
18     C NDA    - NUMBER OF COEFFICIENT DIAGONALS ABOVE CENTRAL
19     C          (OR MAIN) DIAGONAL
20     C PIVMIN - MINIMUM PIVOT
21     C LROW   - ARRAY ROW DIMENSION
22     C LCOL   - ARRAY COLUMN DIMENSION
23
24     C          DOUBLE PRECISION TA,X(LROW),A(LROW,LCOL),ALFA,PIVMIN
25
26     C          NDB=NCD-1
27     C          NDA=NHD-NCD-1
28     C          PIVMIN=1.0D100
29
30     C UPPER TRIANGULATION OF ROWS (2)-(NDB)
31     IF(NDB.EQ.1) GO TO 20
32     DO 5 LR=2,NDB
33     LCOF=NDB+2-LR
34     DO 10 LCO=LCOF,NDB
35     ALFA=A(LR,LCO)/A(LR+LCO-NCD,NCD)
36     DO 15 LC=1,NDA
37     A(LR,LC+LCO)=A(LR,LC+LCO)-ALFA*A(LR+LCO-NCD,LC+NCD)
38     15 CONTINUE
39     A(LR,NHD)=A(LR,NHD)-ALFA*A(LR+LCO-NCD,NHD)
40     10 CONTINUE
41     5 CONTINUE
42
43     C          20 CONTINUE
44
45     C UPPER TRIANGULARIZATION OF ROWS (NDB+1)-(LRMAX)
46     DO 25 LR=NCD,LRMAX
47     C SEARCH FOR MINIMUM DIAGONAL PIVOT ELEMENT
48     TA=A(LR-NDB,NCD)
49     IF(DABS(TA).LT.DABS(PIVMIN)) PIVMIN=TA
50     DO 30 LCO=1,NDB
51
52     C          ALFA=A(LR,LCO)/A(LR+LCO-NCD,NCD)
53     C          DO 32 LC=1,NDA
54     C          A(LR,LC+LCO)=A(LR,LC+LCO)-ALFA*A(LR+LCO-NCD,LC+NCD)
55     C          32 CONTINUE
56     C          A(LR,NHD)=A(LR,NHD)-ALFA*A(LR+LCO-NCD,NHD)

```

Fig. B.23. Listing for Subroutine BANDA3

```

57      30      CONTINUE
58      25      CONTINUE
59      C
60      C BACK SUBSTITUTION FOR X(LRMAX)-X(LRMAX-NDA+1)
61          LRSTOP=LRMAX-NDA+1
62          DO 45 LR=LRMAX,LRSTOP,-1
63              TA=A(LR,NHD)
64              KK=LR+NBNDTX
65              KSTOP=LRMAX-LR
66              IF(KSTOP.EQ.0) GO TO 40
67              DO 35 K=1,KSTOP
68                  TA=TA-X(K+KK)*A(LR,K+NCD)
69      35      CONTINUE
70      40      CONTINUE
71          X(KK)=TA/A(LR,NCD)
72      45      CONTINUE
73      C
74      C BACK SUBSTITUTION FOR X(LRMAX-NDA)- X(NDB+1)
75          LRST=LRMAX-NDA
76          DO 55 LR=LRST,1,-1
77              KK=LR+NBNDTX
78              TA=A(LR,NHD)
79              DO 50 K=1,NDA
80                  TA=TA-X(K+KK)*A(LR,K+NCD)
81      50      CONTINUE
82          X(KK)=TA/A(LR,NCD)
83      55      CONTINUE
84      C
85      C
86          RETURN
87          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*   . (1)
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*    . (1)
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*    . (1)
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 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.

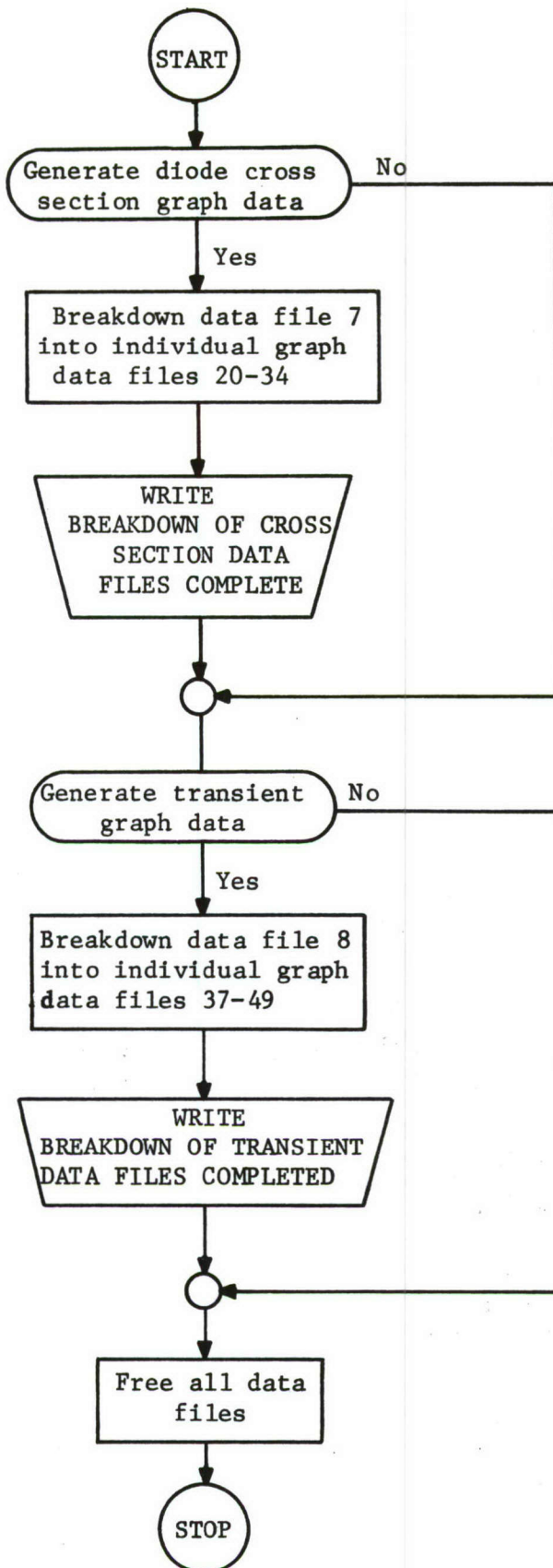


Fig. B.25. Flow Chart for Program GDG

```

1 C***** GRAPH DATA GENERATOR *****
2 C
3 C OPTIONAL BREAKDOWN OF CROSS SECTION AND/OR TRANSIENT DATA FILES
4 C (GENERATED BY 'COMP') INTO INDIVIDUAL GRAPH DATA FILES
5 C REQUIRED BY 'GRAPH'.
6 C
7     DIMENSION LFCS(15), LFT(13), XMIN(20), XMAX(20), W(210,15)
8 C
9 C     OUTPUT DATA FILE DIRECTORIES
10 DATA LFCS/20,21,22,23,24,25,26,27,28,29,30,31,32,33,34/
11 DATA LFT/37,38,39,40,41,42,43,44,45,46,47,48,49/
12 C
13 C     INITIALIZE NUMBER OF CROSS SECTIONS AND TRANSIENT OUTPUT DF.
14 DATA NCSDF,NTDF/15,13/
15 C
16 C     ASSIGN INPUT DATA FILES
17 CALL ERTRAN (6,'WASG,AX 7. . ') @ CROSS SECTIONS
18 CALL ERTRAN (6,'WASG,AX 8. . ') @ TRANSIENT
19 C
20 C     ASSIGN OUTPUT DATA FILES
21 C     CROSS SECTION OUTPUT DF (SPACIAL)
22 CALL ERTRAN (6,'WASG,AX 20. . ') @ XXN
23 CALL ERTRAN (6,'WASG,AX 21. . ') @ DXN
24 CALL ERTRAN (6,'WASG,AX 22. . ') @ DOPN
25 CALL ERTRAN (6,'WASG,AX 23. . ') @ HOL
26 CALL ERTRAN (6,'WASG,AX 24. . ') @ ELE
27 CALL ERTRAN (6,'WASG,AX 25. . ') @ E
28 CALL ERTRAN (6,'WASG,AX 26. . ') @ V
29 CALL ERTRAN (6,'WASG,AX 27. . ') @ TEMP
30 CALL ERTRAN (6,'WASG,AX 28. . ') @ CURHOL
31 CALL ERTRAN (6,'WASG,AX 29. . ') @ CURELE
32 CALL ERTRAN (6,'WASG,AX 30. . ') @ CURDIS
33 CALL ERTRAN (6,'WASG,AX 31. . ') @ Q
34 CALL ERTRAN (6,'WASG,AX 32. . ') @ CI
35 CALL ERTRAN (6,'WASG,AX 33. . ') @ GS
36 CALL ERTRAN (6,'WASG,AX 34. . ') @ GI
37 C
38 C     TRANSIENT OUTPUT DF (TEMPORAL)
39 CALL ERTRAN (6,'WASG,AX 37. . ') @ TIME
40 CALL ERTRAN (6,'WASG,AX 38. . ') @ DTIME
41 CALL ERTRAN (6,'WASG,AX 39. . ') @ DHOLM
42 CALL ERTRAN (6,'WASG,AX 40. . ') @ DELEM
43 CALL ERTRAN (6,'WASG,AX 41. . ') @ DEM
44 CALL ERTRAN (6,'WASG,AX 42. . ') @ DTEMPM
45 CALL ERTRAN (6,'WASG,AX 43. . ') @ PIBM
46 CALL ERTRAN (6,'WASG,AX 44. . ') @ PIVMIN
47 CALL ERTRAN (6,'WASG,AX 45. . ') @ TEMPM
48 CALL ERTRAN (6,'WASG,AX 46. . ') @ CIM
49 CALL ERTRAN (6,'WASG,AX 47. . ') @ GSGR
50 CALL ERTRAN (6,'WASG,AX 48. . ') @ CDISM
51 CALL ERTRAN (6,'WASG,AX 49. . ') @ VDBIAS
52 C
53     WRITE (6,20)
54 20     FORMAT ('GENERATE CROSS SECTION GRAPH DATA?, 1=YES')
55     READ (5,30) LGCSGD
56 30     FORMAT ( )

```

Fig. B.26. Listing for Program GDG

```

57      C
58      WRITE (6,40)
59      40  FORMAT (' GENERATE TRANSIENT GRAPH DATA?, 1=YES,')
60      READ (5,30) LGTGD
61      C-----
62      C    CREATE INDIVIDUAL SPACIAL DATA FILES
63      C-----
64      C    GENERATE CS GRAPH DATA?
65      IF (LGCSGD.NE.1) GO TO 180
66      C
67      C    READ DATE AND TIME
68      READ (7,50) IDATE,ITIME
69      50  FORMAT (A6)
70      C
71      C    WRITE DATE AND TIME ON CS DATA FILES?
72      DO 60 K=1,NCSDF
73      KK=LFCS(K)
74      WRITE (KK,50) IDATE,ITIME
75      60  CONTINUE
76      C
77      70  CONTINUE
78      C    INITIALIZE MINIMUMS AND MAXIMUMS
79      DO 80 K=1,NCSDF
80      XMIN(K)=1.0E20
81      XMAX(K)=-1.0E20
82      80  CONTINUE
83      C
84      C    READ CROSS SECTION
85      READ (7,90,END=150) NT,TIME,NP
86      90  FORMAT (I15,/,E15.8,/,I15)
87      READ (7,100,END=150) (IBLANK,(W(J,K),K=1,NCSDF),J=1,NP)
88      100 FORMAT (I15,/, (E15.8))
89      C
90      C    EVALUATE NET CHARGE, MINS AND MAXS
91      DO 120 J=1,NP
92      W(J,12)=W(J,4)-W(J,5)+W(J,3)
93      DO 110 K=1,NCSDF
94      XMIN=AMIN1(XMIN,X)
95      XMAX=AMAX1(XMAX,X)
96      110  CONTINUE
97      120  CONTINUE
98      C
99      TNP=NP
100     C
101     C    WRITE NP, CS, TIME, MIN, AND MAX ON OUTPUT DF
102     DO 140 K=1,NCSDF
103     KK=LFCS(K)
104     WRITE (KK,130) TNP,(W(J,K),J=1,NP),TIME,XMIN(K),XMAX(K)
105     130  FORMAT (E15.8)
106     140  CONTINUE
107     C
108     C    TRANSFER NEXT CROSS SECTION
109     GO TO 70
110     C
111     150  CONTINUE
112     C    EOF REACHED. ON FILE 7., WRITE EOF ON FILES 20.-36.
113     DO 160 K=1,NCSDF

```

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

```

114         KK=LFC(S(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 8., 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. . ')	@ VDBIAS
235		
236	C	STOP
237		END

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

TABLE B.3

GRAPH CODES FOR PROGRAM GRAPH

<u>Graph Code</u>	<u>Graph</u>	<u>Graph Data File Number</u>	<u>Variable</u>
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	$\Delta x_N *x$	31	Q
DOPX	$N_I *x$	32	N_i
QX	$Q*x$	33	G_{SRH}
CIX	$N_i *x$	34	G_I
GSX	$G_{SRH} *x$	37	t
GLX	$G_I *x$		
GSIX	$(G_{SRH} + G_I) *x$		
Transient Graph:			
VT	$V*t$		

TABLE B.3 (Continued)

<u>Graph Code</u>	<u>Graph</u>	<u>Graph Data File Number</u>	<u>Variable</u>
DTT	$\Delta t * t$	38	Δt
DPT	$\Delta p_{\max} * t$	39	$\Delta p_{\max}$
DNT	$\Delta n_{\max} * t$	40	$\Delta n_{\max}$
DPNT	$\Delta p_{\max}, \Delta n_{\max} * t$	41	$\Delta E_{\max}$
DET	$\Delta E_{\max} * t$	42	$\Delta T_{\max}$
DTEMT	$\Delta T_{\max} * t$	43	$PIB_{\max}$
TEMT	$T_{\max} * t$	44	PIV
QSGRT	$QSGR * t$	45	$T_{\max}$
JDT	$J_D * t$ $\max$	46	$N_{i \max}$
PIVT	$PIV * t$	47	GSGR
		48	$J_D_{\max}$
		49	V

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], in addition to the subroutines described below.

Subroutine NTAB\$

NTAB\$ is described in Appendix B.1.

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 Fig. 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 HEADER

HEADER generates a ledger for each graph consisting of the graph title, the numbers of the cross sections plotted, and 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.

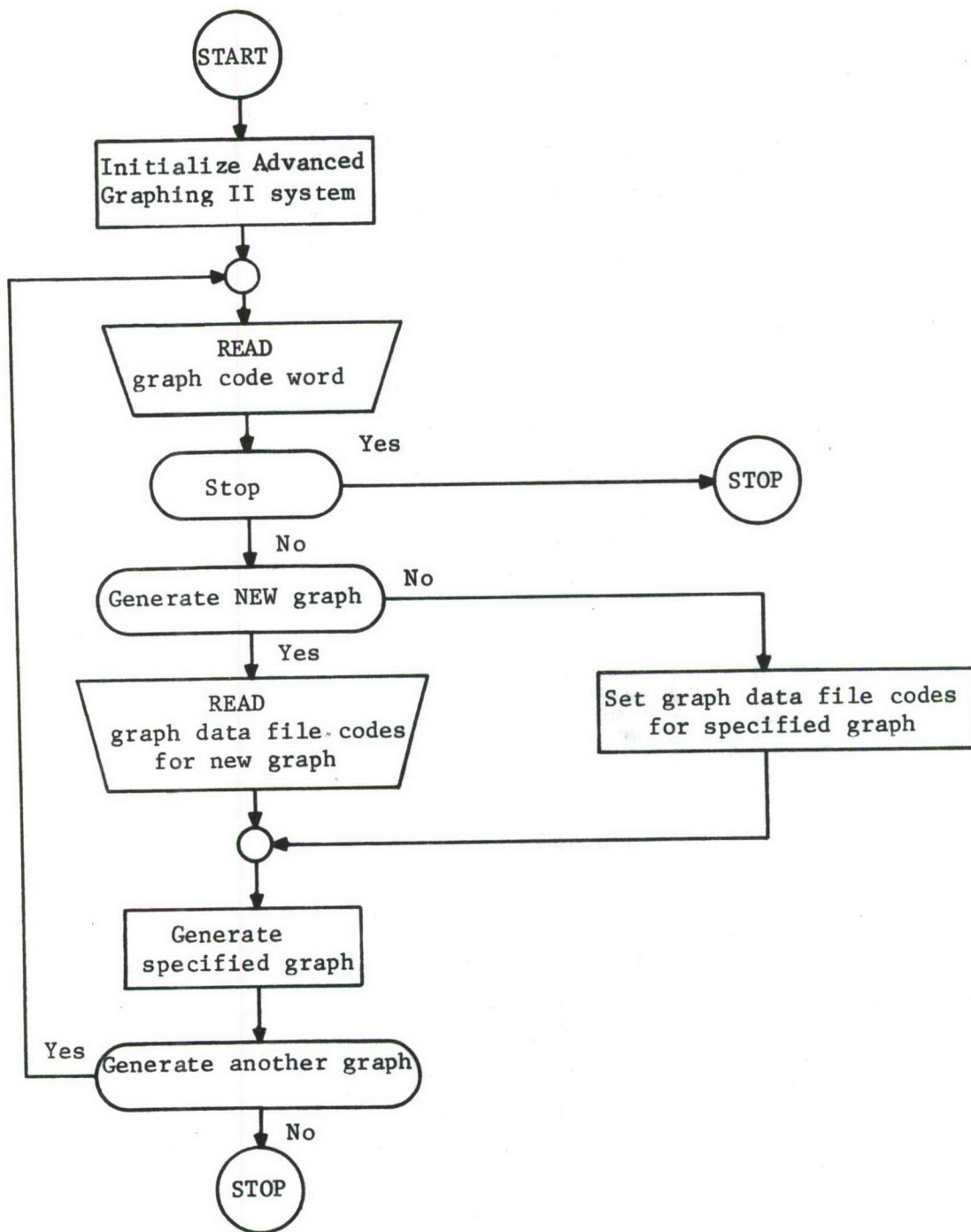


Fig. B.27. Flow Chart for Program GRAPH

```

1 C***** GRAPH *****
2 C
3 C INTERACTIVELY GRAPHS SIMULATION RESULTS ON A TEKTRONICS
4 C GRAPHICS TERMINAL.  REQUIRES INDIVIDUAL GRAPH DATA FILES
5 C GENERATED BY GDG (GRAPH DATA GENERATOR).
6 C
7     DIMENSION IRUN(3),KGC(12)
8     DIMENSION KGCODE(29),NU(4,29)
9     DIMENSION NSCS(35),CSTIME(35)
10    COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
11 C
12    DATA KONE/'000001'/KSTOP/'STOP'/
13    DATA IRUN(2)/' ' /KNFW/'NEW'/
14    DATA NGC/15/
15    DATA KGC/12*' ' /
16 C
17    DATA KGCODE/'PX','NX','PNX',
18    1'EX','TX','JPX','JNX',
19    2'JUX','JPNX','JPNDX',
20    3'VX','VT','DXX','DOPX','QX',
21    4'CIx','GSX','GIX','GSIX','DTT','DPT','DNT',
22    5'DPNT','DET','DIENT','TEMT','QSGRT','JDT','PIVT'/
23 C
24    DATA NU/20,23,0,0,20,24,0,0,
25    120,23,24,0,20,25,0,0,
26    220,27,0,0,20,28,0,0,
27    320,29,0,0,20,30,0,0,
28    420,28,29,0,20,28,29,30,
29    520,26,0,0,37,49,0,0,
30    620,21,0,0,20,22,0,0,
31    720,31,0,0,20,32,0,0,
32    820,33,0,0,20,34,0,0,
33    920,33,34,0,37,38,0,0,
34    137,39,0,0,37,40,0,0,
35    237,39,40,0,37,41,0,0,
36    337,42,0,0,37,45,0,0,
37    437,47,0,0,37,48,0,0,
38    537,44,0,0/
39 C
40 C ASSIGN DATA FILES
41    CALL ERTRAN (6,'WASG,AX 20. . ') @ XXN
42    CALL ERTRAN (6,'WASG,AX 21. . ') @ DXN
43    CALL ERTRAN (6,'WASG,AX 22. . ') @ DOPN
44    CALL ERTRAN (6,'WASG,AX 23. . ') @ HOL
45    CALL ERTRAN (6,'WASG,AX 24. . ') @ ELE
46    CALL ERTRAN (6,'WASG,AX 25. . ') @ E
47    CALL ERTRAN (6,'WASG,AX 26. . ') @ V
48    CALL ERTRAN (6,'WASG,AX 27. . ') @ TEMP
49    CALL ERTRAN (6,'WASG,AX 28. . ') @ CURHOL
50    CALL ERTRAN (6,'WASG,AX 29. . ') @ CURELE
51    CALL ERTRAN (6,'WASG,AX 30. . ') @ CURDIS
52    CALL ERTRAN (6,'WASG,AX 31. . ') @ Q
53    CALL ERTRAN (6,'WASG,AX 32. . ') @ CI
54    CALL ERTRAN (6,'WASG,AX 33. . ') @ GS
55    CALL ERTRAN (6,'WASG,AX 34. . ') @ GI
56 C

```

Fig. B.28. Listing for Program GRAPH


```

57      CALL ERTRAN (6,'WASG,AX 37. . ') @ TIME
58      CALL ERTRAN (6,'WASG,AX 38. . ') @ DTIME
59      CALL ERTRAN (6,'WASG,AX 39. . ') @ DHOLM
60      CALL ERTRAN (6,'WASG,AX 40. . ') @ DELEM
61      CALL ERTRAN (6,'WASG,AX 41. . ') @ DEM
62      CALL ERTRAN (6,'WASG,AX 42. . ') @ DTEMPM
63      CALL ERTRAN (6,'WASG,AX 43. . ') @ PIBM
64      CALL ERTRAN (6,'WASG,AX 44. . ') @ PIVMIN
65      CALL ERTRAN (6,'WASG,AX 45. . ') @ TEMPM
66      CALL ERTRAN (6,'WASG,AX 46. . ') @ CIM
67      CALL ERTRAN (6,'WASG,AX 47. . ') @ GSGR
68      CALL ERTRAN (6,'WASG,AX 48. . ') @ CDISM
69      CALL ERTRAN (6,'WASG,AX 49. . ') @ VDBIAS
70      C
71      C OBTAIN DATE AND TIME FROM DATA FILE 22
72      READ(22,2) IRUN(1),IRUN(3)
73      2   FORMAT(A6)
74      REWIND 22
75      C
76      C INITIALIZE ADVANCED GRAPHICS II SYSTEM
77      CALL INITT(30)
78      C
79      5   CONTINUE
80      C
81      C SPECIFY WHICH GRAPH
82      WRITE(6,10)
83      10  FORMAT(/,' WHICH GRAPH')
84      READ(5,15) KWG
85      15  FORMAT(A6)
86      C
87      DO 20 K=1,NGC
88      IF(KWG.NE.KGCODE(K)) GO TO 20
89      C
90      KGC(1)=KGCODE(K)
91      NUX=NU(1,K)
92      NUY1=NU(2,K)
93      NUY2=NU(3,K)
94      NUY3=NU(4,K)
95      GO TO 100
96      C
97      20  CONTINUE
98      C
99      C DEFINE NEW GRAPH COMBINATION
100     IF(KWG.NE.KNEW) GO TO 24
101     WRITE(6,21)
102     21  FORMAT(' ENTER GRAPH TITLE')
103     READ(5,30) KGC
104     30  FORMAT(12A6)
105     WRITE(6,22)
106     22  FORMAT(' SPECIFY NUX,NUY1,NUY2,NUY3')
107     READ(5,23) NUX,NUY1,NUY2,NUY3
108     23  FORMAT()
109     GO TO 100
110     C
111     24  CONTINUE
112     C
113     C TERMINATE XGT

```

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


```

114         IF(KWG.NE.KSTOP) GO TO 26
115         WRITE(6,27)
116 27      FORMAT(' ***** XOT 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

```

1      SUBROUTINE GENCUR(IFLAG,INEGY,NUX,NUY1,NUY2,NUY3,NSCS,TIME)
2      C
3      C SUB GENCUR LOADS APPROPRIATE DATA FROM DATA FILES,
4      C INTERACTIVELY UPDATES MINS. AND MAXS. AND DISPLAYS
5      C THE SUBSEQUENT CURVES. A MAX OF THREE DEPENDENT
6      C VARIABLES CAN BE PLOTTED. INDEPENDENT AND RESPECTIVE
7      C DEPENDENT VARIABLES STORED IN SEPARATE DATA FILES
8      C AS SPECIFIED IN ARG. LIST.
9      C
10     COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
11     DIMENSION TIME(1),NSCS(1)
12     C
13     C SUPPRESS GRID LINES
14     IG=2
15     CALL XFRM(IG)
16     CALL YFRM(IG)
17     C
18     C SELECT CROSS SECTIONS TO BE DISPLAYED
19     CALL SELCS(IFLAG,NSCS,NDEFCS)
20     C
21     C LOADING REQUIRED?
22     IF(IFLAG.NE.0.AND.NDEFCS.EQ.0) GO TO 235
23     C
24     C LOAD SPECIFIED CROSS SECTIONS
25     C
26     C READ DATE AND TIME SUCH AS TO SKIP
27     READ(NUX,213) IDATE,ITIME
28     IF(NUY1.NE.0) READ(NUY1,213) IDATE,ITIME
29     IF(NUY2.NE.0) READ(NUY2,213) IDATE,ITIME
30     IF(NUY3.NE.0) READ(NUY3,213) IDATE,ITIME
31     213  FORMAT(A6)
32     C
33     C INITIALIZE MINS. AND MAXS.
34     CALL INMIMA(XMIN,XMAX,YMIN,YMAX)
35     C
36     C INITIALIZE NUMBER OF CROSS SECTION TIMES SAVED
37     TIME(1)=NSCS(1)
38     C
39     K=1
40     JX=1
41     DO 230 I=1,99
42     IF(NSCS(K+1).NE.I) GO TO 225
43     C
44     C LOAD CROSS SECTION AND UPDATE MINS. AND MAXS.
45     CALL LOAD(INEGY,IEOF,NUX,X(JX),XTIME,TXMIN,TXMAX)
46     C
47     IF(IEOF.EQ.0) GO TO 214
48     NSCS(1)=K
49     TIME(1)=K
50     GO TO 233
51     214  CONTINUE
52     C
53     CALL SMIMA(XMIN,TXMIN,XMAX,TXMAX)
54     CALL LOAD(INEGY,IEOF,NUY1,Y1(JX),Y1TIME,TYMIN,TYMAX)
55     CALL SMIMA(YMIN,TYMIN,YMAX,TYMAX)
56     IF(NUY2.NE.0) CALL LOAD(INEGY,IEOF,NUY2,Y2(JX),Y2TIME,TYMIN,TYMAX)

```

Fig. B.29. Listing for Subroutine GENCUR

```

57         IF(NUY2.NE.0) CALL SMIMA(YMIN,TYMIN,YMAX,TYMAX)
58         IF(NUY3.NE.0) CALL LOAD(INEGY,IEOF,NUY3,Y3(JX),Y3TIME,TYMIN,TYMAX)
59         IF(NUY3.NE.0) CALL SMIMA(YMIN,TYMIN,YMAX,TYMAX)
60     C
61     C CHECK CROSS SECTION COMPONENT CORRESPONDENCE
62         IF(XTIME.NE.Y1TIME) GO TO 217
63         IF(NUY2.NE.0.AND.XTIME.NE.Y2TIME) GO TO 217
64         IF(NUY3.NE.0.AND.XTIME.NE.Y3TIME) GO TO 217
65         GO TO 220
66     217  WRITE(6,215) XTIME
67     215  FORMAT(' ERROR: XTIME=',E15.8,', XTIME.NE.YTIME')
68         STOP
69     C
70     220  CONTINUE
71     C
72     C SAVE CROSS SECTION TIME, TIME(1)=NSCS(1)
73         TIME(K+1)=XTIME
74     C
75     C COMPUTE X AND Y POSITION OF NEXT CROSS SECTION
76         JX=JX+X(JX)+1
77     C
78     C ALL SPECIFIED CROSS SECTION LOADED?
79         IF(K.EQ.NSCS(1)) GO TO 233
80         K=K+1
81         GO TO 230
82     225  CONTINUE
83     C
84     C SKIP NEXT CROSS SECTION
85         CALL SKIP(NUX)
86         CALL SKIP(NUY1)
87         IF(NUY2.NE.0) CALL SKIP(NUY2)
88         IF(NUY3.NE.0) CALL SKIP(NUY3)
89     230  CONTINUE
90     C
91     233  CONTINUE
92         REWIND NUX
93         REWIND NUY1
94         IF(NUY2.NE.0) REWIND NUY2
95         IF(NUY3.NE.0) REWIND NUY3
96     C
97     235  CONTINUE
98     C
99     C SPECIFIED CROSS SECTIONS LOADED!
100    C DEFINE MINS. AND MAXS., WITHOUT CHANGING
101        CALL SPMIMA(XMIN,XMAX,YMIN,YMAX)
102    C LINEAR OR LOG Y-AXIS
103        CALL LILOY(INEGY,YMIN,YMAX,NSCS(1),NUY1,NUY2,NUY3,ILLY)
104    C
105    C LINEAR OR LOG X - AXIS
106        WRITE(6,237)
107    237  FORMAT(' 1-LINEAR, 2-LOG, X-AXIS SCALE')
108        READ(5,238) ILL
109    238  FORMAT()
110        CALL XTYPE(ILL)
111        CALL YTYPE(ILLY)
112    C
113    C GENERATE GRAPH

```

Fig. B.29. Listing for Subroutine GENCUR

```

114      C PLOT FIRST CROSS SECTION
115          CALL ERASE
116          CALL CHECK(X(1),Y1(1))
117          CALL DSPLAY(X(1),Y1(1))
118          IF(IG.LT.5) CALL FRAME
119          IF(NUY2.NE.0) CALL LINE(34)
120          IF(NUY2.NE.0) CALL CPLLOT(X(1),Y2(1))
121          IF(NUY3.NE.0) CALL LINE(52)
122          IF(NUY3.NE.0) CALL CPLLOT(X(1),Y3(1))
123      C
124          IF(NSCS(1).EQ.1) GO TO 245
125      C
126      C PLOT REMAINING CROSS SECTIONS
127          KK=NSCS(1)
128          JX=1
129          DO 240 K=2, KK
130              JX=JX+X(1)+1
131              CALL LINE(1)
132              CALL CPLLOT(X(JX),Y1(JX))
133              IF(NUY2.NE.0) CALL LINE(34)
134              IF(NUY2.NE.0) CALL CPLLOT(X(JX),Y2(JX))
135              IF(NUY3.NE.0) CALL LINE(52)
136              IF(NUY3.NE.0) CALL CPLLOT(X(JX),Y3(JX))
137      240      CONTINUE
138      245      CONTINUE
139      C
140          IFLAG=1
141      C
142          RETURN
143      END

```

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


```

1      SUBROUTINE LILOY(INEGY,YMIN,YMAX,INCS,NUY1,NUY2,NUY3,ILLY)
2      C
3      C SUB. LILOY PROVIDES LINEAR OR LOG Y-AXIS OPTION
4      C IF LOG OPTION REQUESTED, Y-AXIS DATA IS CONDITIONED
5      C ACCORDING TO SIGNS ASSOCIATED WITH YMIN AND YMAX
6      C
7      COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
8      C LINEAR OR LOG Y-AXIS SCALE
9      WRITE(6,5)
10     5   FORMAT(' 1-LINEAR, 2-LOG Y-AXIS SCALE')
11     READ(5,10) I
12     10  FORMAT()
13     C
14     C ABSOLUTE Y-AXIS PLOT
15     WRITE(6,11)
16     11  FORMAT(' 1-ABSOLUTE Y-AXIS PLOT')
17     READ(5,10) IABS
18     IF(IABS.NE.1) GO TO 14
19     C
20     9   CONTINUE
21     C GENERATE ABS VERSION OF DEPENDENT VARIABLE ARRAYS AND
22     C REEVALUATE YMIN AND YMAX
23     YMIN=1.0D20
24     YMAX=-1.0D20
25     NP=Y1(1)+1.5
26     DO 12 K=2,NP
27     Y1(K)=ABS(Y1(K))
28     YMIN=AMIN1(YMIN,Y1(K))
29     YMAX=AMAX1(YMAX,Y1(K))
30     IF(NUY2.LE.0) GO TO 12
31     Y2(K)=ABS(Y2(K))
32     YMIN=AMIN1(YMIN,Y2(K))
33     YMAX=AMAX1(YMAX,Y2(K))
34     IF(NUY3.LE.0) GO TO 12
35     Y3(K)=ABS(Y3(K))
36     YMIN=AMIN1(YMIN,Y3(K))
37     YMAX=AMAX1(YMAX,Y3(K))
38     12  CONTINUE
39     C
40     C UPDATE USER SPECIFIED YMIN, AND YMAX
41     CALL SMIMAY(YMIN,YMAX)
42     C
43     14  CONTINUE
44     C
45     IF(I.EQ.2) GO TO 15
46     IF(INEGY.LT.0) CALL NEGY(INEGY,INCS,NUY1,NUY2,NUY3)
47     ILLY=1
48     RETURN
49     C
50     15  CONTINUE
51     C RETRIVE SPECIFIED YMIN AND YMAX
52     TYMIN=COMGET(IBASEY(11))
53     TYMAX=COMGET(IBASEY(12))
54     C
55     IF(TYMIN.GT.0) GO TO 30
56     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 LILLO

```

1      SUBROUTINE SELCS(IFLAG,NSCS,NDEFCS)
2      C
3      C SUB. SELCS PROVIDES FOR SELECTION OF CROSS SECTIONS
4      C NDEFCS=0 - NSCS UNCHANGED - LOADING NOT REQUIRED!
5      C
6      DIMENSION NSCS(1)
7      C
8      IF(NSCS(1).LT.1.OR.IFLAG.EQ.0) GO TO 20
9      KK=NSCS(1)+1
10     WRITE(6,5) (NSCS(K),K=2,KK)
11     5  FORMAT(' SPECIFIED CROSS SECTIONS',/,
12     11X,I2,30(' ',I2))
13     C
14     WRITE(6,10)
15     10  FORMAT(' 1 - REDEFINE CROSS SECTIONS')
16     READ(5,15) NDEFCS
17     15  FORMAT()
18     C
19     IF(NDEFCS.EQ.0) RETURN
20     C
21     20  CONTINUE
22     NDEFCS=1
23     WRITE(6,25)
24     25  FORMAT(' HOW MANY CROSS SECTIONS?')
25     C
26     READ(5,15) NSCS(1)
27     IF(NSCS(1).LT.1) GO TO 20
28     C
29     WRITE(6,30)
30     30  FORMAT(' WHICH CROSS SECTIONS')
31     KK=NSCS(1)+1
32     READ(5,15) (NSCS(K),K=2,KK)
33     C
34     RETURN
35     END

```

(a) Listing for SELCS

```

1      SUBROUTINE SMIMA(XMIN,TXMIN,XMAX,TXMAX)
2      C
3      C UPDATES MINIMUM AND MAXIMUM.
4      C
5      XMIN=AMIN1(XMIN,TXMIN)
6      XMAX=AMAX1(XMAX,TXMAX)
7      C
8      RETURN
9      END

```

(b) Listing for SMIMA

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

```

1      SUBROUTINE HEADER(IX,IY,ITITLE,NSCS,IRUN)
2      C
3      C SUB HEADER GENERATES GRAPH TITLE, CS-CODE, RUN NO.
4      C
5      DIMENSION NSCS(1),IRUN(1),ITITLE(12)
6      DIMENSION ICS(33),IARRAY(15)
7      C
8      DATA IFILL/32/
9      DATA ICS/32,67,83,32,32,32,44,
10     132,32,44,32,32,44,32,32,44,
11     232,32,44,32,32,44,32,32,44,
12     332,32,44,32,32,44,32,32/
13      C
14      KK=NSCS(1)
15      ICS(1)=2+3*KK
16      DO 5 K=1,KK
17      J=2+3*K
18      FNUM=NSCS(K+1)
19      CALL IFORM(FNUM,IWIDTH,IARRAY,IFILL)
20      ICS(J)=32
21      IF(IWIDTH.GE.2) ICS(J)=IARRAY(IWIDTH-1)
22      ICS(J+1)=IARRAY(IWIDTH)
23      5 CONTINUE
24      C
25      CALL MOVABS(IX,IY)
26      DO 10 K=1,12
27      CALL AOUTST(6,ITITLE(K))
28      10 CONTINUE
29      CALL NOTATE(IX,IY-30,ICS(1),ICS(2))
30      CALL MOVABS(IX,IY-55)
31      CALL AOUTST(6,IRUN(1))
32      CALL AOUTST(3,IRUN(2))
33      CALL AOUTST(6,IRUN(3))
34      C
35      RETURN
36      END

```

Fig. B.32. Listing for Subroutine HEADER


```

1      SUBROUTINE LOAD(INEGY,IEOF,NU,X,TIME,XMIN,XMAX)
2      C
3      C SUB 'LOAD' LOADS NEXT CROSS SECTION
4      C
5      C     DIMENSION X(1)
6      C
7      C SET INEGY
8      INEGY=1
9      IEOF=0
10     C
11     C READ NUMBER OF DATA POINTS
12     READ(NU,5,END=100) X(1)
13     5    FORMAT(E15.8)
14     C
15     C LOAD CROSS SECTION
16     NP=X(1)+1
17     DO 10 K=2,NP
18     READ(NU,5) X(K)
19     10   CONTINUE
20     C
21     READ(NU,5) TIME,XMIN,XMAX
22     C
23     RETURN
24     C
25     100  CONTINUE
26     IEOF=1
27     RETURN
28     C
29     END

```

(a) Listing for LOAD

```

1      SUBROUTINE INMIMA(XMIN,XMAX,YMIN,YMAX)
2      C
3      C INITIALIZES MINIMUMS AND MAXIMUMS.
4      C
5      XMIN= 1.0E20
6      XMAX=-1.0E20
7      YMIN= 1.0E20
8      YMAX=-1.0E20
9      C
10     RETURN
11     END

```

(b) Listing for INMIMA

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

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.

```

1      SUBROUTINE SPMIMA(XMIN,XMAX,YMIN,YMAX)
2      C
3      C ALLOWS OPERATOR TO DEFINE BOTH Y-AXIS AND X-AXIS BOUNDS
4      C FOR GRAPH BEING GENERATED.
5      C
6      WRITE(6,5) XMIN,XMAX
7      5   FORMAT(E11.4,' XMIN',/,E11.4,' XMAX')
8      READ(5,10) TXMIN,TXMAX
9      10  FORMAT()
10     C
11     WRITE(6,15) YMIN,YMAX
12     15  FORMAT(E11.4,' YMIN',/,E11.4,' YMAX')
13     READ(5,10) TYMIN,TYMAX
14     C
15     C SET MINS. AND MAXS.
16     CALL DLIMX(TXMIN,TXMAX)
17     CALL DLIMY(TYMIN,TYMAX)
18     C
19     RETURN
20     END

```

(a) Listing for SPMIMA

```

1      SUBROUTINE SKIP(NU)
2      C
3      C SUB. 'SKIP' SKIPS NEXT CROSS SECTION
4      C
5      C READ NUMBER OF DATA POINTS
6      READ(NU,5,END=100) TNP
7      5   FORMAT(E15.8)
8      C
9      C READ CROSS SECTION
10     NP=TNP
11     DO 10 K=1,NP
12     READ(NU,5) X
13     10  CONTINUE
14     C
15     C READ TIME,XMIN,XMAX
16     READ(NU,5) X,X,X
17     C
18     RETURN
19     C
20     100  CONTINUE
21     WRITE(6,110) NU
22     110  FORMAT(' ERROR: UNEXPECTED EOF FOR SUB SKIP, NU=',
23     113)
24     END

```

(b) Listing for SKIP

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

```

1      SUBROUTINE NEGY(INEGY,INCS,NUY1,NUY2,NUY3)
2      C
3      C SUB. NEGY NEGATES Y-AXIS DATA VALUES
4      C
5      COMMON X(1000),Y1(1000),Y2(1000),Y3(1000)
6      INEGY=-INEGY
7      C
8      N=0
9      DO 5 K=1,INCS
10     N=N+1
11     NP=Y1(N)
12     DO 5 J=1,NP
13     N=N+1
14     Y1(N)=-Y1(N)
15     IF(NUY2.EQ.0) GO TO 5
16     Y2(N)=-Y2(N)
17     IF(NUY3.EQ.0) GO TO 5
18     Y3(N)=-Y3(N)
19     5  CONTINUE
20     C
21     RETURN
22     END

```

(a) Listing for NEGY

```

1      SUBROUTINE SMIMAY(YMIN,YMAX)
2      C
3      C ALLOWS OPERATOR TO DEFINE Y-AXIS BOUNDS FOR GRAPH
4      C BEING GENERATED.
5      C
6      WRITE(6,15) YMIN,YMAX
7      15  FORMAT(E11.4,' YMIN',/,E11.4,' YMAX')
8      READ(5,10) TYMIN,TYMAX
9      10  FORMAT()
10     C
11     C SET CYDMIN AND CYDMAX
12     CALL DLIMY(TYMIN,TYMAX)
13     C
14     RETURN
15     END

```

(b) Listing for SMIMAY

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

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