DESIGN AND MODELING OF SCHOTTKY BARRIER PHOTODIODES
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By

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A Project Report
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the degree
Master of Engineering

McMaster University
April 1981
TITLE: Design and Modeling of Schottky Barrier Photodiodes

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NO. OF PAGES: ix, 88
ABSTRACT

The computer program developed by T.B. Remple for the analysis of PiN photodiodes has been modified to handle Schottky barrier cases. The fundamental physics involved in the original model is summarized and the theories for a metal-semiconductor interface are presented. The boundary values for n, p, and ψ are then defined in such a way that ψ(x) would be in agreement with the thermionic-diffusion theory. An equivalent circuit approach is used to determine the RC response of the photodetector. While the modified version of the computer model provides very detailed analysis of the device, it is also very expensive to run. A simplified model is therefore employed for the design process. The objective is to design an Au-nGe photodiode with a risetime less than 50 psecs. The set of optimum design parameters obtained with the simplified model is then taken as the input to the modified version of Remple's program for further analysis. The theoretical risetime of the optimum design is found to be about 45 psecs.
ACKNOWLEDGEMENTS

The author would like to sincerely thank Dr. J.P. Marton for his helpful suggestions and supervision of this project.

The author also wishes to express his regards to his parents who have given him constant encouragement and moral support throughout these years.
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<td>n</td>
<td>electron concentration</td>
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<td>p</td>
<td>hole concentration</td>
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<td>ψ</td>
<td>electric potential</td>
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<tr>
<td>J_n</td>
<td>electron current</td>
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<td>J_p</td>
<td>hole current</td>
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<td>J_{disp}</td>
<td>displacement current</td>
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<td>total current</td>
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<td>μ_n</td>
<td>electron mobility</td>
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<td>D</td>
<td>diffusion constant</td>
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<td>τ_n</td>
<td>electron lifetime</td>
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<tr>
<td>τ_p</td>
<td>hole lifetime</td>
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<tr>
<td>qφ_T</td>
<td>energy level of trapping centres</td>
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<tr>
<td>n_A</td>
<td>atomic density of metal</td>
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<tr>
<td>E_F</td>
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<td>quasi-Fermi level for electrons</td>
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CHAPTER 1
INTRODUCTION

Computer modeling has been widely used in different applications for the past decade. This is due to the fact that it is usually much cheaper and easier to predict the behaviour of a certain device with a computer model than to achieve the same goal by actually building and testing the device. The computer approach is also more efficient in terms of the amount of time involved. In addition, sometimes the solution to the set of equations defining the model cannot be obtained analytically. Computer analysis is therefore necessary for obtaining a solution numerically or graphically. These features make designing with a computer model highly desirable. In this paper, a computer model which describes the performance characteristics of semiconductor photodiodes is presented. The original program was written by T. Remple (1) for the analysis of PiN photodiodes. The
present work involves the modification of the program to model Schottky barrier diodes and the design of an Au-nGe Schottky diode with risetime less than 50 psecs. The physics of metal-semiconductor interface which leads to the establishment of boundary conditions for the model is described in Chapter 2. An equivalent circuit of the photodiode is used to determine the electronic response time and to overcome the instability in convergence as discovered by Remple. A simplified model for the photodiode is presented in Chapter 3. The model is used to obtain a set of optimum design values which can give a minimum current risetime of 45 psecs. In this chapter, the fundamental physics of semiconductor devices is summarized and a brief description of PHODIM, the original computer program, is given.

1.1 Review of Physics

The photodiode model is set up to predict the output current as a function of time when the doping profile of the semiconductor diode, the applied voltage and the input light intensity as a function
of time are all given. Six basic mathematical equations are involved in the model and they are described as follows:

Maxwell's equation: The current density is expressed as the sum of electron current, hole current and the displacement current.

\[ J(t) = J_n(x,t) + J_p(x,t) + J_{\text{disp}}(x,t) \]

\[ = J_n(x,t) + J_p(x,t) + \frac{\partial}{\partial t} \frac{\partial \psi}{\partial x}(x,t) \quad (1.1.1) \]

**Carrier-Transport equations:** Each of the particle currents consists of a drift component and a diffusion component.

\[ J_n(x,t) = \mu_n(x,t) \left[ n(x,t) \frac{\partial \psi}{\partial x}(x,t) - \frac{\partial n}{\partial x}(x,t) \right] \quad (1.1.2) \]

\[ J_p(x,t) = \mu_p(x,t) \left[ p(x,t) \frac{\partial \psi}{\partial x}(x,t) + \frac{\partial p}{\partial x}(x,t) \right] \quad (1.1.3) \]

**Continuity equations:** The net influx of carriers into a region is determined by the generation and recombination of carriers in that region, and the particle currents flowing in and out of the region.

\[ \frac{\partial n}{\partial t}(x,t) = G(x,t) - U(x,t) - \frac{\partial J}{\partial x}(x,t) \quad (1.1.4) \]
\[ \frac{\partial p}{\partial t}(x,t) = G(x,t) - U(x,t) - \frac{\partial J}{\partial x}(x,t) \quad (1.1.5) \]

**Poisson's equation**: The electrostatic potential is defined in terms of the net space charge density.

\[ \frac{\partial^2 \psi}{\partial x^2}(x,t) = n(x,t) - p(x,t) - N_D(x) + N_A(x) \quad (1.1.6) \]

It is noted that the above equations are given in their dimensionless form. The normalization factors employed are listed in Appendix A. In addition, the Einstein's relation has also been used to simplify the equations into the above forms. It is given by

\[ D = \frac{kT}{q} \mu \quad (1.1.7) \]

where

\[ \begin{cases} k = \text{Boltzmann constant} \\ T = \text{temperature in °K} \\ q = \text{electronic charge} \end{cases} \]

Both of the carrier mobilities and the recombination function can be defined in terms of carrier densities and semiconductor material properties. Mobility is given by
\[
\mu' = \frac{v_{sat}}{E} \tanh \left( \frac{\mu E}{v_{sat}} \right) \tag{1.1.8}
\]

where \( E = -\frac{\partial \psi}{\partial x} \) and \( v_{sat} \) is the saturation velocity.

\( \mu \) is defined as

\[
\mu = \left( \frac{\mu_I \mu_L}{\mu_I + \mu_L} \right) F_s(w) \tag{1.1.9}
\]

where

\[
\mu_I = \frac{K_1}{(N_A + N_D + \Theta p)} \left\{ \ln \left[ 1 + \left( \frac{K_2}{n + \Theta p} \right) \right] \right\} \tag{1.1.10}
\]

The quantities \( \mu_L, K_1, K_2 \) and \( \Theta \) are material properties and are given in Appendix B for Germanium. \( F_s(w) \) is a transcendental function which is defined in Appendix C.

The standard Shockley-Read model is used for the recombination function \( U(x,t) \).

\[
U(x,t) = \frac{n(x,t) p(x,t)}{\tau_p [n(x,t) + \exp(\phi_T)] + \tau_n [p(x,t) + \exp(\phi_T)]} \tag{1.1.11}
\]
It is assumed that the energy level of the trapping centres is coincide with the Fermi level in this model. Hence $\phi_T$ is equal to zero in the present case.

The photo-generation term and the doping profile are determined by the operating condition and the type of diode respectively. Both quantities are pre-defined functions. The generation term $G(x,t)$ can be one of the three different forms which are given in Appendix D. Now the six fundamental equations can be expressed in terms of the variables $J$, $J_n$, $J_p$, $n$, $p$, and $\psi$. Only three of these variables are independent and they are arbitrarily chosen to be $n$, $p$ and $\psi$.

1.2 Description of PHODIM

A computer program PHODIM written by T. Remple solves the above set of differential equations and obtains the output current as a function of time. A detailed description of the numerical methods employed in the program can be found in Stark's or Remple's
The basic steps of operation of the program can be summarized by a flow diagram shown in Figure 1.

The approximations and assumptions made in the derivation of the model are listed as follows:

(i) One dimension: Current crowding and spreading effects are ignored.

(ii) No avalanching or breakdown: The model does not include an avalanche mechanism and does not predict when breakdown is going to occur.

(iii) No degeneracy: Effects of heavily doped region on the operation of the main part of the photodiode are assumed to be small.

(iv) No thermoelectric effects or thermal transport: The carrier temperature gradient is assumed to be zero. Otherwise, two additional components would have to be included in the current-transport equations.

PHODIM was originally written for the analysis of PiN photodiodes. Attempts were made by Remple to model for the Schottky barrier case by assuming a $P^+N$
FIGURE 1

Flow Diagram for PHODIM
structure. This approach, however, did not work due to several problems. First, a heavily doped P region does not exist in practice. Second, the approach predicted that the total current consists of electron and hole currents instead of electron current only (for n-type semiconductor). Third, instability in convergence was observed for the Schottky case. The present work is therefore carried out to solve these problems.
CHAPTER 2

MODELING OF SCHOTTKY BARRIER PHOTODIODES

The fundamental equations given in the previous chapter are derived from the semiconductor physics and therefore hold true for both the PiN and the Schottky barrier photodiodes. The major difference is the boundary conditions used for solving the set of equations. In this chapter, the physics of a metal-semiconductor interface which leads to the setting up of appropriate boundary conditions is discussed. The electric potential $\psi$ is assumed to be a specific profile which is predicted by the thermionic-diffusion theory. The original program PHODIM used to have problems in stability and convergence. The problems can be removed if the electronic response of the photodiode is accounted for as described in Section 2.3. Finally, SCHOT, the modified version of PHODIM, is evaluated in terms of the physical meaning of the solution.
2.1 Schottky Barrier Formation

The barrier height of a metal-semiconductor junction is, in general, determined by the metal work function and the semiconductor surface states. The effects of these two quantities can be illustrated theoretically by considering two limiting cases. Figure 2(a) shows the case in the absence of surface states. At the beginning, the metal and the semiconductor are kept far away from each other and the system is not in thermal equilibrium. As the semiconductor is brought closer to the metal, an electric field builds up between the surfaces as electrons flow from the semiconductor to the metal to lower the Fermi level in the semiconductor. Equilibrium is reached when the Fermi levels on both sides are lined up. Since there are no surface states in this case, the electrons that flow to the metal must come from the ionization of impurity atoms. Because of the relatively low doping concentration, the flowing of electrons into the metal causes the energy levels in the semiconductor to bend upwards and a depletion region is resulted. In the limit, \( \delta \) is decreased
FIGURE 2

Schottky Barrier Formation
to atomic distance and the gap becomes transparent to electrons. The barrier height $\phi_{bn}$ is then given by the difference between the metal work function and the electron affinity of the semiconductor.

Figure 2(b) shows the case where a large density of surface states is present on the semiconductor surface. When the metal and the semiconductor are separated, the surface states are assumed to be occupied to the Fermi level $E_F$. Once again, when the surfaces are brought close to each other and the system is in equilibrium, an electric field is produced in the gap. However, now the density of the surface states is sufficiently large to supply the electrons flowing into the metal without altering the Fermi level significantly. The Fermi level is said to be 'pinned' and the barrier height in the limiting case ($\delta \to 0$) is determined by the properties of the semiconductor alone.

An interfacial layer of permittivity $\varepsilon_1$ is usually introduced in the derivation of an expression for the barrier height. It is assumed that the layer
is of atomic dimensions and that it is transparent to electrons and can withstand electric potential across it. Figure 3 illustrates the situation for n-type semiconductor. As mentioned before, electrons will flow from the semiconductor to occupy the surface states in the interfacial layer adjacent to the metal surface. At equilibrium, the density of the negative charge accumulated on the metal surface must be equal to the atomic density of the metal, $n_A$. The boundary condition at $x = 0$ can be defined as follows:

$$ n(0) = n_A \quad (2.1.1) $$

Also, the quasi-Fermi potentials for electrons and holes are assumed to be equal to that of the metal at $x = 0$.

$$ E_F(0,t) = \phi_n(0,t) = \phi_p(0,t) = V_e(t) \quad (2.1.2) $$

The quasi-Fermi potential relationships are:

$$ n = \exp(\psi - \phi_n) \quad (2.1.3) $$
\[ p = \exp(\phi_p - \psi) \]  

(2.1.4)

Combining the above three equations gives

\[ p(0) = 1/n(0) \]  

(2.1.5)

The electric potential at \( x = 0 \) is then written as

\[ \psi(0,t) = \ln(n_A) + V_e(t) \]  

(2.1.6)

Since the interfacial layer has a permittivity that is different from that of the semiconductor, the quantities in the above equations should be normalized by a different factor. This means that the energy levels would be, in general, discontinuous at the interface (i.e. similar to the case of a heterojunction). For the purpose of numerical analysis, the photodiode is divided into a number of mesh points along its length. In the case of a homojunction (e.g. PiN), the same set of normalization factors is used for the entire mesh region. For a heterojunction, two mesh regions of different normalization factors would be required. In the present study, another approach
FIGURE 3

Notations used for Schottky Barrier Theories
is employed. Since the interfacial layer is a theoretical one and the value of \( \varepsilon_i \) is an unknown anyway, it was assumed that \( \varepsilon_i = \varepsilon_s \) in the calculations and a correction factor \( \Delta \psi \) is introduced. 

\[
\psi(0,t) = \ln(n_A) + \Delta \psi + V_e(t) \tag{2.1.7}
\]

It should be noted that the quantities in eq. (2.1.7) are normalized with the same factors as for the semiconductor region (and are different from those for eq. (2.1.6)). This approach simplifies the case by defining a continuous energy band at the interface. The high concentration of negative charge accumulated on the surface causes an electric potential barrier for the holes to form near the interface. \( \Delta \psi \) is adjusted in such a way that \( \psi(x) \) is in accordance with that predicted by the thermionic-diffusion theory. Further discussion on the theory will be given in the next section.

Boundary conditions at \( x = x_L \) are set up by assuming an ohmic contact as 

\[
n(L) \cdot p(L) = 1 \tag{2.1.8}
\]
and

\[ E_p(L,t) = \phi_n(L,t) = \phi_p(L,t) = V_C(t). \quad (2.1.9) \]

In addition, charge neutrality requires that

\[ n - p - N_D = 0. \quad (2.1.10) \]

Substituting eq. (2.1.3) and eq. (2.1.4) into the above equation and solving, we get

\[ \psi(L,t) = V_C(t) + \ln \left\{ \left[ \frac{N_D}{2} \right]^2 + 1 \right\}^{1/2} + \frac{N_D}{2} \right\}. \quad (2.1.11) \]

The boundary values for \( n, p \) and \( \psi \) are now completely defined and a particular solution to the set of fundamental equations can be obtained.

2.2 Thermionic-Diffusion Theory

In the present model, it is assumed that the thermionic-diffusion theory will apply so that the electric potential can be expressed as

\[ \frac{E_C(x)}{q} = \phi_{bn} + \Delta \phi - V(x) - \frac{q}{16 \pi \varepsilon_s x}. \quad (2.2.1) \]
where

\[
\begin{align*}
\phi_{bn} &= \text{barrier height} \\
\Delta \phi &= \text{barrier lowering due to image force} \\
V(x) &= \text{barrier lowering due to applied field} \\
\frac{q}{16\pi \varepsilon_s x} &= \text{image force potential}.
\end{align*}
\]

Assuming that the voltage drops across the depletion layer only and the electric field varies linearly within this region, we get

\[
E(x) = \begin{cases} 
\frac{qN_D}{\varepsilon_s} (x_d - x) = E_m - \frac{qN_D}{\varepsilon_s} x & ; \ 0 \leq x \leq x_d \\
0 & ; \ x_d \leq x \leq x_L 
\end{cases} \quad (2.2.2)
\]

where

\[
E_m = \frac{qN_D x_d}{\varepsilon_s}.
\]

The potential variation due to the applied field can then be derived as

\[
V(x) = \int_0^x E(x) \, dx
\]

\[
= \begin{cases} 
\frac{E_m x - \frac{qN_D}{2\varepsilon_s} x^2}{2} & ; \ 0 \leq x \leq x_d \\
\frac{E_m x_d}{2} & ; \ x_d \leq x \leq x_L. \quad (2.2.3)
\end{cases}
\]

The width of the depletion region can be obtained by employing the one-sided abrupt junction approximation as
\[ x_d = \left\{ \frac{2e_s}{qN_D} \left( V_{bi} - V - \frac{kT}{q} \right) \right\}^{\frac{1}{2}} \]  \hspace{1cm} (2.2.4)

where \( V_{bi} = \phi_{bn} - V_n \)

and \( V_n = \frac{E_q}{2} - \ln \left\{ \left[ \left( \frac{N_D}{2} \right)^2 + 1 \right]^{\frac{1}{2}} + \frac{N_D}{2} \right\} \).

\( x_m \), which is defined as the location of the maximum potential, is given by setting \( \frac{\partial E}{\partial \psi} = 0 \) and using the fact that \( E \equiv E_m \).

\[ x_m = \left[ \frac{q}{16\pi\varepsilon_s E_m} \right]^{\frac{1}{2}} \] \hspace{1cm} (2.2.5)

The barrier lowering is then given by

\[ \Delta\phi = \left[ \frac{q E_m}{4\pi\varepsilon_s} \right]^{\frac{1}{2}} = 2E_m x_m \] \hspace{1cm} (2.2.6)

Since \( \phi_n \) is an unknown and is required for the evaluation of \( x_d \), \( x_m \) and \( \Delta\phi \), an iterative scheme has to be set up to solve for the parameters. This can be achieved (refer to Figure 3) with two additional relations.

\[ \phi_{bn} = \phi_{b0} - \Delta\phi \] \hspace{1cm} (2.2.7)

\[ \phi_{b0} = \phi_m - \chi - \Delta \] \hspace{1cm} (2.2.8)
The iterating routine starts with an initial guess of \( \phi_{bn} = \phi_{bo} \) and stops when the change in \( \phi_{bn} \) between successive iterations is small (smaller than, say, one percent). A flow diagram of the procedure is given in Figure 4.

\[
\text{Once } \frac{E_c(x)}{q} \text{ is determined, } \psi(x) \text{ can be evaluated according to}
\]

\[
\psi(x) = \frac{E_g}{2q} - \frac{E_c(x)}{q} \quad (2.2.9)
\]

The initial estimates for \( n \) and \( p \) are given by

\[
n(x) = N_D \quad (2.2.10)
\]

\[
p(x) = \frac{1}{n(x)} \quad (2.2.11)
\]

Since \( \psi(x) \) is a pre-defined function, an initial estimate to the variable is not required. Instead, one has to provide a suitable value for \( \Delta \psi \) which is a part of the boundary conditions. This has already been discussed in detail in the previous section.
FIGURE 4

Flow Diagram for Evaluation of $\phi_{bn}$

\[
X_d = \sqrt{\frac{2 \varepsilon_s (V_{bi} - V - \frac{\Delta T}{g})}{g N_b}}
\]

\[
\varepsilon_m = \frac{q N_b X_d}{\varepsilon_s}
\]

\[
\chi_m = \frac{q}{16 \pi \varepsilon_s \varepsilon_m}
\]

\[
\Delta \phi = 2 \varepsilon_m \chi_m
\]

\[
\phi_{bn}' = \phi_{bo} - \Delta \phi
\]

\[
\Delta \phi_{bn} = |\phi_{bn} - \phi_{bn}'|
\]

\[
\frac{\Delta \phi_{bn}}{\phi_{bn}} \leq 0.01
\]

no

yes

continue

$\phi_{bn} = \phi_{bn}'$
2.3 Electronic Response Time

In PHODIM, the boundary values for $\psi$ are time dependent. The bias voltage for each time step is calculated by taking into account the voltage drop across the load resistor in the previous time step. The approach has been shown to cause both convergence and stability problems near the end points of the diode and at the barrier for the Schottky barrier case. A different method is therefore employed here to determine the electronic response of the circuit.

An equivalent circuit of the photodiode is set up. This is shown in Figure 5(c). For $R_j \gg (R_L + R_i)$ and $R_L \gg R_i$, which are usually the cases, the circuit can be further simplified to that in Figure 5(d). The simplified circuit is easily identified to be a RC circuit and Kirchhoff's law gives

$$\frac{di}{dt} = \frac{1}{RC} (I_{\text{gen}} - i) \quad (2.3.1)$$

The short-circuited current output of the diode ($I_{\text{gen}}$) can be calculated with SCHOT (or PHODIM) by setting
(a) Basic photodetector system

(b) Equivalent circuit for photodiode

(c) Equivalent circuit for photodetector system

(d) Simplified equivalent circuit

FIGURE 5

Equivalent Circuit for the Photodetector
\( R_L = 0 \). Once \( I_{gen}(t) \) is obtained, the actual current output can be determined by solving eq.(2.3.1). A computer program JPLOT employing the Runge-Kutta method of order two is used to obtain numerical solutions to the first order differential equation. The modified version of PHODIM, SCHOT, provides a punched deck of the results of the transient analysis which can then be used as the input to JPLOT for determining the RC response of the circuit.

2.4 Computer Model SCHOT

SCHOT was written according to the theories outlined in the previous sections. An user's guide to the operation of the computer program is given in Appendix E and a full listing of the program is given in Appendix G.

Convergence is usually not a problem for the case of PiN diodes but this is no longer true for the Schottky barrier diodes. Since both \( n \) and \( p \) change significantly and \( \frac{\partial \psi}{\partial x} \) reverses in sign within 0.01 \( \mu \)m near the metal-semiconductor interface, it is important that a very fine mesh \((x_{i+1} - x_i) \sim x_m\)
is chosen for this region. In addition, the user should minimize the number of points in the charge neutrality region (by defining $x_L \approx x_d$). The reason is that the change in $\psi$ between successive iterations is much smaller than that in the depletion region and hence the acceleration parameter for convergence would impose too large a correction for $\psi$ in the neutral region. A slow convergence rate therefore results. When the mesh points are properly chosen, solution to each time step should be obtainable for less 100 iterations.

The steady state solution for $n$, $p$ and $\psi$ is shown in Figure 6. It can be seen that by choosing appropriate boundary conditions, a potential barrier and a depletion region are created in the semiconductor. In addition, the existence of an inversion layer (i.e. a p-region) near the metal-semiconductor interface is also predicted. A sudden jump in the potential function is usually found near $x = x_m$. This is believed to be caused by a numerical instability in that region.

The steady state solution also indicates
that the majority carriers (electrons in this case) are responsible for the current flow \(J_n >> J_p\). This is in agreement with accepted theories. However, the magnitude of the total current predicted by the model is smaller than that by the thermionic-diffusion theory. This is so because electrons are injected from the metal with a different velocity than that used in the present Shockley-Read model. Hence a thermionic recombination velocity should be defined at the interface for exact modeling of the steady case. However, since it is the photo-response of the diode that is of major interest, the fact that \(\psi(x)\) agrees with the thermionic-diffusion theory insures that the transient analysis would not be affected.

Figure 7 shows the general profile of the photo-generated carrier currents. It can be seen that the hole current \(J_p\) is blocked by the barrier at \(x = x_m\) and drops rapidly to close to zero at \(x = 0\). It is also noticed that the electron current \(J_n\) reverses in direction (changes in sign) near the interface. The reversal is caused by the emission
FIGURE 7 Photo-generated Carrier Currents in the Depletion Region
current towards the metal. The same effect has also been predicted by a theoretical analysis based on a different approach carried out by M. Lavagna et al.\textsuperscript{(4)} Lavagna also suggested that quantum efficiency of the diode would decrease for an increasing absorption coefficient because of this effect. However, no attempt has been made to study this aspect with the present model.
CHAPTER 3
DESIGN OF SCHOTTKY BARRIER PHOTODIODES

The computer model SCHOT described earlier provides a very detailed analysis of the photodiode device. However, the program is very expensive to run. For this reason, a much simpler model is employed here for the design process. Once the region of interest is defined, the program SCHOT can be used to carry out further analysis. The theory of the simplified model and the method of analysis are presented in this chapter. The optimum design parameters are given in Section 3.3 and detailed analysis of the design is discussed in the last section.

3.1 Theory

A simple model based on the abrupt junction approximation is used to determine the step response of Schottky barrier photodiodes. The derivation of
the model is summarized as follows:

The depletion layer width of the photodiode is given by

\[ x_d = \left( \frac{2eS}{qND} (V_{bi} - V) \right)^{\frac{1}{2}} \]  \hspace{1cm} (3.1.1)

where

\[ V_{bi} = \phi_{bn} - V_n \approx \phi_{bo} - V_n \]  \hspace{1cm} (3.1.2)

\[ V_n = \frac{1}{q} (E_C - E_F) \]  \hspace{1cm} (3.1.3)

The maximum electric field occurs near the metal-semiconductor junction and is given by

\[ E_m = \frac{qND}{\varepsilon_s} x_d \]  \hspace{1cm} (3.1.4)

Now, assuming that the electrons generated by the input light traverse the depletion region with saturation velocity, one can calculate the transit time required as follows.

\[ \tau_t = 0.79 \frac{x_d}{v_{sat}} \]  \hspace{1cm} (3.1.5)
Another factor that affects the response of the photodiode is the electrical characteristics of the circuit. In general, the device can be represented by a simple RC circuit (refer to Figure 5). The RC response time of the circuit can then be given by

$$\tau_{RC} = 2.2 R_L C_j$$ \hspace{1cm} (3.1.6)

The constants 0.79 and 2.2 in equations (3.1.5) and (3.1.6) come from the fact that the 10-90% risetime is being considered. The junction capacitance is defined as

$$C_j = \frac{\varepsilon_s A}{x_d}$$ \hspace{1cm} (3.1.7)

where A is the cross-sectional area of the diode.

The risetime of the diode can then be calculated by adding $\tau_t$ and $\tau_{RC}$ orthogonally:

$$\tau = (\tau_t^2 + \tau_{RC}^2)^{1/2}$$ \hspace{1cm} (3.1.8)

Finally, the quantum efficiency of the diode can be
obtained from the following equation.

\[ \eta = 1 - \exp \left( \frac{x_d}{\alpha} \right) \]  \hspace{1cm} (3.1.9)

where \( \alpha \) is the absorption length of the semiconductor material for a particular wavelength.

The approximations and assumptions used in the model are described as below:

(i) In order for the above theory to apply, the following condition must hold true:

\[ V_{\text{valid}} < V < V_{\text{br}} \]

where \( V_{\text{valid}} \) is the voltage at which \( E_m = 10 \ E_{\text{sat}} \)

\( E_{\text{sat}} \) is the saturation field

and \( V_{\text{br}} \) is the breakdown voltage and is given by

\[ V_{\text{br}} \approx 60 \ \left( \frac{E_q}{1.1} \right)^{3/2} \left( \frac{N_D}{10^{16} \ \text{cm}^{-3}} \right)^{-3/4} \text{ volts} \] \hspace{1cm} (3.1.10)

(ii) Semiconductor is non-degenerate.

(iii) By taking the approximation made in eq. (3.1.2),
the effect of image force is being neglected. If this effect were to be included, an iterative scheme would have to be set up to calculate for the barrier lowering (refer to Section 2.2). However, since the lowering is only a very small value, the inclusion of the image force seems to be unnecessary.

3.2 Analysis and Results

From the above equations, one can see that the risetime of the photodiode depends on four parameters, namely, doping density \( N_D \), applied voltage \( V \), load resistance \( R_L \), and area of the diode \( A \). A computer program based on the above theory was written and was used to compute the risetimes of the photodiode for different values of the parameters. The range of analysis is defined as follows:

\[
A = 0.5 \times 10^{-3}, 0.5 \times 10^{-4}, 0.5 \times 10^{-5} \text{ cm}^2
\]

\[
R_L = 10, 30, 50 \text{ ohms}
\]

\[
N_D = 0.1 \times 10^{16} \text{ to } 1.0 \times 10^{16} \text{ cm}^{-3} \text{ at } 0.1 \times 10^{16} \text{ cm}^{-3} \text{ intervals}
\]

\[
V = 0 \text{ to } 80 \text{ volts with } 1 \text{ volt intervals}
\]

A set of graphs is then obtained by carrying
out the above analysis. Each plot gives τ vs. V for the whole range of doping densities and for a fixed value of cross-sectional area and load resistance. In addition, four more curves are present in each plot and they are

(A) Breakdown limit: \( V = V_{br} \)
(B) Saturation limit: \( E_m = 10 E_{sat} \)
(C) \( \frac{1}{4} \) Breakdown voltage: \( V = \frac{1}{4} V_{br} \)
(D) 2x Absorption length: \( x_d = 2\alpha \).

Finally, another plot of τ vs. \( \eta \) is given to provide information about the amount of quantum efficiency that one must give up in order to gain better response. This single plot contains all of the data points within the range of analysis as defined before.

3.3 Optimum Design

The objective is to design a photodetector with a minimum risetime less than 50 psecs. The materials to be used are gold and germanium. All values used for calculations are therefore based on
FIGURE 8

Photodetector Risetime as a Function of $V$, $N_D$, $R_L$ and Area
FIGURE 9  QUANTUM EFFICIENCY

Quantum Efficiency of Photodetector versus risetime
material properties of these two elements.

From equation (3.1.5), it can be seen that the transit time can be reduced by choosing a smaller depletion width. However, the capacitance is inversely proportional to $x_d$ and hence a certain optimum value for $x_d$ must exist. In addition, the RC response of the device depends also on the area of the diode and the value of the load resistance. Decreasing $A$ and/or $R_L$ would therefore produce better response characteristics. It can be seen from Figure 8 that a risetime of 7 psec can be achieved for a photodiode with $A = 0.5 \times 10^{-5}$ cm$^2$, $R_L = 10$ ohms and $N_D = 1.0 \times 10^{16}$ cm$^{-3}$. However, these numbers are not very practical ones since several other factors must be taken into consideration in the design of photodiodes. These factors are to be described as follows.

(1) Breakdown and saturation limits:

It is important that the operating voltage of the diode is far enough away from both $V_{valid}$ and $V_{br}$ so that small variation of applying field will not cause maximum electric field to fall below satura-
tion value nor to drive the device into breakdown. Hence one would like to choose a doping density for which \((V_{br} - V_{valid})\) is large enough and that the operating point (minimum risetime) is far away from both limits.

(2) Power matching:

In order to deliver maximum power to the external circuitry, the value of the load resistor must not be too small. A value of about 50 ohms is most typical.

(3) Intensity problem:

In order for the device to operate under low light intensity condition, the cross-sectional area of the diode must be large enough. Otherwise, a lens must be used to focus the beam down to a spot of size comparable to that of the diode. If the area of the diode were made too small, then the focusing of light may become a problem. Furthermore, direct compatibility with optical fibres requires an area of approximately \(0.8 \times 10^{-4} \text{ cm}^2\) (i.e. a circular spot of 100 µm in diameter).
(4) Quantum efficiency:

Quantum efficiency can be improved significantly by increasing $x_d$ until up to a certain point (about twice the absorption length). The price that one must pay for this improvement in sensitivity is, of course, the increase of the risetime. Figure 9 is provided especially for the observation of this effect. Notice that each 'single' curve that appears in the plot is actually an overlap of curves with different values of $N_D$ ranging from $0.1 \times 10^{16}$ to $1.0 \times 10^{16}$ cm$^{-3}$.

By making use of Figures 8 and 9, and by taking all of the above factors into account, it is concluded that the following set of values seems to be able to provide an optimum operating condition (see also Figure 10):

$$A = 0.5 \times 10^{-4} \text{ cm}^2$$
$$R_L = 50 \text{ ohms}$$
$$N_D = 0.3 \times 10^{16} \text{ cm}^{-3}$$
$$V = 10 \text{ volts}$$

Finally, if one demands a risetime better
AREA = $0.5 \times 10^{-4}$ cm$^2$
RESISTANCE = 50.0 ohms

$N_D = 0.1 \times 10^{16}$ cm$^{-3}$

$\frac{1}{4}$ breakdown

breakdown

2x absorption length

optimum operating point

FIGURE 10  APPLIED VOLTAGE (VOLT)

Optimum Design Parameters
than 45 psecs, one can achieve this goal only by giving up some of the other desirable features as discussed before. For applications where light intensity is high, further reduction of the risetime may be possible. A compromise must then be made with all factors being specified according to the needs of a particular application.

3.4 Detailed Analysis of Optimum Design

The set of parameters obtained with the simplified model for the optimum design is used as the input to SCHOT for a more detailed analysis. The theoretical light input is assumed to be a step function (increases from zero to peak power in less than 0.5 psec). The wavelength of the light input is chosen to be 1.3 \( \mu \text{m} \) because both signal attenuation and chromatic dispersion through a high quality fiber made of silica are minimum in this wavelength region. Smaller bandgap materials are required for operation at this wavelength and hence germanium is selected for this purpose. The constants listed in Appendix B for germanium are used for analysis. Finally, variable time steps are employed.
because of the rapid change in light power within the first 0.5 psec of the transient analysis.

With the above input values, SCHOT was run to iterate $\psi$ down to a tolerance of $2.0 \times 10^{-8}$ volt. JPLLOT was then used to determine the RC response and to obtain a plot of the current output. Figure 11 shows the current as a function of time together with the theoretical light input profile (both are in normalized units). It can be seen that the 10-90% risetime of the output current is about 44 psec. The depletion width of the diode is 2.45 µm. Both of these values are very close to those obtained with the simplified model. Hence one can conclude that the simple model is indeed a fairly accurate one and that the results of the design analysis are therefore quite dependable.
FIGURE 11  Photo-generated Current as a Function of Time

- AREA = 50E-04 CM²
- DOPING DENSITY = 30E+16 CM⁻³
- RESISTANCE = 50.0 OHMS
- VOLTAGE = 10.0 VOLTS

INPUT POWER, OUTPUT CURRENT

TIME (PSEC)
CHAPTER 4
CONCLUSIONS

The computer model PHODIM for the analysis of PiN photodiodes and the physics behind it are described at the beginning of this paper. In order to modify the program to handle Schottky barrier diodes, a different set of boundary conditions is required. In the present model, it is assumed that an interfacial layer exists between the metal and the semiconductor. The Fermi-level difference across the layer causes electrons to flow from the semiconductor into the metal resulting in the formation of a depletion layer. The boundary value for \( n \) is assumed to be equal to the atomic density of the metal. \( p(0) \) is then defined as the reciprocal of \( n(0) \). It is also assumed that \( \psi(x) \) is given by the thermionic-diffusion theory. \( \psi(0) \) is defined in such a way that the above condition will be satisfied. In order to overcome the instability and convergence problem of PHODIM, another computer program JPLOT was written to determine the RC response of the device. By solving the first order differential equation of the equivalent circuit num-
erically, a plot of the output current as a function of time can be obtained. Since the modified program is expensive to run, a much simpler model is used to calculate for the design parameters. SCHOT is then employed for a detailed analysis of the set of optimum design parameters chosen.

No new experimental data is available at this moment for the testing of the model. However, the results obtained for the optimum design parameters appear to be quite reasonable as compared to previous experimental results given in Remple's paper. Both the detailed and the simplified model predict a 45 psec risetime for a diode with a depletion width of about 2.5 µm. Despite the problems with the steady state solution, the present model should be very useful in ultra-high speed photodiode design.
<table>
<thead>
<tr>
<th>quantity</th>
<th>variable normalized by germanium</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>position coordinate</td>
<td>$x$</td>
<td>$L_D = \frac{\varepsilon_0 V_t}{e n_t}$</td>
</tr>
<tr>
<td>time coordinate</td>
<td>$t$</td>
<td>$L_D^2/D_0$</td>
</tr>
<tr>
<td>electrostatic potential</td>
<td>$V_t = \frac{kT}{e}$</td>
<td></td>
</tr>
<tr>
<td>quasi-Fermi levels</td>
<td>$\phi_n, \phi_p$</td>
<td>$V_t$</td>
</tr>
<tr>
<td>applied voltages</td>
<td>$V_e, V_c$</td>
<td>$V_t$</td>
</tr>
<tr>
<td>electric field</td>
<td>$E$</td>
<td>$V_t/L_D$</td>
</tr>
<tr>
<td>carrier densities</td>
<td>$n, p$</td>
<td>$n_t$</td>
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<td>impurity densities</td>
<td>$N, N_D, N_A$</td>
<td>$n_t$</td>
</tr>
<tr>
<td>current densities</td>
<td>$J, J_n, J_p$</td>
<td>$-eD_0 n_t/L_D$</td>
</tr>
<tr>
<td>generation-recombination rate</td>
<td>$U$</td>
<td>$D_0 n_t/L_D^2$</td>
</tr>
<tr>
<td>carrier-diffusion constants</td>
<td>$D_n, D_p$</td>
<td>$1/D_0$</td>
</tr>
<tr>
<td>carrier mobilities ($\mu = 1/\gamma$)</td>
<td>$\gamma_n, \gamma_p$</td>
<td>$D_0/V_t$</td>
</tr>
</tbody>
</table>
## APPENDIX B

### MATERIAL PROPERTIES OF GERMANIUM

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Variable</th>
<th>Value at 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic density</td>
<td>$n_A$</td>
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<tr>
<td>relative permittivity</td>
<td>$\varepsilon_r$</td>
<td>15.8</td>
</tr>
<tr>
<td>electron affinity</td>
<td>$\chi$</td>
<td>4.0 V</td>
</tr>
<tr>
<td>energy gap</td>
<td>$E_g$</td>
<td>0.66 eV</td>
</tr>
<tr>
<td>intrinsic concentration</td>
<td>$n_i$</td>
<td>$2.4 \times 10^{23} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>lattice mobility</td>
<td>$\mu$</td>
<td>$\mu_n - 3900 \text{ cm}^2/\text{Vs}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu_p - 1900 \text{ cm}^2/\text{Vs}$</td>
</tr>
<tr>
<td>recombination lifetime</td>
<td>$\tau$</td>
<td>$\tau_n - 10^{-3} \text{ s}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tau_p - 10^{-3} \text{ s}$</td>
</tr>
<tr>
<td>saturation velocity</td>
<td>$v_{sat}$</td>
<td>$n - 0.6 \times 10^7 \text{ cm/s}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p - 0.1 \times 10^8 \text{ cm/s}$</td>
</tr>
<tr>
<td>saturation field</td>
<td>$E_{sat}$</td>
<td>$5.0 \times 10^3 \text{ V/cm}$</td>
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<td>absorption length</td>
<td>$\alpha$</td>
<td>1.3 $\mu$m for $\lambda = 1.3 \mu$m</td>
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<td>quantum efficiency</td>
<td>$\eta$</td>
<td>0.45 for $\lambda = 1.3 \mu$m</td>
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<td></td>
<td>$\Theta$</td>
<td>n - 0.5</td>
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<td></td>
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<td>$K_1$</td>
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<tr>
<td></td>
<td>$K_2$</td>
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</table>
APPENDIX C

TRANSCENDENTAL FUNCTION

\( F_S(w) \) is a transcendental function that can be approximated as follows.

\[
\begin{align*}
    &w \leq 0.08, \quad F_S = 1 - 3.44w + 13.99w^2 \\
    &0.08 < w \leq 3.8, \quad F_S = \frac{14.16 + 45.22w + 31.06w^2}{15.72 + 76.34w + 36.00w^2} \\
    &3.8 < w, \quad F_S = 1 - \frac{1.442}{w} + \frac{2.137}{w^2}
\end{align*}
\]
APPENDIX D

GENERATION TERM

The function that is used to model the photo-generation process is given by

\[ G(x,t) = \frac{P\xi}{E_{ph}aA} \exp\left(-\frac{x}{a}\right) t_{\text{fact}} \]

where

- \( P \) = maximum power of light input
- \( \xi \) = efficiency of diode
- \( E_{ph} \) = energy per photon
- \( a \) = absorption length
- \( A \) = area of diode
- \( t_{\text{fact}} \) = time factor which is determined by the shape of the light pulse.

Three time functions for the light input are permitted by the program.

(1) Pulse:

\[ t_{\text{fact}} = \left(\frac{t}{\tau}\right)^2 \exp\left\{\frac{1}{2}(1 - \frac{x}{\tau})^2\right\} \]
(2) Step function:

\[ t < 0, \quad t_{\text{fact}} = 0 \]
\[ 0 \leq t \leq \tau, \quad t_{\text{fact}} = \frac{t}{\tau} \]
\[ \tau < t, \quad t_{\text{fact}} = 1 \]

(3) Sinusoidal:

\[ t_{\text{fact}} = \sin\left(\frac{\pi}{2\tau} t\right) \]
APPENDIX E

USER'S GUIDE TO SCHOT

The procedures for running the present program are quite similar to those for PHODIM. The variable directory at the beginning of the program has been updated to include variables used in the Schottky barrier case. Some of the variables are also defined along with their mathematical symbols in the Glossary of Symbols. The array TEST is consisted of switches which control program flow and provide different options. Several new switches have been introduced and they are described below.

TEST(19): Selects iteration limit-
The switch allows the user to define a limit to the number of iterations per time step.

TEST(20): Selects type of diodes-
Three choices are available, namely, PiN, P^+N and Schottky barrier diodes. The
switch determines the necessary parameters to be read into the computer, and provides appropriate initial estimates and boundary conditions.

TEST(22): Selects semiconductor material-
Either germanium or silicon can be selected. The switch will decide the correct normalization factors to be used and define suitable values for the mobilities of the carriers.

TEST(23): Gives transient output on punched cards-
When this switch is on, the output will include a deck of punched cards. Each card provides information (JTOT and POWER) of a mesh point for a certain time step. The point for which results are desired is specified by the input variable IXT.

TEST(24): Selects light intensity functions-
Three different functions are possible. They are pulse, step function and sinusoidal. Further details are given in Appendix D.
Other TEST options have already been described in Remple's paper. The input procedure is also very similar to that of PHODIM's. The only thing that needs to be noted is that the boundary value for $\psi(0,t)$ is set by defining $\text{PIMGS}$ as

$$\text{PIMGS} = \psi(0,t) + \phi_{bn}.$$
APPENDIX F
USER'S GUIDE TO JPLOT

The input deck for JPLOT is mainly comprised of the punched outputs from SCHOT. Several sets of data can be processed at the same time. The number of sets of data is indicated by the first card. For each set of data, two additional cards are required for providing information on the design parameters of the photodiode. Finally, the number of time steps (the number of cards obtained from SCHOT) is given by another card. The punched deck from SCHOT is then put behind the above cards. The input deck arrangement is summarized as follows.

Card #1  NSET - number of sets of data
Card #2  R, AREA, XDPLE - load resistance, area of diode and depletion width
Card #3  N_D, V, XL - doping density, applied voltage and length of diode
Card #4  N - number of time steps
Card #5  IXT, TIME, JTOT, POWER
Card #6  "
        "
        "
        "
Card #5+N  "
          }
          punched deck
          from SCHOT
APPENDIX G

PROGRAM LISTING OF SCHOT

PROGRAM SCHOT INPUT, OUTPUT, PUNCH, TAPE5 = INPUT, TAPE6 = OUTPUT,
+ TAPE7 = PUNCH,
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USES OMEGA OPTIMIZATION ROUTINE IN SYSTEM.
USES ALGORITHM TO DETERMINE PROFILE.

19 - USES OMEGA OPTIMIZATION ROUTINE IN SYSTEM.
18 - ZEROTH FIXED MESH.
ONE FOUR REGIONS OF DIFFERENT FIXED MESH.
20 - HAX HX FROM PROFILE USED.

19 - SETS UP ITERATION LIMIT.
ONE = UNLIMITED.
0 = MAXIMUM NO. OF ITERATIONS IS 100.
ONE = MAXIMUM NO. OF ITERATIONS IS 200.
THREE = MAXIMUM NO. OF ITERATIONS IS 300.
FOUR = MAXIMUM NO. OF ITERATIONS IS 400.
FIVE = MAXIMUM NO. OF ITERATIONS IS 500.

20 - GIVES BETTER INITIAL ESTIMATES AND BOUNDARY CONDITIONS.
ZERO = PIN DIODES.
ONE = P N DIODES.
TWO = SCHOTTKY DIODES.

22 - SELECTS MATERIAL.
ZERO = SILICON.
ONE = GERMANIUM.

23 - GIVES PUNCHED DECK OF TRANSIENT STATES.

24 - CHOOSES INPUT PULSE SHAPE.
0 = RECTANGULAR.
1 = EXPONENTIAL.
2 = SINE-SINUSOIDAL.

ABSCOEF - ABSORPTION COEFFICIENT OF PHOTODIODE TO INCIDENT RADIATION.
AREA - AREA OF PHOTODIODE.
BETA - IMPULSIVITY FACTOR, DEFINED ON PAGE 44.
DPSIAVE - MAXIMUM CHANGE IN PSI BETWEEN ITERATIONS.
EPSIAVE - AVERAGE CHANGE IN PSI BETWEEN ITERATIONS.
DPSISO - STANDARD DEVIATION OF THE CHANGE IN PSI BETWEEN ITERATIONS.
DOT = NUMBER OF GUESSES USED TO STEP OFF NE MESH SIZE.
EFMAX = MAX. ELECTRIC FIELD ACROSS DEPLETION LAYER.
EPI - LENGTH OF TRANSISTOR (INX(MESH+1)) DIVIDED BY NMESH.
HVE - HOLDS VE WHILE MONITOR CALCULATES STEADY STATE.
HFAC - MOBILITY NORMALIZATION FACTOR USED IN SYSTEM.
HVC - HOLDS VC WHILE MONITOR CALCULATES STEADY STATE.
HVFAC - MOBILITY NORMALIZATION FACTOR USED IN TRANSIENT ANALYSIS.
JDISP - DISPLACEMENT CURRENT DENSITY.
JFAC - CURRENT DENSITY NORMALIZATION FACTOR = 5.319547E-7 A/CM**2.
JRESIS - CURRENT GOING THROUGH LOAD RESISTOR.
JTOT - TOTAL CURRENT DENSITY.
LAMBDA - WAVELENGTH OF INCIDENT PHOTONS.
LFAC - LENGTH NORMALIZATION FACTOR = 3.5943 E-3 CM.
MFAC = MOBILITY NORMALIZATION FACTOR = 39.6473 CM**2/V-S.
NA = ATOMIC DENSITY OF METAL.
NFAC = DOPING NORMALIZATION FACTOR = 1.3281E+10 CH-3.
OMEGA = ACCELERATION PARAMETER USED IN SYSTEM.
PEA - ELECTRON AFFINITY.
PF = SCALAR FACTOR TO TAKE MEAN OF EQUATION 3.2 AND 3.3 (POISSON)
PIMGS - MAX. VALUE OF PING.
PIT = POTENTIAL IN INTERFACIAL STATES.
PM = WORK FUNCTION FOR METAL.
POWER = POWER OF INCIDENT BEAM IN WATTS.
PROF - VALUE OF DOPING PROFILE AT COLLECTOR.
PROFM - MAXIMUM DOPING CONCENTRATION (CH**3).
PSINT = PSI AT THERMAL EQUILIBRIUM.
PVN = POTENTIAL BETWEEN CONDUCTION BAND AND QUASI-FERMIII LEVEL IN N TYPE SEMICONDUCTOR.
QNTEFF - QUANTUM EFFICIENCY OF PHOTOEJIDE.
QTQTSUM - SUM OF QUANTUM CHOSEN UPON WHICH TO BASE REMESH.
RLOAD - LOAD RESISTOR IN SERIES WITH DIODE.
TAU = TIME STEP, OR INCREMENT.
TFAC - TIME NORMALIZATION FACTOR = 1.29207 E-5 S.
TIMEFAC - SPECIFIES AMPLITUDE OF INPUT PULSE WITH RESPECT TO TIME.
TPEAK - TIME AT WHICH INPUT PULSE REACHES ITS PEAK.
TRGA - GAUSSIAN RISE TIME OF INPUT PULSE.
TRN - TIME FOR RECOMBINATION OF ELECTRONS.
TRP - TIME FOR RECOMBINATION OF HOLE.
TSTOP - TIME AT WHICH TRANSIENT ANALYSIS IS TO BE STOPPED.
UFAC - RECOMBINATION NORMALIZATION FACTOR = 1.02794 E+15 1/ICM**3 - SEC
VC - COLLECTOR VOLTAGE.
VCSS - STEADY STATE APPLIED COLLECTOR VOLTAGE.
VE - EMITTER VOLTAGE.
VEK - PREVIOUS VALUE IN TIME OF VE.
VCK - PREVIOUS VALUE IN TIME OF VC.
VESS - STEADY STATE APPLIED EMITTER VOLTAGE.
VPAC - VOLTAGE NORMALIZATION FACTOR = 0.029875 V.
VIFAC = 1/(0.1*14.59*UFAC*ICM**3)
VOLUME - VOLUME THROUGH WHICH ONE SECOND OF LIGHT IS SPREAD.
VSTOP - SATURATION VELOCITY OF ELECTRONS (CM/SEC).
VSATP - SATURATION VELOCITY OF HOLES (CM/SEC).
WS1, WS2,... - WORKING STORAGE.
XDP - DEPLETION REGION THICKNESS.
XIMG - IMAGE FORCE EFFECT IS DOMINANT FROM X=0 TO X=XIMG.
XL - LENGTH OF DIODE.
XM - MAX. BARRIER LOCATION.
X0 - USED IN REMESH.

REAL CVOLTS, DFSPL, DFSPH, DX, EVOLTS, MN, MP, PSI, INPROF, INPROFG,
+ INX, JN, JNK, JP, JPK, M11, M12, M13, MN, MP, PROF, PROFG, SP, SSTIME,
+ TATIME, TVTIME, UK, X, PAV, PING

CVOLTS - COLLECTOR VOLTAGE AT SUCCESSIVE POINTS IN TIME.
DFSPL - LOWEST BOUNDARY OF MESH REGION TO HAVE DIFFERENT SPACING.
DFSPH - HIGHEST BOUNDARY OF MESH REGION TO HAVE DIFFERENT SPACING.
DX - DISTANCE BETWEEN ADJACENT MESH POINTS.
MN - HOLDS N WHILE MONITOR CALCULATES STEADY STATE.
MP - HOLDS P WHILE MONITOR CALCULATES STEADY STATE.
INPROF - INPUT (DONOR - ACCEPTOR) DOPING PROFILE.
INPROFG - INPUT (DONOR + ACCEPTOR) DOPING PROFILE.
INX - SPATIAL POSITIONS AT WHICH DOPING WAS READ.
JN - ELECTRON CURRENT DENSITY.
JNK - HOLDS ELECTRON CURRENT DENSITY OF PRECEDING TIME STEP.
JP - HOLE CURRENT DENSITY.
JPK - HOLDS HOLE CURRENT DENSITY OF PRECEDING TIME STEP.
M11, M12, M13 - PARABOLIC INTEGRATION COEFFICIENTS.
MN - ELECTRON MOBILITY.
MP - HOLE MOBILITY.
P - POTENTIAL FUNCTION DUE TO APPLIED BIAS.
PROF - INTERPOLATED DOPING PROFILE FROM INPROFN TO ACTUAL MESH USED.
PROFG - INTERPOLATED DOPING PROFILE FROM INPROFNG TO ACTUAL MESH USED.
SSTIME - TIMES AT WHICH STEADY STATE ANALYSIS IS DESIRED.
TATIME - TIME AT WHICH TIMES AT WHICH STEADY STATE ANALYSIS IS DESIRED.
U - RECOMBINATION TERM.
UK - HOLDS RECOMBINATION TERM OF PRECEDING TIME STEP.
X - POSITION COORDINATE. NUMBER OF POINTS IS FIXED. MESH SIZES CHANGE.

DOUBLE N, NK, P, PK, PSI, PSIK, PSIOLD

N - ELECTRON CARRIER DENSITY FOR EACH SPACIAL POINT.
NK - HOLDS ELECTRON CARRIER DENSITY OF PRECEDING TIME STEP.
P - HOLE CARRIER DENSITY FOR EACH SPACIAL POINT.
PK - HOLDS HOLE CARRIER DENSITY OF PRECEDING TIME STEP.
PSI - POTENTIAL FOR EACH SPACIAL POINT.
PSIK - HOLDS POTENTIAL OF PRECEDING TIME STEP.
PSIOLD - HOLDS POTENTIAL OF PRECEDING ITERATION STEP.
READ IN PROGRAM TEST OPTIONS.

DO 10 I=1,26,5
  READ 5,TEST(I),TEST(I+1),TEST(I+2),TEST(I+3),TEST(I+4)
  FORMAT (5I9.11)
  PRINT 12,TEST(I),I+1,TEST(I+1),I+2,TEST(I+2),I+3,TEST(I+3),
  I+4,TEST(I+4)
  FORMAT (8TEST(I+0),"="I5/
  + "TEST(I+1)="I5/
  + "TEST(I+2)="I5/
  + "TEST(I+3)="I5/
  + "TEST(I+4)="I5/

******************************************************************************

NORMALIZATION FACTORS FOR SILICON.

IF ( TEST(22) .NE. 0 ) GOTO 1
  JFAC=5.919547 E-7
  LFAC=35.946 E-4
  MFAC=38.5473
  NFAC=1.328168 E+10
  TFAC=1.2920718 E-5
  UFAC=1.02794 E+15
  VFAC=0.25875

******************************************************************************

NORMALIZATION FACTORS FOR GERMANIUM.

IF ( TEST(22) .NE. 1 ) GOTO 2
  JFAC=-3.96253 E-2
  LFAC=9.70290 E-5
  MFAC=38.6473
  NFAC=3.8 E+13
  TFAC=9.41463 E-9
  UFAC=2.55070 E+21
  VFAC=0.25875
CONTINUE

******************************************************************************

READ IN LOCATION FOR TRANSIENT PUNCHED OUTPUT.

IF ( TEST(23) .NE. 1 ) GOTO 14

READ 13,IXT
  FORMAT(I10)
CONTINUE

******************************************************************************

READ IN DIODE PARAMETERS.

READ 15,ABSCOEF,AREA,LAMBDA,POWER,RLOAD
READ 15,QNTMEFF,HTAU,TPEAK,TRISE
  FORMAT (5F10.0)
  PRINT 18,ABSCOEF,AREA,LAMBDA,POWER,RLOAD,QNTMEFF,HTAU*1.E12,
  "TPEAK=","TRISE",".*1.E12"
  FORMAT (2F10.4,2F10.4,2F10.4,2F10.4,2F10.4,2F10.4,2F10.4,2F10.4,2F10.4)
  ABSCOEF=ABSCOEF/LFAC/1.E4
  EPHOTON=1.98647E-19/LAMBDA
  HTAU=HTAU/TFAC
  JFAC=JFAC*AREA
  TPEAK=TPEAK/TFAC
  TRISE=TRISE/TFAC
  VOLUME=AREA*ABSCOEF/LFAC
  G=POWER/VOLUME/EPHOTON*QNTMEFF/UFAC

******************************************************************************

READ IN TOLERANCES.

READ 15,OMEGA,EPSDMAX,EPSDAVE,EPSDSD
  FORMAT (I10,4F10.0)
  PRINT 30,OMEGA,EPSDMAX,EPSDAVE,EPSDSD
  FORMAT (4F10.4,3F10.4,3F10.4,3F10.4)
  EPSDMAX=EPSDMAX/UFAC
  EPSDAVE=EPSDAVE/UFAC
  EPSDSD=EPSDSD/UFAC
**READ IN MOBILITY DATA.**

```plaintext
READ 15, ESAT, VSATN, VSATP
PRINT 140, ESAT, VSATN, VSATP
```

**READ IN RECOMBINATION DATA.**

```plaintext
READ 15, ETRAP, TRN, TRP
PRINT 120, ETRAP, TRN, TRP
```

**READ IN TRANSIENT DRIVING VOLTAGES.**

```plaintext
READ 20, NTV, VCSS, VEPP, JEST
PRINT 140, VCSS, VEPP
```

**READ TIMES AT WHICH STEADY-STATE CALCULATIONS ARE TO BE MADE.**

```plaintext
READ 20, NSS
IF ( NSS .EQ. 0 ) GOTO 270
DO 260 I=1, NSS
READ 15, SSTIME(I), SSTIME(I) = SSTIME(I) / TFAC
```

**READ IN TRANSIENT ANALYSIS TIMES.**

```plaintext
READ 20, NTA, INBETA, TSTOP
PRINT 275, NTA, INBETA, TSTOP = 1.E12
```

**READ IN SCHOTTKY DIODE PARAMETERS.**

```plaintext
IF ( TEST(20) .NE. 2 ) GOTO 299
```

```plaintext
READ 295, NA
READ 15, PM, PEA, PIT, EGAP, PIMGS
PBO = PM - PEA - PIT
PRINT 297, PBO, PM, PEA, PIT, EGAP, PIMGS, NA
```
READ IN MESH SPACING

H = 0.
IF TEST(18) = 0, USE UNIFORMLY SPACED MESH.

IF ( TEST(18) .NE. 0 ) GOTO 310
READ 20, N MESH, XL
XL = XL / LFAC / 1.4
H = XL / N MESH
N MESH P1 = N MESH + 1
DO 300 I = 1, N MESH P1
X(I) = I * H
DX(I) = H
JN(I) = JN (I) = JP (I) = NK(I) = PK(I) = PSIK(I) = U(I) = UK(I) = 1.4 - 35
GOTO 300

IF TEST(18) = 1, USER SPECIFIES REGIONS OF DIFFERENT MESH SPACING.

IF ( TEST(18) .NE. 1 ) GOTO 347
READ 15, XL, H
H = H / LFAC / 1.4
CHANGE 10H
DO 350 I = 1, 4
READ 15, DFSPL(I), DFSPIH(I), S P(I)
PRINT 315, CHAR, I, DFSPL(I), DFSPIH(I), I, S P(I)
FORMAT (A, F10.4, 10X, "DFSPL(", I1, ") = ",F10.4,
+ 10X, "DFSPIH(", I1, ") = ", F10.4, 10X, "MICROMETERS.")
DFSPL(I) = DFSPL(I) / LFAC / 1.4
DFSPIH(I) = DFSPIH(I) / LFAC / 1.4
SP(I) = SP(I) / LFAC / 1.4
CONTINUE

CHAR = 10H
X(I) = 0.
JN(I) = JN(I) = JP(I) = NK(I) = PK(I) = PSIK(I) = U(I) = UK(I) = 1.4 - 35
I = I + 1
GOTO 340
CONTINUE
X(I) = X(I-1) + SP(I)
GOTO 340

340 CONTINUE

IF ( TEST(17) .NE. 2 ) GOTO 330
READ 15, EPI, PROFINT, PROFCOL
READ 15, XEFLAT, XEGAU S
READ 15, XCMIN, XCMAX, ACOLL, BCOLL, CCOLL
PRINT 385, EPI, PROFINT, PROFCOL, XEFLAT, XEGAU S, XCMIN, XCMAX, ACOLL, BCOLL, CCOLL
C EPI=EPI/NFAC
PRFINT=PRFINT/NFAC
PRFCOL=PRFCOL/NFAC
XEFLAT=XEFLAT/LFAC/1.E4
XEGAUS=XEGAUS/LFAC/1.E4
XMN=XMN/LFAC/1.E4
XCHAX=XCHAX/LFAC/1.E4
XCMIN=XCMIN/LFAC/1.E4
BCOLL=XCMIN+BCOLL/LFAC/1.E4
CCOLL=CCOLL/LFAC/1.E4

C CALCULATE PARABOLIC INTEGRATION COEFFICIENTS.
DO 400 I=2,NHESH
  WS11=DX(I)
  WS12=DX(I+1)
  WS13=WS11
  WS14=WS12
  WS15=WS12
  WS16=WS12
  M11(I)=(WS13-2.*(WS14-WS15))/24./WS12
  M12(I)=(WS15-WS12)/2.-M11(I)
400

C CALCULATES PARAMETERS FOR SCHOTTKY DIODE.

IF ( TEST(20).NE. 2 ) GO TO 650
  WS1=PROFEM
  WS2=SQRT(WS1/4.+1.)*ABS(WS1/2.)
  PVN=SIGN(ALOGIABS(WS2),WS1)
  PVN=EGAP/2.-PVN
  APPROXIMATION - PBN=PBO
  PBI=PBO-PVN
  WS70=I
defs=2/PI*WS1/2
  VIFAC=1./(16.314159*NFAC*LFAC**3.)
  XH=SQRT(2.*EFMAX/XFAC)
  PBL=2.*EFMAX/XH
  PBI=WS50
  IF ( I GE. 100 ) GOTO 605

600 FORMAT ("*********** ERROR IN PBI IS .GT. 1 PER CENT."), EOS. 1 PAGE
610 PRINT 620, PBN*VFAC,PBL*VFAC, WS70/VFAC**XH*LFAC*1.E4
620 FORMAT (" PBN = \"F10.4,\" VOLTS.
+ " PBL = \"F10.4,\" VOLTS."
+ " XH = \"F10.4,\" MICROMETERS.\"
+ " CONTINUE
650
C DETERMINE PROFILE FOR MESH BEING USED.
C CALL PROFILE

IF ( TEST(9).NE. 1 ) GOTO 800
  WS1=ALOGIABS(EPI(1,E4))
  RANGE=ALOGIABS(ABS(PROFEM))=WS1/100.
  DO 530 I=1,NMESH
  WS1=(ALOGIABS(PROF(I))=WS1)/RANGE
  IF ( WS1 .LT. 0 ) WS1=0
  IF ( PROF(I) .GT. 0 ) CHAR=10H-
  IF ( PROF(I) .LT. 0 ) CHAR=10H+
  P=PRINT 540, (I-1)*X(I)*LFAC**1.E4,PROF(I)*NFAC,WS1+3,CHAR
  FORMAT (14,F9.4,E13.5,=X,A1)

540

C SET UP INITIAL ESTIMATES.
T=-3
C
C CALL INITIAL
SOLVE FOR STEADY STATE SOLUTION.

BETA=1.
TAU=1.E100
FORCES STEADY STATE.

IF TEST(14)=1, OUTPUT INITIAL ESTIMATE.
IF ( TEST(14) .NE. 1 ) GOTO 860
PRINT 850
FORMAT ("INITIAL ESTIMATE")
CALL OUTVALU

IF TEST(13)=0, CALCULATE FIXED MESH STEADY STATE VALUES.
IF ( TEST(13) .NE. 0 ) GOTO 900
PRINT 880, EPSMAX*VFAC, EPSAVE*VFAC, EPSDSD*VFAC, OMEGA
PRINT 940
FORMAT ("OMEGA",E8.4," NO. OF POS. PNTS.")
CALL SYSTEMS

IF TEST(13)=1, CALCULATE REMESHED STEADY STATE VALUES.
IF ( TEST(13) .NE. 1 ) GOTO 1340
T=-1.
CALL REMESH
CALL INITIAL
PRINT 980, EPSMAX*VFAC, EPSAVE*VFAC, EPSDSD*VFAC, OMEGA
CALL OUTVALU

BEGIN TRANSIENT ANALYSIS.

T=0.
TAU=HTAU
BETA=INBETA
REST OF PROGRAM IS CALCULATED FOR EACH STEP.

IF TEST(1)=1, USER HAS INPUT TRANSIENT ANALYSIS TIMES.
IF ( TEST(1) .NE. 1 ) GOTO 1900
IF ( TINDEX .GT. NTA ) GOTO 2350
TAU=TATIME(TINDEX)

IF TEST(1)=0, A CONSTANT TAU DETERMINES TRANSIENT ANALYSIS TIMES.
T = T + TAU
VCK = VC, VEK = VE

CALL VOLTAGE

FORMAT ("0///" STEP = ", I3, 4X, "TIME = ", E11.5)

DO 2110 I = 1, NHESH
    JNK(I) = JNII
    JPK(I) = PKII
    PSI(KII) = PSI(I)
    UK(I) = UII

DO 2120 PSI(I) = PSI(I) + (VE-VEK) * INPLUS(I) + (I-IPPLUS) * (VC-VCK)

CALL PRINT

CALL CURRENT

CALCULATE STEADY STATE MONITOR POINTS.

GOTO 2330

CALL MONITOR

IF ( T .GE. SSINDEX ) AND SSINDEX .LE. NSS GOTO 2330

CHECK TO SEE IF PROGRAM IS DONE.

IF ( T .LE. TSTOP ) GOTO 1700

CALL PRINT

REAL CVOLTS, DFSPL, DFSPH, DX, EVOLTS, HN, HP, HPSI, INPROF, INPROFG, 
+ INX, INJ, JNK, JP, JPK, MI, M2, M3, MN, MP, PROF, PROFG, SP, SSTIME, 
+ STIME, TVTIME, U, UK, PAV, PING

DOUBLE N, NK, P, PSI, PSIK, PSIOLD

DOUBLE PRECISION AN(201), BN(201), CN(201), DN(201), AP(201), DP(201), 
+ CP(201), DP(201), M1, M2, M3, WS1, WS2, WS3, WS4, WS5, WS6, WS7, WS8, WS9,
+ WS10, WS11

DO 100 I = 2, NMESH
  M1 = MI(1)
  M2 = MI(2)
  M3 = MI(3)
  WS1 = DX(I) 
  WS2 = DX(I+1)
  WS3 = PSI(I+1) - PSI(I-I)
  WS4 = PSI(I+1) - PSI(I-I)
  WS5 = DEXP(WS4) 
  WS6 = DEXP(WS4)
  IF ( DABS(WS6) .GT. 1.E-7 ) GOTO 10
  WS7 = 2./((1.+WS3*(1./3.00+WS3/12.)))/2./WS1
  GOTO 20
10  WS7 = WS3/(1.-WS5)/2./WS1

IF ( DABS(WS4) .GT. 1.E-7 ) GOTO 30
  WS8 = 2./((1.+WS4*(1./3.00+WS4/12.)))/2./WS2
  GOTO 40
30  WS8 = WS4/(1.-WS6)/2./WS2

SET UP THE N TRIDIAGONAL MATRIX.

40  WS9 = (MN(1)+MN(1-I))*WS7
  WS10 = (MN(1)+MN(1-I))*WS8
  WS11 = 1./BETA/TAU
  AN(I) = KS9*WS5 + M1*WS11
  BN(I) = WS9 - WS10*WS6 + M2*WS11
  CN(I) = WS10 + M3*WS11
  DN(I) = M1*(-UI-I)+MK-I-1J*WS11 + M2*(-UI-I)+MK-I-1J*WS11 + 
    M3*(-UI-I)+MK-I-1J*WS11
  IF ( BETA .EQ. 1. ) GOTO 50
  DN(I) = DN(I)*(-1.-BETA)/BETA*JN(I+1)+JN(I)-MJ(U(I-I))-
    M2*UK(I)-M3*UK(I+1)

SET UP THE P TRIDIAGONAL MATRIX.

50  WS9 = (MP(I)+MP(I-I))*WS7
  WS10 = (MP(I)+MP(I-I))*WS8
  AP(I) = WS9 - M1*WS11
  BP(I) = WS9*WS5 + M2*WS11
  CP(I) = WS10 + M3*WS11
  DP(I) = M1*(UI-I)-PK(I-I)*WS11 + M2*(UI-I)-PK(I-I)*WS11 + 
    M3*(UI-I)-PK(I-I)*WS11
  IF ( BETA .EQ. 1. ) GOTO 100
  DP(I) = DP(I)*(-1.-BETA)/BETA*JN(I+1)+JN(I)-MJ(U(P+1)-
    M2*UK(I)+M3*UK(I+1))

CONTINUE

SOLVE THE N TRIDIAGONAL MATRIX.

DN(2) = CN(2)/BN(2)
DO 120 I = 3, NMESH
  WS1 = BN(I)*AN(I)*CN(I-1)
  WN(I) = CN(I)/WS1
  DN(I) = (DN(I)-AN(I)*DN(I-1))/WS1
120  I = NMESH
  WN(I) = DN(I)-CN(I)*NI+1
  I = I-1
  IF ( I .GE. 2 ) GOTO 130

SOLVE THE P TRIDIAGONAL MATRIX.

AP(NMESH) = AP(NMESH)/AP(NMESH)
DP(NMESH) = (DP(NMESH)-CP(NMESH)*PN(MESH+1))/AP(NMESH)
DO 150 I = 2, NMESH
  WS1 = BP(I)-CP(I)*AP(I)+1
  AP(I) = AP(I)/WS1
  DP(I) = (DP(I)-CP(I)*DP(I+1))/WS1
  I = I-1
  IF ( I .GE. 2 ) GOTO 150
DO 170 I = 2, NMESH
SUBROUTINE CURRENT
CALCULATES PARTICLE CURRENTS JN AND JP ACCORDING TO EQUATION 5.11.

COMMON DIVSUM, INDEX, INPLUS, INXJC, IPPLUS, JCN, IWS1, IWS2, IWS3,
+ IWS4, LOC, MESHIN, MESH, MESHPI, NWS, NTA, NTV, SSINDEX, TAINDEX,
+ TINDEX, TEST(30), IXT,
+ A/BSCOF, AREA, BETA, DPSIAVE, DPSMAX, DPSISO, DOTTY, EPHOTON,
+ EPS, EPSMAX, EPSISO, ESAT, STRAP, G, H, MT, MTAU, HVC,
+ HVE, INBETA, JDISP, JEST, JFAC, JRESIS, JTO, LAHADA, LFAC, MFAC,
+ NFAC, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QNUMEEF,
+ QITSYN, LOAD, T, TAU, TFAC, TIMEFA, PEAK, TRISE, TRN, TRP,
+ TSTOP, UFAC, VC, VCK, VCSS, VE, VEK, VESS, VFAC, VOLUME, VSAI,
+ VSAT, XL, X0, ACOLL, DCOLL, ACCOL, ACMAX, ACME, XFLAT, XGAUS,
+ XPLE, PSINT, PB0, PBN, PIT, PM, PEA, PBL, EGAP, PIMGS, EMAX, XM, PBI,
+ PVN, XIMG, VIFAC, NA,
+ CVOLTS(20), DFSPL(4), DFPH(4), DX(20), EVOLTS(20), HM(20),
+ HP(20), HPSI(20), INFROF(20), INPROF(20), INX(20),
+ JN(20), JNK(20), JP(20), JP(20), JPI(20), NP(20), NSF, NT(20),
+ NSI(20, 20), NSI(20, 20), NSI(20, 20), NSI(20, 20), NSI(20, 20),
+ NSI(20, 20), mass, NWS(20), W0(20), W1(20), W2(20), W3(20),
+ WS(20), W0, W1, W2, W3, W4, W5, W6, W7, W8, W9, W10,
+ WS1, WS2, WS3, WS4

DO 40 I=2, NMESH
WS1=(PSI(I)-PSI(I-1))
WS2=0.5*EXP(WS1)
FOR (ABS(W3)=1.E-3) GOTO 20
WS3=2.-(WS1/WS2)
GOTO 30
WS3=WS3
JN(I)=(HN(I)+HN(I-1))/2.*WS3.(N(I)-N(I-1)*WS3)
JP(I)=(MP(I)+MP(I-1))/2.*WS3.(P(I)-P(I-1)*WS3)
RETURN
END

SUBROUTINE INITIAL
SET UP INITIAL GUESS FOR PSI AND CARRIERS.
COMMON DIVSUM, INDEX, INPLUS, INXJC, IPPLUS, JCN, IWS1, IWS2, IWS3,
+ IWS4, LOC, MESHIN, MESH, MESHPI, NWS, NTA, NTV, SSINDEX, TAINDEX,
+ TINDEX, TEST(30), IXT,
+ A/BSCOF, AREA, BETA, DPSIAVE, DPSMAX, DPSISO, DOTTY, EPHOTON,
+ EPS, EPSMAX, EPSISO, ESAT, STRAP, G, H, MT, MTAU, HVC,
+ HVE, INBETA, JDISP, JEST, JFAC, JRESIS, JTO, LAHADA, LFAC, MFAC,
+ NFAC, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QNUMEEF,
+ QITSYN, LOAD, T, TAU, TFAC, TIMEFA, PEAK, TRISE, TRN, TRP,
+ TSTOP, UFAC, VC, VCK, VCSS, VE, VEK, VESS, VFAC, VOLUME, VSAI,
+ VSAT, XL, X0, ACOLL, DCOLL, ACCOL, ACMAX, ACME, XFLAT, XGAUS,
+ XPLE, PSINT, PB0, PBN, PIT, PM, PEA, PBL, EGAP, PIMGS, EMAX, XM, PBI,
+ PVN, XIMG, VIFAC, NA,
+ CVOLTS(20), DFSPL(4), DFPH(4), DX(20), EVOLTS(20), HM(20),
+ HP(20), HPSI(20), INFROF(20), INPROF(20), INX(20),
+ JN(20), JNK(20), JP(20), JP(20), JPI(20), NP(20), NSF, NT(20),
+ NSI(20, 20), NSI(20, 20), NSI(20, 20), NSI(20, 20), NSI(20, 20),
+ NSI(20, 20), mass, NWS(20), W0(20), W1(20), W2(20), W3(20),
+ WS(20), W0, W1, W2, W3, W4, W5, W6, W7, W8, W9, W10,
+ WS1, WS2, WS3, WS4

DOUBLE PRECISION WS1, WS2, WS3, WS4

DO 30 I=1, NMESH-1
WP(I)=PSI(I) - PSI(I-1)
WS(I)=EXP(WS2)
FOR (ABS(W3)=1.E-3) GOTO 20
WS2=2.-(WS1/WS2)
GOTO 30
>& 30
WP(I)=WP(I) + WP(I-1)
RETURN
END
INTEGER DIVSUM, INDEX, INPLUS, INXCN, IPPLUS, JCN, INSI, INSS1, INSS2, INSS3,
+ IS1, LOC, MESHIN, NMESH, NMESHPI, NSS, NTA, NTV, SSINDEX, TAINDEX,
+ TVINDEX, TEST, TVMESH
REAL ABSQCOFF, AREA, BETA, DQPSAVE, DQPSMAX, DQPSIO, DOTTY, DPHOTON,
+ EPSQ, EPSQMAX, EPSQDEF, ESAT, ETARP, G, H, HTAU, HV, HVE,
+ INF, INPSAVE, JPSAVE, JPSAVE, JPSAVEF, JPSAVEF, JPSAVEF, JPSAVEF, JPSAVENFAC,
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SET UP INITIAL ESTIMATES AND BOUNDARY CONDITIONS FOR SCHOTTKY.

IF ( TEST(20) .NE. 2 ) GOTO 600
VIFAC=PIMGS
NMESH1=NMESH+1
DO 580 I=1,NMESH1
IF ( X(I) .GE. XIHG ) PING(I)=VIFAC/X(I)
IF ( X(I) .LT. XDPLE ) PAV(I)=EFMAX*X(I)-PROFEM*X(I)*X(I)/2.
PSII(I)=EGAP/2.+PAV(I)+PING(I)-PBN-PBL
CONTINUE

N(I)=NA
P(I)=N(I)
N(NMESH1)=DEXP(PSI(NMESH1)-VC+VE)
N(NMESH1)=1./N(NMESH1)

CALL MOBREC
INITIAL GUESS NOW ESTABLISHED.

RETURN ENDO

SUBROUTINE MOBREC
CALCULATES CARRIER MOBILITIES AND RECOMBINATION COEFFICIENTS.

COMMON DIVSUM, INDEX, INPLUS, INJCN, IPPLUS, JCN, IWS1, IWS2, IWS3,
+ IWS4, LOC, MESH1, NMESH, MESH1, NSS, NTA, NTV, SSINDEX, TINDEX,
+ TEST, IXT
REAL ABSCOEF, AREA, ETA, DPMAX, DPMAX, DPISO, DQTY, EPHOTON,
+ EPSAVE, EPSAVE, EPSAVE, EPSAVE, EPSAVE, EPSAVE, EPSAVE, EPSAVE, FN, HTAU, HVC,
+ HVE, INBET, JDISP, JEST, JFA, JFA, JFA, JFA, JFA, JFA, JFA, JFA, JFA, JFA,
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```plaintext
CALCULATE RECOMBINATION COEFFICIENTS.

W2 = T
IF ( T .LT. 0. ) T = 0.

EXPONENTIAL INPUT PULSE.

IF ( TEST(24) .NE. 0 ) GOTO 180
TIMEFAC = (T/TRISE)**2 * EXP((1.-T**2)/TRISE/2.)

RECTANGULAR INPUT PULSE.

IF ( TEST(24) .NE. 1 ) GOTO 190
IF ( T .LT. TPEAK ) TIMEFAC = T/TPEAK
IF ( T .GE. TPEAK ) TIMEFAC = 1.0

SINUSOIDAL INPUT.

IF ( TEST(24) .NE. 2 ) GOTO 195
TIMEFAC = SIN(3.14159/2.0*TPEAK/2)

CONTINUE

SUBROUTINE MONITOR

COMPUTE STEADY-STATE SOLUTION AT TIME MONITOR POINTS.
```
REAL ABSCOEF, AREA, BETA, DPSIAVE, DPSIMAX, DPSISO, DOTY, EPHOTON,
* EP, EPSAVE, EPSMAX, PSOSD, ESAT, ETAP, G, H, HTAU, HVCC,
* HV, INETA, JDISP, JEST, JFAC, JRESIS, JTO, LAMBO, LFA, MFAC,
* NFA, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QNTMEFF,
* QTYSUM, RLOAD, T, TAU, TFA, TIMEFA, TPEAK, TRISE, TRM, TRP,
* TSTOP, UFAC, VC, VCC, VCSS, VE, VK, VESS, VFA, VOLUME, VSATN,
* X, XPPLE, PRINT, POW, PON, PUP, PJM, PE, PLE, PBL, EGA, PIMS, EMAX,
* XM, PBI, PVN, XING, VFA, HT1, NA
REAL CVOLTS, DFSP, DSH, DX, DVO, VOLTS, HN, HP, HPSI, INPROF, INPROF,
* J, JPN, JSM, JSP, JSS, JTP, JWM, JP, JPM, MP, PROF, PROF, SQ, STIME,
* TIME, TTIME, UKY, PAV, PING
DOUBLE NK, PK, PSI, P5K, PSI0L

C
H1 = HVCC
HV = HVCC
TAU = 1.E100
NMESH1 = NMESH + 1
HP(I) = P(I) + 1
HN(I) = HN(I) - 1
100 T = SSINEX(SSINDEX) / 140, SSINDEX, TPEAC
140 FORMAT ('"MONITOR POINT", I3, 5X, "TIME = ", E11.5)
CALL VOLTAGE
SSINDEX = SSINDEX + 1.
IPP1 = IPP1 + 1
DO 180 I = 1, IPP1
   IPPP1 = IPPP1 + (VE - HVE)
   IPPP2 = IPPP2 + 2
180 JCNP = JCNP + 1
DO 200 I = IPPLUS, JCNP
   JCNP1 = JCNP1 + 1
   PSII(I) = PSI(I) + (VE - HVE)*(JCN - I + 1) / (JCN - IPPPLUS)
200 JCNP2 = JCNP2 + 2
DO 220 I = JCNP2, INPLUS
   INPLUS1 = INPLUS1 + 1
   PSI(I) = PSI(I) + (VE - HVE)*(I - JCN) / (NMESH - JCN)
220 INPLUS = INPLUS
DO 240 I = INPLUS, NMESH
   INPLUS = INPLUS + 1
240 DO 260 I = INPLUS, NMESH + 1
   PSI(I) = PSI(I) + (VE - HVE) / (NMESH - JCN)
260 FORMAT ('"MONITOR STEADY-STATE AT TIME = ", E11.5, 5X,
   "N-REGION P-CHARGE = " , E11.5)
CALL OUTVAL
BETA = INBETA
T = TAU
VAR = HTAU
VC = HV
VE = VC
DO 490 I = 1, NMESH1
   HP(I) = HP(I) + 1
490 PSII(I) = HPSII(I)
PRINT 590, 'T' + T, 'FAC, VE' + VFAC, 'VC' + VFAC, 'JN(JCN)' + JFAC
590 PRINT 590, 'T' + T, 'FAC, VE' + VFAC, 'VC' + VFAC, 'JN(JCN)' + JFAC
   ' + E10.4, 'X', 'JN(JCN) = "', E10.4
   + EFAC
END

SUBROUTINE OUTVAL
OUTPUT VALUES OF ALL VARIABLES. DIFFERENT OUTPUT FOR STEADY-STATE
CALCULATIONS AND TRANSIENT CALCULATIONS.
COMMON DIVSUM, INDEX, INPLUS, INXJCN, IPPPLUS, JCN, IWS1, IWS2, IWS3,
* IWS4, LOC, MESHNP, NMSH, NMESHPI, NSS, NTA, NTN, SSINDEX, TAINDEX,
* VSAT, XLP, XCS, XCLL, XCM, XEFL, XEFL, XEG, XEG, XEG, XEG, XEG,
* XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL,
* XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL, XEFL,
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REAL CVOLS(20), DFSP(4), DFSF(4), DX(201), EVOLTS(20), HN(201),
HP(201), HPCI(201), INPROF(201), EVOLTS(20), HN(201),
MI(201), MI(201), MI(201), MI(201), MI(201), MI(201),
MI3(201), MI3(201), MI3(201), NK(201), PI(201), PK(201), PSI(201),
PSIK(201), PSLD(201)

INTEGER DIVSUM, INDEX, INPLUS, INXCN, IPPLUS, JCN, IWS1, IWS2, IWS3,
IWS4, LOC, MESHIN, NMESH, NSS, NT, NTA, NSSINDEX, TAINDEX,
TVINDEX, TEST, IX

REAL ABSCOEF, AREA, BETA, DPSIAVE, EPSMAX, EPSSEP, DATY, EPMHTON,
EPMH, EPSSEP, EPSSEP, EPSSEP, EPSSEP, EPSSEP, EPSSEP, EPSSEP,
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CALL PLOT(0XHX-XHR,0YHX-YHR,2)  
CALL PLOT(0XMX-XMR,0YHN+YMR,2)  
CALL PLOT(0XHN+XMR,0YMN+YMR,2)  
PLOT HEADING.

IF ( T .NE. -3. ) GOTO 35
ENCODE (NT,31,TITLE(1))
FORMAT (40HN,P,PSI VS. X (INITIAL EST,STEADY STAT))
CALL LETTER(3,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
GOTO 35

IF ( T .NE. -2. ) GOTO 40
ENCODE (NT,36,TITLE(1))
FORMAT (40HN,P,PSI VS. X (STEADY STAT,T= ))
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,37,TITLE(1))
FORMAT (74X,HPSEC,2X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
GOTO 45

IF ( T .LT. 0. ) GOTO 49
ENCODE (NTT,41,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,42,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,43,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,44,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,45,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,46,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,47,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,48,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,49,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,50,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,51,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,52,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,53,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,54,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,55,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,56,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,57,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,58,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,59,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
ENCODE (NTTT,60,TITLE(1))
FORMAT (74X,3XHONITOR POINT,31X)
CALL LETTER(NT,2,HGT,0.0,0XHN+.5*(0XMX-0XHN)-NT*HGT,  
+ OYMN+.5*YMR-HGT,TITLE)
PLOT PSI AXIS SCALE.

NPSID=VFAC*(IPSIMX-IPSIMN)/10.*.1
I=1
I=I+1
ENCODE (5,72,PSILABE) IPSIMN*VFAC*I*10.
72
FORMAT (5.1)
CALL LETTER(5,HGT,0.0,OXMX-.70*XMR-2.5*HGT,
+ OYN=+HMR*IPYRNG/NPSID-.5*HGT,PSILABE)
CALL PLOT(0XMX-XMR,OXMN+YMR*IPYRNG/NPSID,3)
CALL PLOT(0XMX-XMR,SCS,OXMN+YMR*IPYRNG/NPSID,2)
IF ( I .LE. NPSID-.99 ) GOTO 70
100
GOTO 150
100
CALL NEWPEN(!)
IF ( I .LT. 6. ) GOTO 150

PLOT TIME IN PREVIOUS PLOT HEADING.

ENCODE (40,105,TITLE(1)) IFIX*(1.E12*TFAC+.5)
105
CALL LETTER(40,2.*HGT,0.0,5*OXMX-NT*HGT,OXMX-.5*YMR-HGT,TITLE)
110
IF ( TAU .LT. 1.E19 ) GOTO 150

PLOT "MONITOR POINT" UNDERNEATH PREVIOUS PLOT HEADING.

ENCODE (40,120,TITLE(1)) FORMAT (60,13HMONITOR POINT,7X)
120
CALL LETTER(40,2.*HGT,0.0,5*OXMX-NT*HGT,OXMX-.5*YMR-HGT,TITLE)

PLOT N VS. X.

NPLTP=NMESH
150
CALL PLOT((X(1J)-IXMN)/XSC+OXMN+XMR,
+ (DLOG10(N(1J)-INMN)/NSC+OYN+YMR,3)
DO 160 I=1,NPLTP
J=I/NPLTP*NMESH+1.1
CALL PLOT((X(J)-IJMN)/XSC+OXMN+XMR,
+ (DLOG10(N(J))-INMN)/NSC+OYN+YMR,2)
160
CONTINUE

PLOT P VS. X.

CALL PLOT((X(1J)-IXMN)/XSC+OXMN+XMR,
+ (DLOG10(P(1J))-INMN)/NSC+OYN+YMR,3)
DO 170 I=1,NPLTP
J=I/NPLTP*NMESH+1.1
CALL PLOT((X(J)-IJMN)/XSC+OXMN+XMR,
+ (DLOG10(P(J))-INMN)/NSC+OYN+YMR,2)
170
CONTINUE

PLOT PSI VS. X.

CALL PLOT((X(1J)-IXMN)/XSC+OXMN+XMR,
+ (PSI(1J)-IPSIMN)/PSISC+OYN+YMR,3)
DO 180 I=1,NPLTP
J=I/NPLTP*NMESH+1.1
CALL PLOT((X(J)-IJMN)/XSC+OXMN+XMR,
+ (PSI(J)-IPSIMN)/PSISC+OYN+YMR,2)
180
CONTINUE

IF ( FLAG .EQ. 0 ) GOTO 30

OUTPUT A PUNCHED DECK OF THE STEADY STATE SOLUTION IF TEST(15)=1.

900
IF (.NOT. ( test(15).EQ.1 ) ) AND. ( (T.EQ.-2).AND. ( test(3).EQ.0) )
+ ( test(9).EQ.1 ) ) GOTO 1330
WRITE (7,1310) NMESH
1310
FORMAT (18.4,E18.10)
1320
WRITE (7,1310) I,XT,LFA,RT,TIME,NS,PSI*VFAC
1330
IF ( ( test(23).NE. 1 ) .OR. (T.EQ.-3) ) GOTO 1500
HT1=T
IF ( HT1 .LT. 0. ) HT1=0.
T=XT
RETURN
END
SUBROUTINE POISSON
SOLVES THE POISSON EQUATION. ONLY ONE CORRECTION USED HERE.

COMMON DIVSUM, INDEX, INPLUS, IJXCN, IPLUS, JCN, IWS1, IWS2, IWS3,
+ IWS4, LOC, MESHIN, NIMSH, NIMSHPL, NSS, NTX, NTY, SSINDEX, TAINDEX,
+ TVINDEX, TEST(30), IXI,
+ ABCSOPF, AREA, BETA, DPSAVE, DPSMAX, DPSISO, DQTY, EPHOTON,
+ EPS, EPSAVE, EPSMAX, EPSISO, ESAV, ETAP, G, N, HT, HTAU, HV,
+ HVE, INBETA, JDISP, JEST, JFACE, JRESIS, JTOT, LAMBO, LAC, MAC,
+ NFAC, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QMTEFF,
+ QTYSUM, RLOAD, T, TAU, TFAC, TIMEFAC, TPEAK, TRISE, TRN, TRP,
+ TSTOP, USFAC, W, V, C, X, Y, Z, WEK, WSS, VFAQ, VOLUME, VSAFN,
+ VMAT, XL, X0, ACOLL, LCOLL, COL, CMAT, MWF, MWFH, MWMAX, XM, XPI,
+ XPL, XPIE, PBO, PBN, PBL, EGAQ, EGAQF, EGAQFM, EGAQPH, EGAQPS,
+ EVOLTS, OFSPL, OFSPH, OX, EVOLTS, OX, OX, OX, OX, OX, OX, OX,
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C

C IF TEST(17)=0, INTERPOLATE PROFILE FROM INPUT VALUES.

IF ( TEST(17) .EQ. 1 ) GOTO 800

PROF(I) = EXP(INPROF(I))

PROF(NMESH+1) = EXP(INPROF(NMESH+1))

DO 90 I=2,NMESH

WS3=XL

X=X(I)

K=2

DO 10 J=2,HESHIN

IF ( ABS(X-XJ) .GE. WS3 ) GOTO 20

K=J

XO=INX(K-1)

X1=INX(K)

X2=INX(K+1)

WS3=((X2-XO)* (X2-X1))/((X1-XO)*(X2-X1))

WS3=((X0-X2)* (X0-X1))/((X1-X2)*(X2-X1))

IF ( K .GE. TEST(30) ) GOTO 30

PROF(I) = EXP(WS1*INPROF(K-1)+WS2*INPROF(K)+WS3*INPROF(K+1))

GOTO 45

10

K=J

X=INX(K-1)

X1=INX(K)

X2=INX(K+1)

WS3=((X1-X)* (X1-X2))/((X2-X)*(X1-X2))

IF ( K .LE. TEST(30) ) GOTO 40

PROF(I) = EXP(WS1*INPROF(K-1)+WS2*INPROF(K)+WS3*INPROF(K+1))

GOTO 45

40

PROF(I) = WS1*EXP(INPROF(K-1))

K=TEST(30) - 3

WS2=2.*WS2*EXP(INPROF(K))

WS3=WS3*EXP(INPROF(K+1))

GOTO 45

45

PROFMAX=MAX1(PROFMAX,ABS(PROF(I)))

GOTO 850

C

C IF TEST(17) = 1, DETERMINE PROFILE FROM ALGORITHM.

800

LNPRFIN=ALOG(INPROFIN)

LNPRFC=ALOG(INPROFCOL)

WS1=EXP((XCMIN-BCOLL)/CCOLL+1.)**ACOLL

WS2=EXP((XMAX-BXCOL)/CCOLL+1.)**ACOLL

DO 830 I=1,NMESHPI

IF ( X(I) .GE. XCMIN ) GOTO 810

IF ( X(I) .LT. XEFLAT ) PROF(I)=PROFEM

GOTO 830

810

PROF(I)=PROFEM

830

IF ( X(I) .GE. XCMAX ) GOTO 820

WS3=EXP((X(I)-BCOLL)/CCOLL+1.)**ACOLL

GOTO 830

820

PROF(I)=PROFCOL

830

IF ( I .NE. 0 ) INPLUS=INPLUS+1

C

C DETERMINES XM AND XPLE LOCATION FOR SCHOTTKY.

850

IF ( TEST (20) .NE. 2 ) GOTO 856

WS1=X(I1)-XM

IWS1=1

IF ( I1 > XM ) GOTO 857

DO 855 I=2,NMESHPI

WS1=X(I)-XM

IWS1=I-1

CONTINUE

856

CONTINUE

855

CONTINUE
SUBROUTINE REMESH
THIS PROCEDURE CALCULATES A NEW SPATIAL MESH DISTRIBUTION FOR THE
PROBLEM SUCH THAT A GIVEN QUANTITY HAS EVENLY DISTRIBUTED STEPS OVER THE MESH. HERE POTENTIAL IS USED.

COMMON DIVSUH, INDEX, INPLUS, INXJCN, IPPLUS, JCN, IWS1, IW2, IWS3,
+ IWS4, LOC, MESHIN, NMESH, NEMSHPL, NSS, NTA, NT, CVSINDEX, TINDEX,
+ ABSCEF, AREA, BETA, DPSAVE, DPSMAX, DPSISO, DQTTY, EPHOTON,
+ EPI, EPSAVE, EPSMAX, EPSISO, ESAT, TRAP, G, MT, HTA, HVC,
+ HVE, INBETA, JISP, JEST, JFA, JREGIS, JDIT, LAMMA, LFAC, MFAC,
+ NFAC, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QNTHEFF,
+ QNTY, QNTYD, RLOAD, T, TAU, FAC, TIMEFAC, TRAP, FRAC, TRAP,
+ TSTOP, UFAC, VE, VC, VGCS, VE, KE, VESS, VFAC, VOLUME, VSATN,
+ VSATP, XL, XE, ACOLD, BCOLL, CCOLD, XCMAX, XEFLAT, XEGAUS,
+ XDPLE, PIPLUS, PIPN, PIP, PEAK, PBL, PEC, PEG, PIGMS, EFMAX, EA, PBI,
+ PNV, XIMG, VFAC, NA,
+ CVOLTS(201), DFSPL(4), DFSPM(4), DX(201), EVOLTS(201), NM(201),
+ MP(201), MPS(201), INPROF(201), INPROFG(201), INXJCN(201),
+ JN(201), JNK(201), JP(201), JPK(201), HI1(201), MI2(201),
+ MI3(201), MN(201), HP(201), INPROF(201), INPROFG(201), SP(4),
+ SSTIME(201), TATIME(100), TVTIME(201), UK(201), UK(201),
+ PAV(201), PIH(201), N(201), NK(201), PK(201), PSK(201), PSIOLD(201),
+ INTEGER DIVSUH, INDEX, INPLUS, INXJCN, IPPLUS, JCN, IWS1, IW3, IWS3,
+ IWS4, LOC, MESHIN, NMESH, NEMSHPL, NSS, NTA, NT, CVSINDEX, TINDEX,
+ TVINDEX, IXT, IXT

REAL ABSCEF, AREA, BETA, DPSAVE, DPSMAX, DPSISO, DQTTY, EPHOTON,
+ EPSAVE, EPSMAX, EPSISO, ESAT, TRAP, G, MT, HTA, HVC,
+ HVE, INBETA, JISP, JEST, JFA, JREGIS, JDIT, LAMMA, LFAC, MFAC,
+ NFAC, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QNTHEFF,
+ QNTY, QNTYD, RLOAD, T, TAU, FAC, TIMEFAC, TRAP, FRAC, TRAP,
+ TSTOP, UFAC, VE, VC, VGCS, VE, KE, VESS, VFAC, VOLUME, VSATN,
+ VSATP, XL, XE, ACOLD, BCOLL, CCOLD, XCMAX, XEFLAT, XEGAUS,
+ XDPLE, PIPLUS, PIPN, PIP, PEAK, PBL, PEC, PEG, PIGMS, EFMAX, EA, PBI,
+ PNV, XIMG, VFAC, NA,
+ CVOLTS, DFSPL, DFSPM, DX, EVOLTS, HM, HP, MPS, INPROF, INPROFG,
+ HI1, MI2, MI3, JNK, JP, JPK, HI1, MN, HP, PROF, PROFMAX, SP, SSTIME,
+ TATIME, TVTIME, UK, PAV, PIH

REAL A(211), B(211), C(211), D(211), E(211), F(211), K(211)
**X**

\[ \text{QTTYSUM} = 0 \]

\[ K(1) = 0 \]

\[ WS1 = \text{ilog}(N(11)) \]

\[ WS2 = \text{ilog}(P(11)) \]

\[ WS3 = \text{ilog}(P(11)) \]

\[ WS4 = \text{ilog}(P(11)) \]

\[ WS5 = \text{ilog}(P(11)) \]

\[ WS6 = \text{ilog}(P(11)) \]

\[ WS7 = \text{NEMESH} \]

\[ NEMESH1 = \text{NEMESH} + 1 \]

\[ \text{DO } 40 I = 2, \text{NEMESH1} \]

\[ WS3 = \text{ilog}(P(11)) \]

\[ WS4 = \text{ilog}(P(11)) \]

\[ WS5 = \text{ilog}(P(11)) \]

\[ WS6 = \text{ilog}(P(11)) \]

\[ WS7 = \text{ilog}(P(11)) \]

\[ WS1 = WS3 \]

\[ WS2 = WS4 \]

\[ WS5 = WS6 \]

\[ WS6 = WS7 \]

\[ WS7 = NEMESH + 1 \]

\[ \text{QTTYSUM} = 0 \]

\[ QTTYSUM = \text{QTY} \]

\[ MESH = 0 \]

\[ X = 0 \]

\[ I = 1 \]

\[ J = 1 \]

\[ \text{INDEX} = 1 \]

\[ \text{DO } 240 I = 2, \text{NEMESH} + 1 \]

\[ \text{INDEX} = \text{INDEX} + 1 \]

\[ \text{QTY} = \text{QTY} + \text{DQTY} \]

\[ \text{INDEX} = \text{INDEX} + 1 \]

\[ \text{DO } 300 I = 2, \text{INDEX1} \]

\[ \text{INDEX1} = \text{INDEX1} + 1 \]

\[ \text{DQTY} = \text{QTY} \]

\[ \text{INDEX1} = \text{INDEX1} + 1 \]

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\[ \text{INDEX1} = \text{INDEX1} + 1 \]
IF ( IWS4 .EQ. 0 ) IMIN=NMESH-1
NO POINT FOUND THEREFORE NEAREST TO ENDPOINT.
X0=X(IMIN)
X1=X(IMIN+1)
WS1=-(X2-X0)/(X1-X0)*(X2-X1)
WS2=(X2-X0)/(X1-X0)*(X2-X1)
WS3=-(X2-X0)/(X1-X0)*(X2-X1)
AI=EXP((WS1*DLOG(N(IMIN)))+WS2*DLOG(P(IMIN+1)))+
WS3*DLOG(N(IMIN+2)))+
BI=EXP((WS1*DLOG(P(IMIN)))+WS2*DLOG(P(IMIN+1)))+
WS3*DLOG(P(IMIN+2)))+
CI=WS1*PSI(IMIN)+WS2*PSI(IMIN+1)+WS3*PSI(IMIN+2)
DI=EXP((WS1*DLOG(NK(IMIN)))+WS2*DLOG(NK(IMIN+1)))+
WS3*DLOG(NK(IMIN+2)))+
EI=EXP((WS1*DLOG(PK(IMIN)))+WS2*DLOG(PK(IMIN+1)))+
F(I)=WS1*PSK(IMIN)+WS2*PSK(IMIN+1)+WS3*PSK(IMIN+2)
H(I)=WS1*JNK(IMIN)+WS2*JNK(IMIN+1)+WS3*JNK(IMIN+2)
HP(I)=WS1*JPK(IMIN)+WS2*JPK(IMIN+1)+WS3*JPK(IMIN+2)
DO 880 I=2,NMESH
NI=I(I)
PSI(I)=C(I)
NK(I)=DI(I)
PK(I)=EI(I)
PSK(I)=F(I)
JNK(I)=H(I)
JPK(I)=HP(I)
DO =DI(I)-XI(I)-X(I-1)
880 CALL PROFILE
DO 900 I=2,NMESH
MM(I)=WS1+WS2+WS3+MM(I-1)
WS1=DI(I)
WS2=NI(I)
WS3=NI(I)
MI(I)=WS13+2.*(WS12-WS15)/24./WS11
MI3(I)=WS15+2.*(WS14-WS13)/24./WS12
MI2(I)=WS11+WS12/2.-MI(I)-MI3(I)
900 RETURN
END

COMMON DIVSUM,INDEX,INPLUS,JNJCQ,TPPLUS,JN,WS1,WS2,WS3,
+ LS4,LOC,MESH,MESH,NSHNP1,NS,NTA,NT6,SSINDEX,TAINDEX,
+ TNX,INDEX,TEST(30),INT,
+ ABSCOE,AREA,BETA,DPSIAVE,DPSIMA,DPSISO,DQTY,EPHOTON,
+ EPSL,EPSTMAX,EPSIS0,ETRAP,G,H,HT,HTAU,HVC,
+ HXS1=WS1+WS2+WS3=HXS1,HXS2=WS1+WS2+WS3=HXS2,
+ NFA,OMEGA,P,F,PW,POPC,PQ,PQF,PQF,PQF,PQF,PQF,PQF,PQF,PQF,PQF,
+ QI=QI,QI=QI,QI=QI
CALL PROFILE
DO 900 I=2,NMESH
MM(I)=WS1+WS2+WS3+MM(I-1)
WS1=DI(I)
WS2=NI(I)
WS3=NI(I)
MI(I)=WS13+2.*(WS12-WS15)/24./WS11
MI3(I)=WS15+2.*(WS14-WS13)/24./WS12
MI2(I)=WS11+WS12/2.-MI(I)-MI3(I)
900 RETURN
END
IWS1 = NO. OF ITERATION.
IWS2 = PRESENT HAX. POINT.
IWS6 = NO. OF POSITIVE POINTS.

DPSIMAX = DPSIAVE = DPSISO = 0.
IWS1 = 0.
WS20 = 2E-8

SET UP ITERATION LIMIT.
IF ( TEST(19) .EQ. 0 ) GOTO 150
IF ( TEST(19) .EQ. 1 ) ILIMIT = 100
IF ( TEST(19) .EQ. 2 ) ILIMIT = 200
IF ( TEST(19) .EQ. 3 ) ILIMIT = 300
IF ( TEST(19) .EQ. 4 ) ILIMIT = 400
IF ( TEST(19) .EQ. 5 ) ILIMIT = 500

IWS1 = IWS1 + 1
IF ( IHS1 .LE. ILIMIT ) GOTO 150

PRINT 100
FORMAT ( "ITERATION LIMIT EXCEEDED. " )
PRINT 110, ILIMIT
STOP
CONTINUE
CALL OUTVALU

DO 140 I = 1, NMESHP1
PSIOLD(I) = PSI(I)
CALL MOBREC
CALL CARRIER
CALL POISSON
C

OLDPSIM = DPSIMAX
DPSIMAX = DPSIAVE = DPSISO = 0.
IWS6 = 0
DO 280 I = 1, NMESHP1
WS1 = ( PSI(I) - PSIOLD(I) )
IF ( ABS(WS1) .LE. ABS(DPSIMAX) ) GOTO 270
DPSIMAX = WS1
IWS6 = IWS6 + 1
270
DPSIAVE = DPSIAVE + WS1
DPSISO = DPSISO + WS1 * WS1
OPSIAVE = OPSIAVE / NHESH
OPSISD = SQRT ( OPSISO / NMESH )
USES OMEGA OPTIMIZATION ROUTINE.

IF ( TEST(16) .EQ. 1 .AND. IWS1 .EQ. 1 ) OMEGA = 0.9
IF ( OMEGA .LT. 1.0 ) OMEGA = 0.9
IF ( OMEGA .LT. 0.5 ) OMEGA = 0.9

IF ( ABS(OLDPSIM) * OLDPsim .LT. 1.5 ) GOTO 290
IF ( ABS(OLDPSIM) .GT. EPSDMAX .OR. ABS(OPSIAVE) .GT. EPSAVE .OR. OPSISO .GT. EPSISO .OR. IWS1 .LT. 5 ) GOTO 90

FIVE CYCLES MINIMUM.
CALL MOBREC
CALL CARRIER
RETURN
END
SUBROUTINE VOLTAGE

CALCULATES BOUNDARY VOLTAGES AT ANY POINT IN TIME BY LINEAR INTERPOLATION FROM GIVEN DATA VALUES.

COMMON DSYV, INDEX, INPLUS, INJC, IPPLUS, JC, IWS1, IWS2, IWS3,
+ IWS4, MESHIN, MESHPI, NS, NT, SSINDEX, TINDEX,
+ TVINDEX, TESTIT, IX, IT,
+ ABSCOE, AREA, BETA, DPS1AVE, DPSMAX, DPSISO, QITY, EPHOTON,
+ EPS1AVE, EPSMAX, EPSISO, ESAT, ETAP, G, H, HTAU, HVC,
+ HVE, INBETA, JDISP, JEST, JFAC, JRESIS, JRT, LA80A, LFA, LFC, NFAC,
+ NFAC, OMEGA, PF, POWER, PROFCOL, PROFEM, PROFINT, PROFMAX, QNTMEFF,
+ QNTMEFF, QNTMEFF, QNTMEFF, QNTMEFF, QNTMEFF, QNTMEFF, QNTMEFF,
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APPENDIX H

PROGRAM LISTING OF JPLOT

PROGRAM JPLOT (INPUT,OUTPUT)
MAIN PROGRAM
COMMON NIMAX,PMAX,JMAX,RC,R,N,D,V,XL,AREA
COMMON/RCT1/POWER(J),JTOT(J),JRC(J),TIME(J)
REAL TIME,POWER,JTOT,JRC,PMAX,JMAX,J,JGEN,RC,X1,K2
INTEGER N, IWS1

READ NO. OF SETS OF DATA.
READ 10,NSET
DO 1000 K=1,NSET
PRINT 30,K
PRINT 40
FORMAT ("ANALYSIS FOR DATA SET NO. ",I2//)

READ 50, R, AREA, XDPE
READ 50, N, D, V, XL
ESL=8.954E-14
ESLS=15.8*ESL
C=ESLS*AREA/XDPE/1.E-4
RC=R*C*1.E+12

READ IN NO. OF DATA POINTS.
READ 100,N

READ IN DATA POINTS.
DETERMINE MAX VALUES OF INPUTS.
READ 120, IWS1, TIME(J), POWER(J), JTOT(J), X
JTOT(J)=ABS(JTOT(J))
POWER(J)=ABS(POWER(J))
PRINT 130, IWS1,X

FORMAT "JTOT VS. TIME FOR POINT NO. ",I3//
* POSITION X = "F10.5" MICROMETERS."
PRINT 135, AREA,XL,N,D,V,XDPE,R,RC

FORMAT "AREA = "E10.5", CM²//
* " XL = "F10.5", " MICROMETERS."
* " N = "F10.5", " "
* " D = "F10.5", " "
* " V = "F10.5", " VOLTS."
* " XDPE = "F10.5", " "
* " R = "F10.5", " "
* " RC = "F10.2", " PSECS."

83
PMAX=-9999.
JMAX=-9999.
TMAX=-9999.

C DO 230 I=2,N
READ 140,TIME(I),POWER(I),JTOT(I)
140 FORMAT(5X,3(E14.10))
JTOT(I)=ABS(JTOT(I))
POWER(I)=ABS(POWER(I))
IF ( PMAX .LT. POWER(I) ) PMAX=POWER(I)
IF ( JMAX .LT. JTOT(I) ) JMAX=JTOT(I)
IF ( TMAX .LT. TIME(I)*1.E12 ) TMAX=TIME(I)*1.E12
200 CONTINUE
PRINT 220
220 FORMAT (IH1,10X,"TIME(PSEC)",8X,"POWER",10X,"JTOT")//

C DO 300 I=1,N
IF ( TIME(I) .LT. 0. ) TIME(I)=0.
NORMALIZE BOTH POWER AND CURRENT.
C POWER(I)=POWER(I)/PMAX
JTOT(I)=JTOT(I)/JMAX
C TIME(I)=TIME(I)*1.E12
CALL PLOTPT (TIME(I),POWER(I),10)
CALL PLOTPT (TIME(I),JTOT(I),4)
CONTINUE
GIVES A LISTING OF THE NORMALIZED DATA.
CALL TABLE (POWER,JTOT,TIME)
OUTPUT LINEPRINTER PLOT.

CALL OUTPLT
PRINT 500 FORMAT(5X,"-·------·--· 0 DENOTES INPUT POWER "/",X,"- - ·----·- --···-· -·- ··------")
Gives a listing of the normalized data.

C CALCULATES FOR RC RESPONSE.
CALL RC(TIME)
600 FORMAT(IH1,10X,"TIME(PSEC)",9X,"JTOT",11X,"JRC")//
CALL TABLE (JTOT,JRC,TIME)
DO 650 I=1,N
CALL PLOTPT (TIME(I),JRC(I),4)
CONTINUE
CALL OUTPLT
PRINT 660 FORMAT(5X,"-·------·--· 0 DENOTES OUTPUT CURRENT "/")
Gives a listing of the normalized data.

CALL VPLOT (POWER,JTOT,TIME,1)
CALL VPLOT (JTOT,JRC,TIME,2)
CALL VPLOT (POWER,JRC,TIME,3)
CALL VPLOT (POWER,JRC,TIME,0)
1000 CONTINUE
GIVES VERSATEC PLGTS.
END THE PLOT FILE.
1010 CALL PLOT (0.,0.,999)
C STOP
SUBROUTINE RCTHE
CALCULATE FOR RC RESPONSE.
COMMON/RCT1/POWER(50),JTOT(50),JRC(50),TIME(50)
REAL TIME,POWER,JTOT,JRC,PMAX,JMAX,J,JC,J,JRC,RC,K1,K2

DIFFERENTIAL EQUATION FOR RC CIRCUIT.
FDJ(J,JGEN,R)=J(JGEN-J)/RC

JRC(1)=0.0
J=0.0
JGEN=0.0
N1=N-1
DO 1600 K=1,N1
STEP=(TIME(K+1)-TIME(K))/NSTEP
DJGEN=(J(TOT(K+1)-JTOT(K))/NSTEP
IF (DJR=0.0) GO TO 1300
DJGEN=(J(TOT(K+1)-JTOT(K))/2.
NSTEP=2

1300 CONTINUE
DO 1500 I=1,NSTEP
K1=DT*FOJ(J,JGEN,R)
K2=DT*FOJ(J+1,JGEN+DJGEN,R)
J=J+1
JGEN=JGEN+DJGEN
CONTINUE

JRC(K+1)=J
1600 CONTINUE
RETURN
END

SUBROUTINE TABLE (POWER,JTOT,TIME)
LIST DATA POINTS, CALCULATE FOR 10-90 PERCENT RISTIMES AND FWHM.
COMMON N,TPAX,PMAX,JMAX,JRC,P,NC,ND,VL,SL
DIMENSION POWER(50),JTOT(50),JRC(50),TIME(50)
REAL TIME,POWER,JTOT,JRC,PMAX,JMAX,J,JC,J,JRC,RC,K1,K2
+ NC,ND,VL,SL
IWS1=0
IWS2=0
DO 300 I=1,N
X=TIME(I)
Y1=POWER(I)
Y2=JTOT(I)

DETERMINES WHEN INPUT AND OUTPUT EXCEED 10 AND 90 PERCENT.
IF (Y1.EQ. 0) GOTO 240
IF (Y1.EQ. POWER(I-1)) GOTO 232
IF (IWS1.NE. 0) GOTO 225
IF (Y1.EQ. 5) IWS1=1
TS1=(X-TIME(I-1))*(1-POWER(I-1))/(Y1-POWER(I-1)+TIME(I-1)

225 CONTINUE
IF (IWS1.NE. 1) GOTO 230
IF (Y1.EQ. 5) IWS1=2
TM1=(X-TIME(I-1))*(5-POWER(I-1))/(Y1-POWER(I-1)+TIME(I-1)

230 CONTINUE
IF (IWS1.NE. 2) GOTO 231
IF (Y1.EQ. 5) IWS1=3
TF1=(X-TIME(I-1))*(9-POWER(I-1))/(Y1-POWER(I-1)+TIME(I-1)

231 CONTINUE
IF (IWS1.NE. 3) GOTO 232
IF (Y1.EQ. 5) GOTO 232
IWS2=IWS1
TM1=(X-TIME(I-1))*(5-POWER(I-1))/(Y1-POWER(I-1)+TIME(I-1)

232 CONTINUE
IF (Y2.EQ. JTOT(I-1)) GOTO 242
IF (IWS2.NE. 0) GOTO 235
IF (Y2.EQ. 0.1) IWS2=1
TS2=(X-TIME(I-1))*(1-JTOT(I-1))/(Y2-JTOT(I-1)+TIME(I-1)

235 CONTINUE
IF (IWS2.NE. 1) GOTO 240
IF (Y2.EQ. 5) IWS2=2
TM2=(X-TIME(I-1))*(5-JTOT(I-1))/(Y2-JTOT(I-1)+TIME(I-1)

240 CONTINUE
RETURN
END
CONTINUE
IF ( IWS2 .NE. 2 ) GOTO 241
IF ( Y2 .GT. 9 ) IWS2=3
TF2=(X-TIME(I-1))*(9-JTOT(I-1))/(Y2-JTOT(I-1))*TIME(I-1)
CONTINUE
IF ( IWS.2 .NE. 3 ) GOTO 242
IF ( Y2 .GT. 9 ) GOTO 242
IWS2=4
TN2=(X-TIME(I-1))*(5-JTOT(I-1))/(Y2-JTOT(I-1))*TIME(I-1)
CONTINUE
PRINT 250, X,Y1,Y2
FORMAT(10X,3(F10.5,5X))
CONTINUE
IF ( IWS1 .NE. 4 ) GOTO 470
FWHH1=TN1-TRISE1
PRINT 465, FWHM1 FORMAT(10-90 PERCENT INPUT RISE TIME = "F6.2," PSEC.")
CONTINUE
IF ( IWS2 .NE. 4 ) GOTO 480
FWHM2=TN2-TRISE2
PRINT 475, FWHM2 FORMAT(10-90 PERCENT OUTPUT RISE TIME = "F6.2," PSEC.")
RETURN
END

SUBROUTINE VPLOT (POWER, JTOT, TIME, IOPT)

VERSATEC PLOTTING ROUTINE.

COMMON N, MAX, PMAX, JMAX, PC, RC, NC, NJ, X, XL AREA
DIMENSION POWER(50), JTOT(50), JRC(50), TIME(50)

REAL TIME, POWER, JTOT, JRC, PMAX, JMAX, PC, RC, K1, K2

CALL NEWPEN(9)
CALL PLOT (0.02, 3)
CALL PLOT (5.72, 2)
CALL PLOT (6.02, 3)
CALL PLOT (5.02, 2)

SCALE DATA TO ALLOW ONE INCH MARGIN ALL AROUND.

CALL FACTOR (N, TIME, POWER, 7.0, 6.02, 1.1, 1)

DETERMINE MIN AND MAX VALUES OF DATA AND DRAW BORDER USING PEN 2.

CALL NEWPEN(2)
CALL INCHTO (1.01, 1.0, XMN, YMN)
CALL INCHTO (7.0, 6.02, XM, YM)
CALL PTLIN (XMN, YMN, XM, YM)
CALL PTLIN (XMN, YM, XM, YM)
CALL PTLIN (XM, YMN, XM, YM)
CALL PTLIN (XM, YM, XM, YM)

PLOT CURVES WITH PEN 4.

CALL NEWPEN(4)
N1=1
DO 800 I=1, N1
CALL PTLIN (TIME(I), POWER(I), TIME(I+1), POWER(I+1))
CALL PTLIN (TIME(I), JTOT(I), TIME(I+1), JCT(I+1))
PLOT X AXIS LABEL.
CALL LETTER (12..15,0.0,5.2,45," TIME (PSEC)")

PLOT Y AXIS LABEL.
IF ( IOPT .NE. 1 ) GOTO 810
CALL LETTER (35..15,90.,0.5,75," INPUT POWER, SHORT CIRCUIT CURRENT")
CONTINUE
GOTO 810

IF ( IOPT .NE. 2 ) GOTO 820
CALL LETTER (38..13,90.,0.5,1.0," SHORT CIRCUIT CURRENT, OUTPUT CURR")
CONTINUE
GOTO 820

IF ( IOPT .NE. 3 ) GOTO 830
CALL LETTER (28..15,90.,0.5,1.0," INPUT POWER, OUTPUT CURR")
CONTINUE
GOTO 830

PLOT DIVISIONS ON X AXIS.
CALL NEWPEN(2)
NX=INT(TMIX/10.)+1
X1=85
DO 900 I=1,NX
CALL PLOT (X1+.15,1.1,3)
CALL PLOT (X1+.15,1.1,2)
ENCOD (3,850,XSCALE) IW50
FORMAT(F3.1)
IF ( TMIX .GT. 150. ) GOTO 860
CALL LETTER (3.05,0.0,X1,85,XSCALE)
GOTO 870
900 CONTINUE

CONTINUE

PLOT DIVISIONS ON Y AXIS.
Y1=1.0
DO 1000 I=1,11
CALL PLOT (1.0,Y1,3)
CALL PLOT (1.1,Y1,2)
ENCOD (3,950,YSCALE) WSO
950 FORMAT(F3.1)
CALL LETTER (3,0.1,0.0,65,Y1,YSCALE)
Y1=Y1+.5
CONTINUE

PRINT HEADING OF GRAPHS.
ENCOD (8,1002,C1) AREA
ENCOD (8,1002,C2) ND
ENCOD (5,1004,C3) R
ENCOD (5,1004,C4) V
1002 FORMAT (E8.2)
1004 FORMAT (F5.2)
C
CALL LETTER (33..10,0.0,2.50,6.70, AREA)
CALL LETTER (33..10,0.0,2.50,6.50, DOPING DENSITY)
CALL LETTER (33..10,0.0,2.50,6.30, RESISTANCE)
CALL LETTER (33..10,0.0,2.50,6.10, VOLATAGE)
C
CALL LETTER (8.0,10,0.0,4.3,6.70,C1)
CALL LETTER (8.0,10,0.0,4.3,6.50,C2)
CALL LETTER (5.0,10,0.0,4.3,6.30,C3)
CALL LETTER (5.0,10,0.0,4.3,6.10,C4)
END THIS PLOT.
CALL PLOT (.1,.1,-3)
C
1020 RETURN
END
REFERENCES


