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DEPARTMENT OF MATHEMATICAL SCIENCES
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OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23508

SUMMARY OF MATHEMATICAL MODELS FOR A CONVENTIONAL AND VERTICAL JUNCTION PHOTOCONVERTER

By

John H. Heinbockel, Principal Investigator

Progress Report
For the period March 1, 1986 to June 30, 1986

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Under
Research Grant NAG-1-148
Gilbert H. Walker, Technical Monitor
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Old Dominion University Research Foundation
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TABLE OF CONTENTS

LIST OF FIGURES

TABLE OF CONTENTS - Concluded

LIST OF FIGURES - Concluded

SYMBOLS AND UNITS OF MEASUREMENTS

$g(x)$	generation rate [photons/cm^3 s]
ϕ_0	incident photons [cm^{-2} s^{-1}]
R	reflection coefficient (dimensionless)
α	absorption coefficient [cm^{-1}]
ω	width of depletion region [cm]
H	depth of planar cell [cm]
H'	$H-(z_j+W)$ depth parameter [cm]
X_j, Z_j	junction depths [cm]
P_n, P_{no}	density of holes in n-region [cm^{-3}]
n_p, n_{po}	density of electrons in p-region [cm^{-3}]
D_p, D_n	diffusion coefficient of holes, electrons [cm^2/s]
τ_p, τ_n	lifetimes of holes, electrons [s]
S_p, S_n	surface recombination velocity of holes, electrons [cm s^{-1}]
J_p, J_n	current density for holes, electrons [Amp cm^{-2}]
L_p, L_n	diffusion lengths of holes, electrons ($L^2=D\tau$) [cm]
J_{dr}	photocurrent density from depletion region [Amp cm^{-2}]
J_{sc}	short circuit current density [Amp cm^{-2}]
J_{inj}	injection current density [Amp cm^{-2}]
J_{rec}	recombination current density [Amp cm^{-2}]
q	charge of electron [coulomb]
N_a, N_d	doping densities for acceptors, donors [cm^{-3}]
n_i	intrinsic carrier density [cm^{-3}]
V	voltage [volts]
V_{bi}	built in voltage [volts]
K	Boltzmann's constant [ev/deg K]

J	total current density [Amp cm^{-2}]
J_0	dark current density [Amp cm^{-2}]
R_s	series resistance [ohms]
R_{sh}	shunt resistance [ohms]
n	depth parameter [cm]
x,y	coordinates for photoconverter reference [cm]
B	width of vertical junction cell [cm]
A	depth of vertical junction cell [cm]
X_p, X_n	coordinates defining space charge region [cm]
I_{sc}	total short circuit current [Amp]
I_p, I_n	hole, electron current [Amp]
W_0	power density of laser [watts cm^{-2}]
P_{in}, P_{out}	input, output power [watts]
Eff	efficiency [%]
a	half width in x direction [cm]
b	half width in y direction [cm]
$\delta(x_0 - x)$	Dirac delta function
G_1, G_2	Green's function
u	eigenfunctions
S_0, S_1	surface recombination velocities [cm s^{-1}]
U_m, V_m, U_m^*, V_m^*	Eigenfunctions

SUMMARY OF MATHEMATICAL MODELS FOR A CONVENTIONAL AND VERTICAL JUNCTION PHOTOCONVERTER

By

John H. Heinbockel*

1. ONE-DIMENSIONAL CONVENTIONAL PHOTOCONVERTER

The first model considered is for a one-dimensional analysis of a conventional photoconverter as described in References 1, 2. The geometry for this conventional n/p photoconverter is illustrated in Figure 1. We assume a generation rate

$$g(x) = \phi_0 \ (1\text{-Re}) \ \alpha \ \exp \ (-\alpha X) \tag{1.1}$$

and solve for the minority carriers in the n-region. These minority carriers must satisfy the diffusion equation

$$D_p \frac{d^2}{dx^2} (P_n - P_{no}) - \frac{(P_n - P_{no})}{\tau_p} = -g(x) \tag{1.2}$$

subject to the boundary conditions

$$D_p \frac{d}{dx} (P_n - P_{no}) = S_p (P_n - P_{no}) \text{ at } X = 0 \tag{1.3}$$

and

$$P_n - P_{n0} = 0 \quad \text{at} \quad X = X_j. \tag{1.4}$$

The solutions of the equations (1.2) (1.3) (1.4) gives the photocurrent density at the junction edge.

$$J_p = -qD_p \frac{d}{dx} (P_n - P_{no}) \quad \text{at} \quad X = X_j \tag{1.5}$$

*Professor, Department of Mathematical Sciences, Old Dominion University, Norfolk, Virginia 23508.

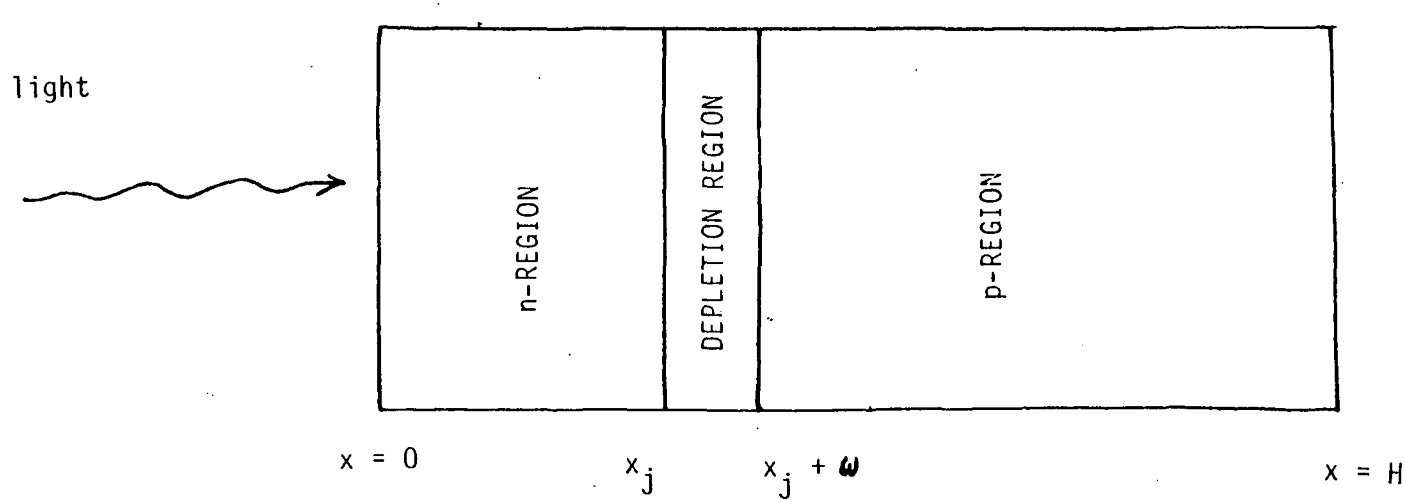


FIGURE 1. Device geometry for conventional photoconverter

which evaluates to

$$J_p = \frac{q\phi_0 \ (1-Re) \ \alpha \ L_p}{\alpha^2 L_p{}^2 - 1} \ \left(f_1/f_2 - \alpha L_p \ \mathrm{Exp} \ (-\alpha X_j)\right) \tag{1.6}$$

where

$$f_1 = \frac{S_p L_p}{D_p} + \alpha L_p \quad -\exp \ (-\alpha X_j) \ f\left(\frac{S_p L_p}{D_p}, \ 1, \ \frac{X_j}{D_p}\right) \tag{1.7}$$

$$f_2 = f(1, \ \frac{S_p L_p}{D_p}, \ X_j/L_p) \tag{1.8}$$

and

$$f(a, \ b, \ c) = a \cosh \ (c) + b\sinh(c) \tag{1.9}$$

The diffusion equation for minority carriers in the p-region is given by

$$D_p \ \frac{d^2}{dx^2} \ (\ n_p - n_{po}) - \frac{(n_p - n_{po})}{\tau_n} = -g(x) \tag{1.10}$$

with boundary conditions

$$n_p - n_{po} = 0 \qquad \text{at} \qquad X = X_j + \omega \tag{1.11}$$

$$-D_n \frac{d}{dx} (n_p - n_{po}) = S_n \ (n_p - n_{po}) \qquad \text{at} \qquad X=H. \tag{1.12}$$

This produces the photocurrent density

$$J_n = q\, D_n \frac{d}{dx} (n_p - n_{po}) \qquad \text{at} \qquad X = X_j + \omega \tag{1.13}$$

which evaluates as

$$J_n = \frac{q\phi_0 (1-R_e)\alpha L_n}{\alpha^2 L_n^2 - 1} \exp\left(-\alpha(X_j+\omega)\right) [\alpha L_n - f_3/f_4] \tag{1.14}$$

where

$$f_3 = [\alpha L_n - \frac{S_n L_n}{D_n}] \exp\left[-\alpha(H - X_j - \omega)\right] + f\left(\frac{S_n L_n}{D_n}, 1, \frac{H - X_j - \omega}{L_n}\right) \tag{1.15}$$

$$f_4 = f\left(1, \frac{S_n L_n}{D_n}, \frac{H - X_j - \omega}{L_n}\right) \tag{1.16}$$

where f is defined by equation (1.9).

The photocurrent from the depletion region is given by

$$J_{dr} = q\phi_0 \; (1-Re) \; e^{-\alpha X_j} \left[1 - e^{-\alpha\omega}\right] \tag{1.17}$$

and the total current due to the light source is

$$J_{sc} = J_p + J_n + J_{dr} \tag{1.18}$$

For the dark currents we have the injection current J_{inj} and the recombination current J_{rec} which are given by

$$J_{inj} = J_0 \left[\exp\left(\frac{qV}{KT}\right) - 1\right] \tag{1.19}$$

with

$$J_0 = \frac{qD_p}{L_p}\frac{n_i^2}{N_d} f\left(\frac{S_pL_p}{D_p}, 1, \frac{X_j}{L_p}\right) \bigg/ f\left(1, \frac{S_pL_p}{D_p}, \frac{X_j}{L_p}\right)$$

$$+ \frac{qD_n}{L_n}\frac{n_i^2}{N_a} f\left(\frac{S_nL_n}{D_n}, 1, \frac{H-X_j-\omega}{L_n}\right) \bigg/ f\left(1, \frac{S_nL_n}{D_n}, H-X_j-\omega\right) \tag{1.20}$$

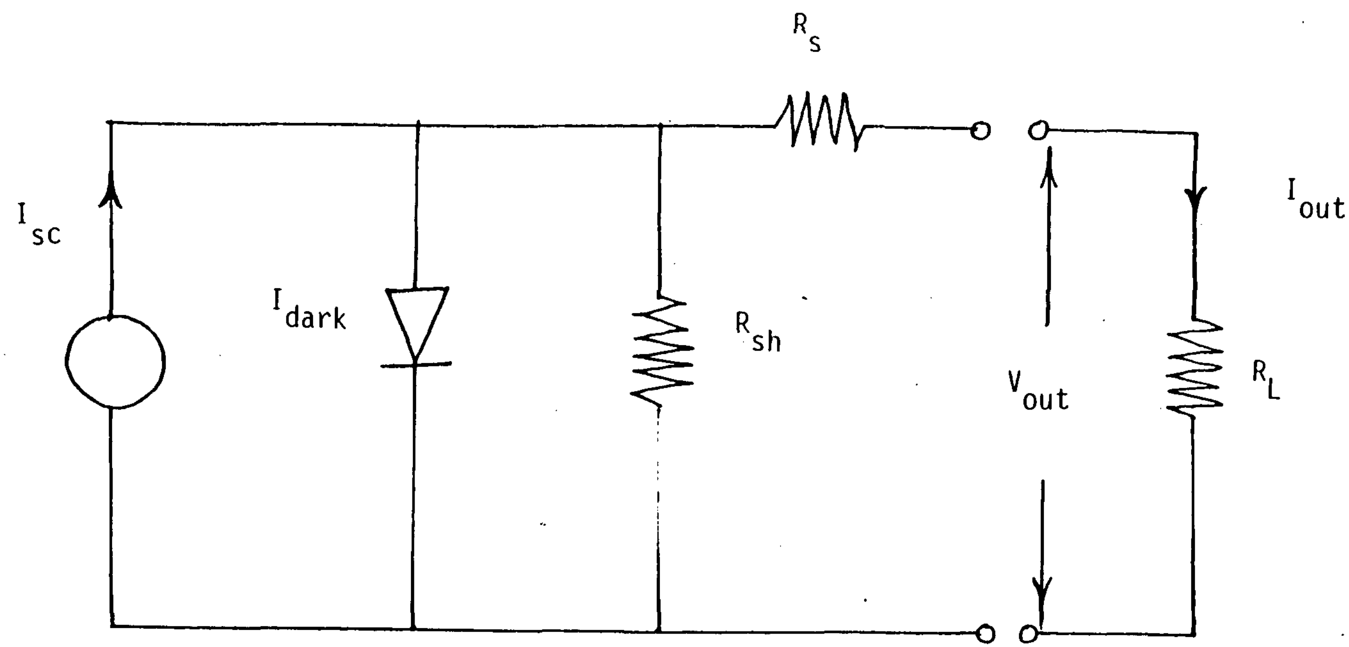
and

$$J_{rec} = \frac{\pi q n_i \omega \sinh\left(\frac{q\ V}{2KT}\right)}{\sqrt{\tau_p\tau_n}\ q(V_{bi}-V)/kT} \tag{1.21}$$

The dark current is $J_D = J_{inj} + J_{rec}$ and the total current is $J = J_{sc} - J_D$.

The effect of a series resistance R_s and shunt resistance R_{sh} can be included in the model by considering the equivalent circuit diagram of Figure 2.

Nominal values for the conventional solar cell parameters are given in the computer program "conven" listed in the Appendix A. In this computer program the absorption coefficient as a function of energy is obtained from interpolation of numerical input data. Empirical formulas approximating lifetimes, mobilities, intrinsic carrier density and bandgap energy as functions of temperature are included in the program.



$$I_{out}(1+R_s/R_{sh}) = I_{sc} - V_{out}/R_{sh} - I_{dark}$$

FIGURE 2. Equivalent circuit for solar cell

2. ONE-DIMENSION VERTICAL JUNCTION PHOTOCONVERTER MODEL

The geometry for the vertical junction photoconverter is illustrated in Figure 3. We consider a narrow strip at a depth η below the surface $y = A$. Following References 3, 4, we treat this strip as a conventional photoconverter and then sum the results over all η, $0 < \eta < A$.

In the n-region we have the diffusion equation

$$D_p \frac{d^2}{dx^2} (P_n - P_{no}) - \frac{(P_n - P_{no})}{\tau_p} = -g(A-y), \tag{2.1}$$

subject to the boundary conditions:

$$P_n - P_{no} = 0 \qquad \text{at} \qquad X = X_j + X_n \tag{2.2}$$

$$-D_p \frac{d}{dx} (P_n - P_{no}) = S_p (P_n - P_{no}) \qquad \text{at} \qquad X = B \tag{2.3}$$

From this equation we obtain the current density at $X_j + X_n$ given by

$$J_p = q D_p \frac{d}{dx} (P_n - P_{no}) \text{ at } X = X_j + X_n \tag{2.4}$$

which simplifies to

$$J_p = - g(A-y) \; qL_p \; \frac{[S_p - f \; (S_p, D_p/L_p, (B-X_j-X_n)/L_p)]}{f(D_p/L_p, S_p, (B-X_j-X_n)/L_p)} \tag{2.5}$$

In the p-region we have the diffusion equation

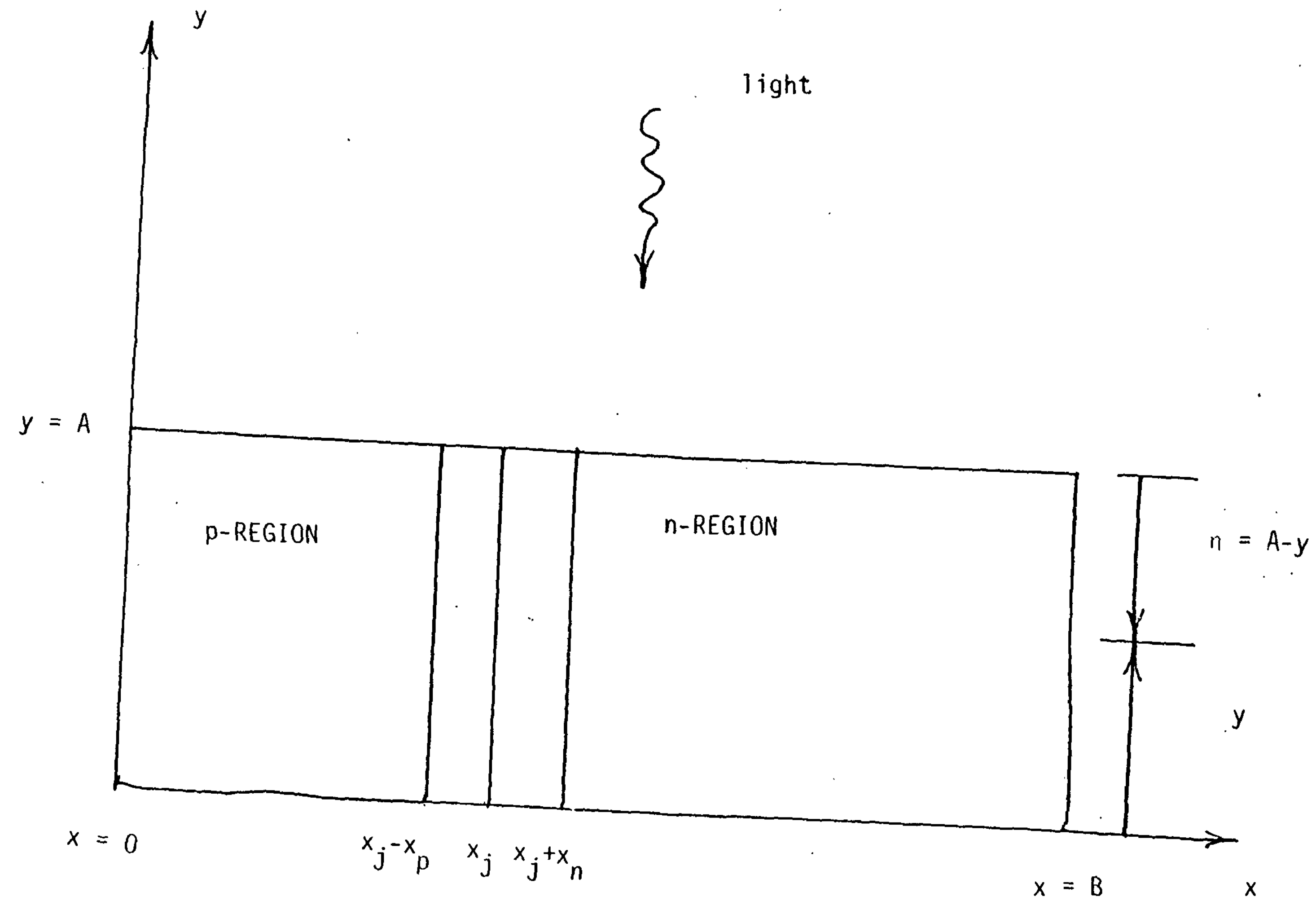


FIGURE 3. Vertical junction photoconverter geometry.

$$D_n \frac{d^2}{dx^2}(n_p-n_{po}) - (n_p-n_{po})/\tau_n = -g(A-y) \tag{2.6}$$

which is subject to the boundary conditions:

$$n_p-n_{po} = 0 \quad \text{at} \quad X=X_j-X_p \tag{2.7}$$

$$D_n \frac{d}{dx}(n_p-n_{po}) = S_n\,(n_p-n_{po}) \quad \text{at} \quad X=0 \tag{2.8}$$

This produces the current density at X_j-X_p given by

$$J_n = -q\,D_n \frac{d}{dx}(n_p-n_{po}) \quad \text{at} \quad X=X_j-X_p \tag{2.9}$$

which simplifies to

$$J_n = -g(A-y)\;qL_n\left[\frac{S_n-f(S_n,\,D_n/L_n,\,(X_j-X_p)/L_n)}{f(D_n/L_n,\,S_n,\,(X_j-X_p)/L_n)}\right] \tag{2.10}$$

The total current is obtained by integrating these current densities over the depth of the photoconverter. Assuming the photoconverter is 1 cm in depth we have:

$$I_{sc} = \int_0^A J_p(n)\,dn + \int_0^A J_n(n)\,dn = I_p + I_n \tag{2.11}$$

The dark current is given by $I_d = I_p{}^* + I_n{}^*$ where

$$I_p^* = \frac{p_{no} q D_p}{L_p} \frac{f(1,\ D_p/L_p S_p,\ (B-X_j-X_n)/L_p)}{f(D_p/L_p S_p,\ 1,\ (B-X_j-X_n)/L_p)} [e^{qV/kT}-1]A \qquad (2.12)$$

$$I_n^* = \frac{n_{po} q D_n}{L_n} \frac{f(1,\ D_n/L_n S_n,\ (X_j-X_p)/L_n)}{f(D_n/L_n S_n,\ 1,\ (X_j-X_p)/L_n)} [e^{qV/kT}-1]A \qquad (2.13)$$

Using $P_{in} = B\ W_0(1000)$ (watts) as the input power and $P_{out} = P_{max}$ as the maximum power obtained from the I-V curve, we calculate the efficiency as

$$E_{ff} = 100\ P_{in}/P_{out} \qquad (2.14)$$

Nominal values for the vertical junction photoconverter are given in the computer program "VJSCP" listed in Appendix B. We use the same empirical formulas approximating the lifetimes, mobilities, intrinsic carrier density and bandgap energy as a function of temperature as listed in the Appendix B. For both computer programs listed in Appendix A and Appendix B the temperature of the photoconverter is assumed controlled by the use of a heat pipe. The current voltage relationship is obtained from the equivalent circuit diagram of Figure 2.

3. THREE-DIMENSIONAL CONVENTIONAL PHOTOCONVERTER

The geometry for the three-dimensional conventional photoconverter model is illustrated in Figure 4. We let $R_n = \{(x,y,z) \mid |x|<a,\ |y|<b,\ 0<Z<Z_j\}$ denote the n-region and let $R_p = \{(x,y,z) \mid |x|<a,\ |y|<b,\ Z_j+w<Z<H\}$ denote the p-region. We assume that the light impinges upon the surfaces z=0. The equation for the diffusion of the minority carriers in the n-

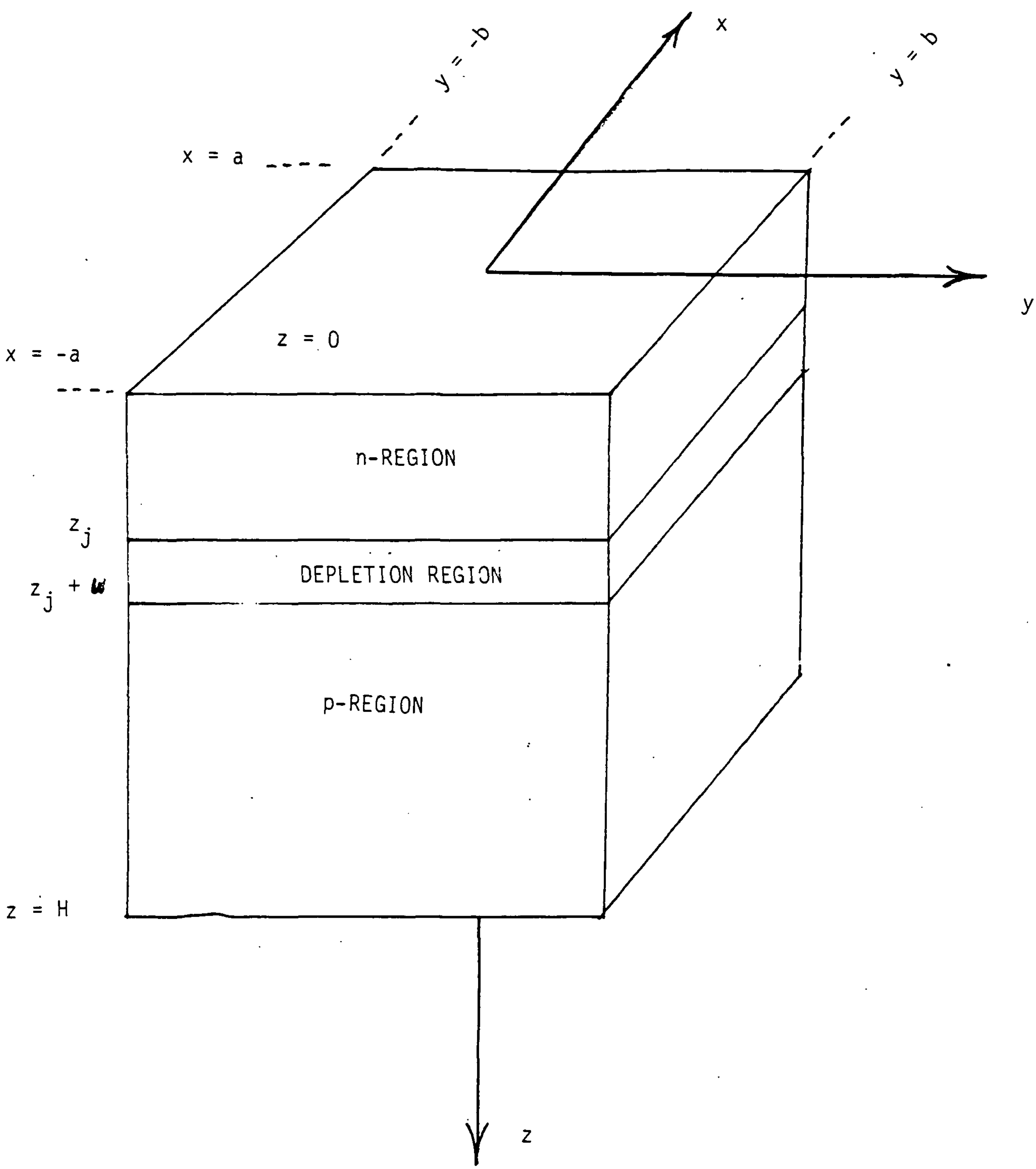


FIGURE 4. Geometry for three dimensional model of photoconverter

material is given by

$$L(P_n-P_{no}) = \nabla^2(P_n-P_{no}) - (P_n-P_{no})/L_p^{\,2} = -g(Z)/D_p, \quad x,y,z\varepsilon R_n \tag{3.1}$$

where L() is the linear operator $\nabla^2() - (\ )/L_p^{\,2}$ and g(x) is the generation rate defined by (1.1). Boundary conditions for the above equation are:

$$D_p \frac{\partial}{\partial Z}(P_n-P_{no}) = S_p(P_n-P_{no}) \text{ at } Z=0, \qquad P_n-P_{no} = 0 \text{ at } Z=Z_j \tag{3.2}$$

$$-D_p \frac{\partial}{\partial x}(P_n-P_{no}) = S_0(P_n-P_{no}) \text{ at } X=a, \qquad D_p \frac{\partial}{\partial x}(P_n-P_{no}) = S_0(P_n-P_{no}) \text{ at } x=-a \tag{3.3}$$

$$-D_p \frac{\partial}{\partial y}(P_n-P_{no}) = S_0(P_n-P_{no}) \text{ at } y=b, \qquad D_p \frac{\partial}{\partial y}(P_n-P_{no}) = S_0(P_n-P_{no}) \text{ at } y=-b \tag{3.4}$$

where we have assumed that the surface recombination velocity is S_0 on the sides and S_p on the surface z=0.

Similarly, the equation for the diffusion of minority carriers in the p-material is given by

$$L(n_p-n_{po}) = \nabla^2(n_p-n_{po}) - (n_p-n_{po})/L_n^{\,2} = -g(z)/D_n, \quad x,y,z\varepsilon R_p \tag{3.5}$$

with the boundary conditions

$$n_p - n_{po} = 0 \text{ at } Z=Z_j+w \qquad -D_n \frac{\partial}{\partial z}(n_p-n_{po}) = S_n(n_p-n_{po}) \text{ at } Z=H \tag{3.6}$$

$$-D_n \frac{\partial}{\partial x}(n_p-n_{po}) = S_1(n_p-n_{po}) \text{ at } X=a, \qquad D_n \frac{\partial}{\partial x}(n_p-n_{po})=S_1(n_p-n_{po}) \text{ at } x=-a \tag{3.7}$$

$$-D_n \frac{\partial}{\partial y}(n_p-n_{po}) = S_1(n_p-n_{po}) \text{ at } y=b, \qquad D_n \frac{\partial}{\partial y}(n_p-n_{po})=S_1(n_p-n_{po}) \text{ at } y=-b \tag{3.8}$$

where S_1, S_n are respectively the surface recombination velocities of the sides and bottom surface z=H.

The solution to the equations (3.1) and (3.5) which satisfy the corresponding boundary conditions is given in terms of Green's functions $G_1(x,y,z;\ x_0,y_0,z_0)$ for the region R_n and $G_2(x,y,z;\ x_0,y_0z_0)$ for the region R_p.

The Lagrange identity associated with the linear operator L() is

$$uL(v) - VL(u) = U\nabla^2 V - V\nabla^2 u. \tag{3.9}$$

By Green's second formula we can write

$$\iiint_{vol}[uL(v)-VL(u)]\, d\tau_0 = \iiint_{vol}[u\nabla^2 V-V\nabla^2 u]\, d\tau_0 = \iint_s (u\nabla V-V\nabla u)\cdot\hat{\nu}\, d\sigma_0 \tag{3.10}$$

where $d\tau_0$ is a volume element, $d\sigma_0$ is an element of surface area and $\hat{\nu}$ is a unit normal to the surface. Let $V = G_1(x,y,z;\ x_0,y_0,z_0)$ be a Green's function and let $U = P_n-P_{no}$ denote the solution to (3.1) with vol = R_n, then the integral (3.10) can be written

$$\iiint_{R_n} (p_n - p_{no})\, L(G_1)\, d\tau_0 - \iiint_{R_n} G_1 \left(\frac{-g(Z_0)}{D_p}\right) d\tau_0 =$$

$$\iint_S [(p_n - p_{no})\nabla G_1 - G_1 \nabla (P_n - P_{no})] \cdot \nu\, d\sigma_0 \qquad (3.11)$$

For $L(G_1) = \delta(x_0 - x)\,\delta(y_0 - y)\,\delta(z_0 - z)$, δ = Dirac delta function, the above gives

$$p_n - p_{no} = \int_0^{Z_j} \int_{-b}^{b} \int_{-a}^{a} \frac{-\alpha\phi_0 (1-Re)\, e^{-\alpha Z_0}}{D_p}\, G_1\,(x,y,z;\, x_0, y_0, z_0)\, dx_0 dy_0 dz_0 \qquad (3.12)$$

where the boundary conditions on G_1 are chosen such that the surface integral vanishes. The surface integral in (3.11) can be written for the region R_n as follows:

$$\int_{-b}^{b} \int_0^{Z_j} \left[(P_n - P_{no}) \left(-\frac{\partial G_1}{\partial x_0}\right) - G_1 \left(\frac{-\partial (P_n - P_{no})}{\partial x_0}\right)\right]_{x_0 = -a} dy_0\, dz_0$$

$$+ \int_{-a}^{a} \int_0^{Z_j} \left[(P_n - P_{no}) \left(+\frac{\partial G_1}{\partial y_0}\right) - G_1 \left(\frac{\partial (P_n - P_{no})}{\partial y_0}\right)\right]_{y_0 = b} dx_0\, dz_0$$

$$+ \int_{-b}^{b} \int_0^{Z_j} \left[(P_n - P_{no}) \left(\left(-\frac{\partial G_1}{\partial x_0}\right) - G_1 \left(\frac{-\partial (P_n - P_{no})}{\partial x_0}\right)\right]_{x_0 = a} dy_0\, dz_0 \qquad (3.13)$$

$$+ \int_{-a}^{a} \int_0^{Z_j} \left[(P_n - P_{no}) \left(-\frac{\partial G_1}{\partial y_0}\right) - G_1 \left(\frac{-\partial (P_n - P_{no})}{\partial y_0}\right)\right]_{y_0 = -b} dx_0\, dz_0$$

$$+ \int_{-a}^{a} \int_{-b}^{b} \left[(P_n - P_{no}) \left(-\frac{\partial G_1}{\partial z_0}\right) - G_1 \left(\frac{-\partial (P_n - P_{n_0})}{\partial z_0}\right)\right]_{z_0 = 0} dx_0\, dy_0$$

$$+ \int_{-a}^{a} \int_{-b}^{b} \left[(P_n - P_{no}) \left(\frac{\partial G_1}{\partial z_0}\right) - G_1 \left(\frac{\partial (P_n - P_{n_0})}{\partial z_0}\right)\right]_{z_0 = Z_j} dx_0 dy_0 = 0$$

The above equation gives the boundary condition for the Green's function and we obtain that G_1 must satisfy

$$\frac{\partial^2 G_1}{\partial x_0^2} + \frac{\partial^2 G_1}{\partial y_0^2} + \frac{\partial^2 G_1}{\partial z_0^2} - G_1/L_p^2 = \delta(x_0 - x)\ \delta(y_0 - y)\ \delta(z_0 - z),\ x_0, y_0, z_0 \varepsilon R_n \quad (3.14)$$

with boundary conditions:

$$\left.\begin{aligned}
&D_p \frac{\partial G_1}{\partial x_0} = SoG_1 \text{ at } x_0 = -a, \quad -D_p \frac{\partial G_1}{\partial x_0} = S_0 G_1 \text{ at } x_0 = a \\
&D_p \frac{\partial G_1}{\partial y_0} = SoG_1 \text{ at } y_0 = -b, \quad -D_p \frac{\partial G_1}{\partial y_0} = S_0 G_1 \text{ at } y_0 = b \\
&D_p \frac{\partial G_1}{\partial z_0} = S_p G_1 \text{ at } z_0 = 0, \quad G_1 = 0 \text{ at } z_0 = z_j
\end{aligned}\right\} \quad (3.15)$$

We perform a similar analysis for the region R_p and find the Green's function G_2 must satisfy

$$\frac{\partial^2 G}{\partial x_0^2} + \frac{\partial^2 G_2}{\partial y_0^2} + \frac{\partial^2 G_2}{\partial z_0^2} - G_2/L_p^2 = \delta(x_0 - x)\ \delta(y_0 - y)\ \delta(z_0 - z),\ x_0, y_0, z_0 \varepsilon R_p \quad (3.16)$$

with boundary conditions

$$\left.\begin{array}{ll} -D_n \dfrac{\partial G_2}{\partial x_0} = S_1 G_2 \text{ at } x_0 = a, & D_n \dfrac{\partial G_2}{\partial x_0} = S_1 G_2 \text{ at } x_0 = -a \\ -D_n \dfrac{\partial G_2}{\partial y_0} = S_1 G_2 \text{ at } y_0 = b, & D_n \dfrac{\partial G_2}{\partial y_0} = S_1 G_2 \text{ at } y_0 = -b \\ -D_n \dfrac{\partial G_2}{\partial z_0} = S_n G_2 \text{ at } z_0 = H, & G_2 = 0 \text{ at } z_0 = z_j + \omega \end{array}\right\} \quad (3.17)$$

and the solution for the minority carrier density in the R_p region is given by

$$n_p - n_{p_0} = \int_{Z_j+\omega}^{H} \int_{-b}^{b} \int_{-a}^{a} \frac{-\alpha\phi_0(1-Re)e^{-\alpha Z_0}}{D_n} G_2\ (x,y,z;\ x_0,y_0,z_0)dx_0 dy_0 dz_0 \quad (3.18)$$

From the relations (3.12) and (3.18) we can obtain the current densities

$$J_p = -qD_p \frac{\partial}{\partial z}(P_n - P_{no}) \text{ at } Z=Z_j \quad \text{and} \quad J_n = qD_n \frac{\partial}{\partial z}(n_p - n_{po}) \text{ at } Z=Z_j+\omega \quad (3.19)$$

To find the Green's functions G_1, G_2 for the regions R_n and R_p we examine the eigenfunctions and eigenvalues associated with the operator L(). We let u=u(r) satisfy the eigenvalue problem

$$\frac{d^2u}{dr^2} + \lambda^2 u = 0 \quad (3.20)$$

with boundary conditions

$$D\frac{du}{dr} + S_3 u = 0 \quad \text{at } r=h, \qquad D\frac{du}{dr} - S_3 u = 0 \quad \text{at } r=-h \tag{3.21}$$

The eigenfunctions of this problem are:

$$u = u_n(r) = \cos(\lambda_n r) = u\,(r;\ D,\ S_3,\ h,\ \lambda_n) \tag{3.22}$$

where $\lambda = \lambda_n$ satisfies the equation

$$(\lambda_n h)\tan(\lambda_n h) = \frac{S_3 h}{D} \tag{3.23}$$

We let $\xi_n = \lambda_n h$ satisfy $\tan(\xi_n) = S_3 h/D\xi_n$ then ξ_n is characterized by the intersection of the curves $y = \tan(\xi)$ and $y = S_3 h/D\xi$ (See Figure 5). Note that for large values of n, ξ_{n+1} approaches $n\pi$, and that the above functions $u_n(r)$ are orthogonal on the interval $(-h, h)$

and

$$(u_n, u_m) = \int_{-h}^{h} u_n(r) u_m(r)\,dr = \begin{cases} 0, & m \neq n \\ \|u_n\|^2, & m=n \end{cases} \tag{3.24}$$

where

$$\|u_n\|^2 = h + \frac{S_3}{D\lambda_n^2}\cos^2(\lambda_n h) = h + \frac{S_3 h^2}{D}\,\frac{\cos^2(\xi_n)}{\xi_n^{\,2}} \tag{3.25}$$

We will use these functions in the construction of our Green's function

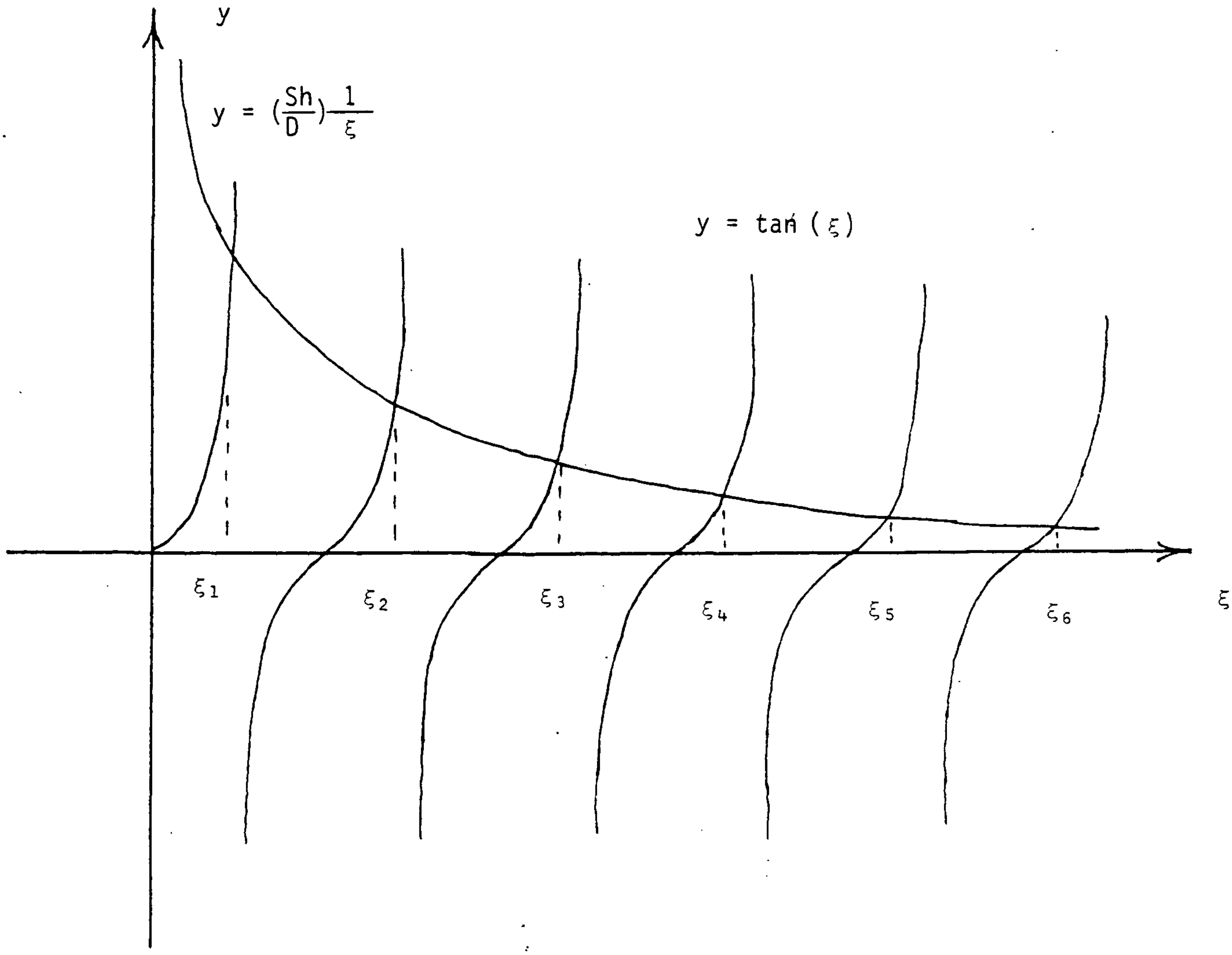


FIGURE 5. Graphical scheme for determining eigenvalues

solutions for G_1 and G_2.

Define the eigenfunctions associated with the region R_n as

$$U_m(x) = \cos(\lambda_m x), \quad -a < x < a, \quad m=1,2,3\ldots$$

with

$$\xi_m = \lambda_m a, \; \| U_m \|^2 = a + \frac{S_0 a^2}{D_p} \frac{\cos^2(\xi_m)}{\xi_m{}^2}$$

and where

$$\xi_m \tan \xi_m = S_0 a/D_p, \quad m=1,2,3,\ldots$$

Also define the eigenfunctions

$$V_m(y) = \cos(\mu_m y), \; -b<y<b$$

with

$$\eta_m = \mu_m b, \quad \| V_m \|^2 = b + \frac{S_0 b^2}{D_p} \frac{\cos^2(\eta_m)}{\eta_m{}^2}$$

where

$$\eta_m \tan(\eta_m) = S_0 b/D_p.$$

There will be a similar set of eigenfunctions associated with the region R_p. We denote these eigenfunctions by $U_m^*(x)$ and $V_m^*(y)$ and note that S_0 is replaced by S_1 in the calculation of these eigenfunctions. We now assume a solution for the Green's functions G_1, G_2 as:

$$G_1 = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} A_{ij}(z_0)\ U_j(x_0)V_i(y_0) \tag{3.26}$$

$$G_2 = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} B_{ij}(z_0)\ U_j^*(x_0)V_i^*(y_0) \tag{3.27}$$

as the functions U_j and V_i satisfy the boundary conditions and

$$U_n(x) = \cos(\lambda_n h) = u(x;\ D_p,\ S_0,\ a,\ \lambda_n),\quad -a<x<a$$

$$U_n^*(x) = \cos(\lambda^* x) = u(x;\ D_n,\ S_1,\ a,\ \lambda_n^*),\quad -a<x<a$$

$$V_m(y) = \cos(\mu_m y) = u(y;\ D_p,\ S_0,\ b,\ \mu_m),\quad -b<y<b$$

$$V_m^*(y) = \cos(\mu_m^* y) = u(y;\ D_n,\ S_1,\ b,\ \mu_m^*),\quad -b<y<b$$

where it is assumed that S_0, S_1 are different from zero. Substituting (3.26) and (3.27) into (3.14) and (3.16) respectively, we find that A_{mn} and B_{mn} must be chosen to satisfy the conditions:

$$A_{ij}'' - \frac{1}{\gamma_{ij}^2} A_{ij} = \frac{U_j(x)V_i(y)\delta(z_0-z)}{\|U_j\|^2\|V_i\|^2},\quad 0< z_0<Z_j \tag{3.28}$$

$$A_{ij}(z_j) = 0, \qquad D_p \frac{dA_{ij}}{dz_0} - S_p A_{ij} = 0 \text{ at } z_0 = 0$$

with $$\gamma_{ij}^{2} = L_p^{2}/(1 + L_p^{2}\ (\lambda_i^2 + \mu_j^2))$$

$$B_{ij}'' - \frac{1}{\sigma_{ij}^{2}}\ B_{ij} = \frac{U_j^*(x)V_i^*(y)\delta(z_0-z)}{\|U_j^*\|^2\|V_i^*\|^2}, \quad Z_j+\omega < z_0<H \tag{3.29}$$

$$B_{ij}(Z_j+\omega) = 0\ , \qquad D_n \frac{dB_{ij}}{dZ_0} + S_n B_{ij} = 0 \quad \text{at} \quad z_0 = H.$$

with $$\sigma_{ij}^2 = L_n^2/(1 + L_n^2\ (\lambda_i^{*2} + \mu_j^{*2})).$$

These equations have the solutions

$$A_{ij}(z_0) = \begin{cases} \dfrac{U_j(x)V_i(y)y_1(z_0)y_2(z)}{\|U_j\|^2\|V_i\|^2\ \Delta_1}, & 0<z_0 z \\[2ex] \dfrac{U_j(x)V_i(y)y_1(z)y_2(z_0)}{\|U_j\|^2\|V_i\|^2\ \Delta_1}, & z<z_0<Z_j \end{cases} \tag{3.30}$$

where

$$y_1(z) = \cosh\ (z/\gamma_{ij}) + (S_p\gamma_{ij}/D_p)\ \sinh\ (z/\gamma_{ij})$$

$$y_2(z) = \frac{\sinh\ (Z_j-z)/\gamma_{ij})}{\sinh(Z_j/\gamma_{ij})}$$

and

$$\Delta_1 = -\frac{1}{\gamma_{ij}} \frac{y_1(Z_j)}{\sinh(Z_j/\gamma_{ij})}.$$

Also,

$$B_{ij} = \begin{cases} \dfrac{U_j^*(x)V_i^*(y)y_4(z)y_3(z_0)}{\|U_j^*\|^2 \|V_i^*\|^2 \cdot \Delta_2}, & Z_j+\omega<z_0<z \\[2ex] \dfrac{U_j^*(x)V_i^*(y)y_3(z)y_4(z_0)}{\|U_j^*\|^2 \|V_i^*\|^2 \cdot \Delta_2}, & z<z_0<H \end{cases} \tag{3.31}$$

with $y_3(z) = \sinh\,(Z-Z_j-\omega)/\sigma_{ij})$

$$y_4(z) = \cosh\left((H-z)/\sigma_{ij}\right) + \frac{S_n\sigma_{ij}}{D_n} \sinh\left((H-z)/\sigma_{ij}\right)$$

$$\Delta_2 = -\frac{1}{\sigma_{ij}}\, y_4\,(Z_j+\omega).$$

From the equations (3.12) (3.18) (3.19) (3.26) and (3.27) we obtain the current density

$$J_p = 4\alpha q_{\phi 0}(1-R) \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \gamma_{mn} \frac{U_n(x)V_m(y)\sin(\lambda_{na})\sin(\mu_{mb})G_{mn}}{\|U_n\|^2 \|V_m\|^2 \quad \lambda_n \qquad\quad \mu_m} \tag{3.32}$$

with

$$G_{mn}=\frac{1}{\alpha^2\gamma^2{}_{mn}-1}\left[\frac{S_p\gamma_{ij}/D_p+\alpha\gamma_{mn}-e^{-\alpha Z_j}\left\{S_p\gamma_{ij}/D_p\cosh(Z_j/\gamma_{mn})+\sinh(Z_j/\gamma_{mn})\right\}\alpha\gamma_{mn}e^{-\alpha Z_j}}{y_1(Z_j)}\right]$$

Observe that G_{mn} has a removable singularity where $\alpha\gamma_{mn} = 1$ and in this case we can write

$$G_{mn} = \frac{1}{\alpha\gamma_{mn+1}}\left[\frac{1+(S_p\gamma_{ij}/D_p+1)\left\{\frac{1-e^{-Z_j/\gamma_{mn}(\alpha\gamma_{mn}-1)}}{\alpha\gamma_{mn}-1}\right\}-e^{-\alpha Z_j}}{y_1(Z_j)}\right]$$

The current density J_n is given by

$$J_n = 4\alpha q\phi_0(1-R)\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{U_n^*(x)V_m^*(y)\ \sigma_{mn}\sin(\lambda_n^* a)\ \sin(\mu_m^* b)\ H_{mn}}{\|V_n^*\|^2\|V_m^*\|^2\qquad\lambda_n^*\qquad\mu_m^*\ \ y_4(Z_j+w)}\tag{3.33}$$

with

$$H_{mn} = \frac{1}{\alpha^2\sigma_{mn}^2-1}\left[e^{-\alpha H}\left(\frac{S_n\sigma_{ij}}{D_n}-\alpha\sigma_{mn}\right)+e^{-\alpha(z_j+w)}\left(\frac{S_n\sigma_{ij}}{D_n}\sigma_{mn}-1\right)\sinh(H'/\sigma_{mn})\right.$$

$$\left.+\ e^{-\alpha(Z_j+w)}(\sigma_{mn}\alpha - S_n\ \sigma_{ij}/D_n)\cosh(H'/\sigma_{mn})\right]$$

with $H' = H-z_j-w$. The total light current is $J_L = J_p+J_n$.

DARK CURRENTS

The equations describing the dark currents associated with the n and p regions may be expressed

$$\nabla^2(P_n - P_{no}) - \frac{(P_n - P_{no})}{L_p^2} = 0$$

with boundary conditions:

$$P \equiv P_n - P_{no} = P_{no}\left[\exp\left(\frac{qV_j}{KT}\right) - 1\right] \quad \text{at } z = z_j$$

$$D_p \frac{\partial P}{\partial z} - S_p P = 0 \quad \text{at} \quad z = 0$$

$$-D_p \frac{\partial P}{\partial x} - S_0 P = 0 \quad \text{at} \quad x = a, \qquad D_p \frac{\partial P}{\partial x} - S_0 P = 0 \quad \text{at} \quad x = -a$$

$$-D_p \frac{\partial P}{\partial y} - S_0 P = 0 \quad \text{at} \quad y = b, \qquad D_p \frac{\partial P}{\partial y} - S_0 P = 0 \quad \text{at} \quad y = -b$$

and

$$\nabla^2 (n_p - n_{po}) - \frac{(n_p - n_{po})}{L_n^2} = 0 \qquad (3.35)$$

with boundary conditions

$$n = n_p - n_{po} = n_{po}\left[\exp\left(\frac{qV_j}{KT}\right) - 1\right] \quad \text{at} \quad Z = Z_j + \omega$$

$$-D_n \frac{\partial n}{\partial z} - S_n n = 0 \quad \text{at} \quad z = H$$

$$-D_n \frac{\partial n}{\partial x} - S_1 n = 0 \quad \text{at} \quad x = a, \qquad D_n \frac{\partial n}{\partial x} - S_1 n = 0 \quad \text{at} \quad x=-a$$

$$-D_n \frac{\partial n}{\partial y} - S_1 n = 0 \quad \text{at} \quad y = b, \qquad D_n \frac{\partial n}{\partial y} - S_1 n = 0 \quad \text{at} \quad y=-b$$

with V_j the junction voltage.

We use the relation (3.11) with g=0 and obtain the Green's second formula

$$\iiint_{R_n} (P-P_{no})\, L(G_1)\, d\tau_0 = P_n-P_{no} = \sum_{i=1}^{6} I_i \tag{3.36}$$

where I_i, i=1,...6 are the surface integrals defined by (3.13). Applying the boundary conditions from (3.34) the relation (3.36) reduces to

$$P_n-P_{no} = \int_{-b}^{b} \int_{-a}^{a} P_{no} \left[\exp\left(\frac{qV_j}{KT}\right) -1\right] \frac{\partial G_1}{\partial Z_0}\Bigg|_{z_0=Z_j} dx_0\, dy_0 \tag{3.37}$$

and the dark current opposing the photo current is given by

$$J_{pd} = -q\, D_p \operatorname{grad} (P_n-P_{no}) \cdot \hat{k} \Bigg|_{Z=Z_j} \tag{3.38}$$

A similar analysis for the region R_p produces the electron density

$$n_p - n_{po} = \int_{-b}^{b} \int_{-a}^{a} -n_{po} \left[\exp\left(\frac{qV_j}{KT}\right) - 1 \right] \left. \frac{\partial G_2}{\partial z_0} \right|_{z_0 = Z_j + w} dx_0 \, dy_0 \tag{3.39}$$

and the dark current opposing the photocurrent is given by

$$J_{nd} = -qD_n \text{ gnd } (n_p - n_{po}) \cdot (-\hat{k}) \Big|_{z = Z_j + w} \tag{3.40}$$

The equations (3.38) and (3.40) simplify to

$$J_{pd} = 4abq \; D_p P_{no} (e^{qV_j/kT} - 1) \sum_m \sum_n \frac{U_n(x) V_m(y) y_1'(Z_j) \sin(\lambda_n a) \sin(\mu_m b)}{\| U_n \|^2 \| V_m \|^2 \; y_1(Z_j) \; (\lambda_n a) \; (\mu_m b)} \tag{3.41}$$

and

$$J_{nd} = 4abq \; D_n n_{po} (e^{qV_j/kT} - 1) \sum_m \sum_n \frac{U_n^*(x) V_m^*(y) y_4'(Z_j + w) \sin(\lambda_n^* a) \sin(\mu_m^* b)}{\| U_n^* \|^2 \| V_m^* \|^2 \; y_4(Z_j + w) \; (\lambda_n^* a) \; (\mu_m^* b)} \tag{3.42}$$

where $P_{no} = n_i^2/N_d$ and $n_{po} = n_i^2/N_a$

The total dark current density is

$$J_{dark} = J_{pd} + J_{nd} = J_0 \left(\exp\left(\frac{qV_j}{KT}\right) - 1\right) \tag{3.43}$$

We use the recombination current density from (1.21) and calculate the total currents by integration

$$I_{sc} = \int_{-b}^{b} \int_{-a}^{a} J_L \, dxdy \qquad (3.44)$$

$$I_{rec} = J_{rec} \cdot 4ab \qquad (3.45)$$

$$I_0 = \int_{-b}^{b} \int_{-a}^{a} J_0 \, dxdy \qquad (3.46)$$

$$I_{dark} = \int_{-b}^{b} \int_{-a}^{a} J_{dark} \, dxdy \qquad (3.47)$$

The current voltage relation is obtained from the equivalent circuit diagram of Figure 2. The computer program "SC3D" which utilizes the above equations is given in Appendix C.

4. THREE-DIMENSIONAL VERTICAL JUNCTION SOLAR CELL

With reference to the geometry illustrated in Figure 4, we assume the photoconverter is illuminated from the side x=a. For this assumption, we use the generation term g(a-x) where g(x) is defined by equation (1.1). Also we must modify the Green's functions G_1, G_2 used in the conventional photoconverter. Note that G_1, G_2 were expanded as double Fourier series which were symmetric in both x and y. For illumination from the side x=a we must remove the symmetry in the x-direction. Consequently, for the n-region and p-region we construct Green's functions g_1, g_2 having the following form:

$$g_1 = \sum_{m=1}^{\infty} \sum_{\ell=1}^{\infty} \frac{V_m(y_0) W_\ell(z_0) V_m(y) W_\ell(z) \psi_{3m\ell}}{\| V_m \|^2 \| W_\ell \|^2 \rho_{m\ell}} \qquad (4.1)$$

$$g_2 = \sum_{m=1}^{\infty} \sum_{\ell=1}^{\infty} \frac{V_m^\star(y_0)W_\ell^\star(z_0)V_m^\star(y)W_\ell^\star(z)\psi_{4m\ell}}{\|V_m^\star\|^2 \|W_\ell^\star\|^2 \ \rho_{m\ell}^\star} \tag{4.2}$$

where $$W_\ell = \sin\left(n_\ell(Z_j - z)\right), \quad 0 < z < Z_j, \ \ell=1,2,3.... \tag{4.3}$$

and $$W_\ell^\star = \sin\left(n_\ell^\star(z - Z_j - w)\right), \quad Z_j+\omega<z<H, \ \ell=1,2,3.... \tag{4.4}$$

are eigenfunctions with eigenvalues determined by the roots of the equations

$$-D_p \ (n_\ell Z_j)/(S_p Z_j) = \tan\ (n_\ell Z_j) \tag{4.5}$$

and

$$-D_n \ (n_\ell^\star H')/S_n H') = \tan\ (n_\ell^\star H') \ , \quad H'=H-Z_j-\omega \tag{4.6}$$

respectively. These eigenfunctions have the norm squared

$$\|W_\ell\|^2 = \frac{1}{2} Z_j - \frac{1}{4} \ \frac{\sin(2n_\ell Z_j)}{n_\ell} \tag{4.7}$$

$$\|W_\ell^\star\|^2 = \frac{1}{2} H' - \frac{1}{4} \ \frac{\sin(2n_\ell^\star H')}{n_\ell^\star} \tag{4.8}$$

In (4.1) and (4.2) V_m, $V_m^\star$ have been previously defined in (3.26) and (3.27). Also in (4.1) and (4.2) we have

$$\rho_{ij} = \left(\frac{1}{\Gamma_{ij}} + \frac{S_0{}^2\Gamma_{ij}}{D_p{}^2}\right) \sinh\left(\frac{2a}{\Gamma_{ij}}\right) + \frac{2S_0}{D_p} \cosh\left(\frac{2a}{\Gamma_{ij}}\right) \tag{4.9}$$

$$\rho^*_{ij} = \left(\frac{1}{\varepsilon_{ij}} + \frac{S_1{}^2\varepsilon_{ij}}{D_n{}^2}\right) \sinh\left(\frac{2a}{\varepsilon_{ij}}\right) + \frac{2S_1}{D_n} \cosh\left(\frac{2a}{\varepsilon_{ij}}\right) \tag{4.10}$$

$$\Gamma_{ij}{}^2 = L_p{}^2/(1 + L_p{}^2(\mu_i{}^2 + \eta_j{}^2)) \ , \qquad \varepsilon_{ij}{}^2 = L_n{}^2/(1 + L_n{}^2(\mu^*_i{}^2 + \eta^*_j{}^2)) \tag{4.11}$$

$$\psi_{3mn} = \begin{cases} -y_1(X)y_2(X_0), & -a<X_0<X \\ -y_1(X_0)y_2(X), & X<X_0<a \end{cases} \tag{4.12}$$

$$\psi_{4ij} = \begin{cases} -y_4(X)y_3(X), & -a<X_0<X \\ -y_4(X_0)y_3(X), & X<X_0<a \end{cases} \tag{4.13}$$

$$y_1(X) = \cosh\left(\frac{a-X}{\Gamma_{mn}}\right) + \frac{S_0\Gamma_{mn}}{D_p} \sinh\left(\frac{a-X}{\Gamma_{mn}}\right) \tag{4.14}$$

$$y_2(X) = y_1(-X) \tag{4.15}$$

$$y_3(X) = \cosh\left(\frac{a-X}{\varepsilon_{ij}}\right) + \frac{S_1\varepsilon_{ij}}{D_n} \sinh\left(\frac{a-X}{\varepsilon_{ij}}\right) \tag{4.16}$$

$$y_4(X) = y_3(-X) \tag{4.17}$$

In the n-region we can represent the solution to the boundary value problem

(3.1) by

$$P_n - P_{no} = \int_0^{Z_j} \int_{-b}^{b} \int_{-a}^{a} \frac{-g(a-X_0)}{D_p} g_1(x,y,z; \quad x_0, y_0, z_0)\ dx_0\, dy_0\, dz_0 \tag{4.18}$$

and in the p-region we can represent the solution to the boundary value problem (3.5) by

$$n_p - n_{po} = \int_{Z_{j+\omega}}^{H} \int_{-b}^{b} \int_{-a}^{a} \frac{-g(a-X_0)}{D_n} g_2(x,y,z; \quad x_0, y_0, z_0)\ dx_0\, dy_0\, dz_0 \tag{4.19}$$

where the source term has been replaced by $g(a-X_0)$ which models the illumination from the side $X_0 = a$. From these equations we use (3.19) to obtain the photocurrents. The computer program "VSC3D" describing the vertical junction model is given in the Appendix D together with representative graphic output.

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APPENDIX A

BASIC COMPUTER PROGRAM FOR ONE-DIMENSIONAL CONVENTIONAL PHOTOCONVERTER

```
10    OPTION BASE 1
20    !*********************************************************************
30    !
40    !     PROGRAM CONVEN
50    !
60    !CONVENTIONAL SOLAR CELL PROGRAM SET UP FOR Si SOLAR CELL CHARACTERISTICS
70    !
80    REM CONVENTIONAL SOLAR CELL PROGRAM CONSTANT TEMPERATURE
90    !
100   !**********************************************************************
110   DIM X(50),Xx(50),Aa(50,4),Z(50),Volts(100),Amps(100)
120   DIM Esi(20),Asi(20)
130   !*********************************************************************
140   !
150   !        READ IN Silcon ABSORPTION COEFFICIENT DATA
160   Nsi=20                  ! THIS IS NUMBER OF DATA POINT PAIRS TO READ
170                          !IF YOU CHANGE THIS NUMBER CHANGE DIM STATEMENT ABOVE
180   FOR I=1 TO Nsi
190   READ Esi(I),Asi(I)           !READ IN ENERGY(EV) AND ABSORPTION COEFF CM-1
200   NEXT I
210   DATA 1.1,1,1.15,10,1.24,100,1.378,350,1.46,950,1.77,2000
220   DATA 2.067,4500,2.48,1E4,2.76,2E4,3.1,5E4,3.26,1E5,3.5,1E6,3.6,1.1E6
230   DATA 4,1.8E6,4.2,2.5E6,5,1.9E6,5.2,2E6,6,1.5E6,8,1.3E6,10,1.1E6
240   GINIT
250   GRAPHICS ON
260   GCLEAR
270   WINDOW 0,100,0,100
280   CSIZE 9
290   LORG 5
300   MOVE 50,50
310   LABEL "SPECTRAL RESPONSE CURVE"
320   CSIZE 5
330   MOVE 50,40
340   LABEL "IT TAKES A MOMENT TO CALCULATE"
350   !SOLAR CELL CONSTANTS
360   !CONSTANTS FOR MOBILITY Mun
370   A0=65.02  !FOR Si;  FOR GaAs A0=5076.11 ; FOR Ge A0=458.68
380   A1=5.72E-9 !FOR Si;FOR GaAs A1=6.03E-8 ; FOR Ge A1=7.92E-9
390   A2=2.49E+9 !FOR Si;FOR GaAs A2=2.13E6  ; FOR Ge A2=6.08E7
400   A3=2.5   !FOR Si ; FOR GaAs A3=1.0     ; FOR Ge A3=1.66
410   !CONSTANTS FOR MOBILITY Mup
420   B0=54.46 !FOR Si ; FOR GaAs B0=37.33 ; FOR Ge B0=3140.27
430   B1=6.76E-9 !FOR Si; FOR GaAs B1=8.51E-9; FOR Ge B1=1.79E-7
440   B2=2.93E+9!FOR Si; FOR GaAs B2=6.05E7 ; FOR Ge B2=1.18E9
450   B3=2.7 !FOR Si; FOR GaAs B3=2.1; FOR Ge B3=2.33
460   !CONSTANTS FOR BANDGAP AS FUNCTION OF TEMPERATURE
470   Eggo=1.16        !FOR Si; FOR GaAs 1.522 ; FOR Ge .741
480   Alphao=7.02E-4 !FIR Si; FOR GaAs 5.8E-4; FOR Ge 4.56E-4
490   Betao=1108. !FOR Si; FOR GaAs 300; FOR Ge 210
500   !CONSTANTS FOR INTRINSIC CARRIER DENSITY
510   Nia1=4.9E+15
520   Nia2=1.61
530   B=7.1E+15        !CONSTANT FOR LIFETIME CALCULATIONS
540   Xkko=1.2E-3      !CONSTANT FOR ABSORPTION SHIFT
550   Xkk1=.95         !CONSTANT FOR ABSORPTION SHIFT -SEE BELOW
560   T0=300           ! FIXED REFERENCE TEMPERATURE
570   Kb=8.6172E-5      ! BOLTZMANN'S CONSTANT EV/K
580   Q=1.6E-19         ! ELECTRON CHARGE
590   !******************************************************************
600   !
610   !          ADJUSTABLE SOLAR CELL PARAMETERS
620   !
```

```
630    !****************************************************************
640 Parameters:   !  CHANGE THE VALUES BELOW IF DESIRED
650    Sn=0.E+0                   !SURFACE RECOMBINATION VELOCITY CM/SEC
660    Sp=0.E+0                   !SURFACE RECOMBINATION VELOCITY CM/SEC
670    Na=1.25E+17                ! DOPING DENSITY P REGION CM-3
680    Nd=5.0E+19                 ! DOPING DENSITY N-REGION CM-3
690    Tn0=1.86E-4                ! CONSTANT FOR LIFETIME CALCULATION
700    Tp0=3.52E-3                ! CONSTANT FOR LIFETIME CALCULATION
710    Wo=1.000                    !LASER POWER KW/CM2
720                               !Wo DETERMINES TEMPERATURE IN CELL
730                               !SEE BELOW
740    Hh2=100                    !HEAT TRANSFER COEFFICIENT TO BACK SURFACE
750                               !UNITS OF WATTS/CM2-DEG C
760    Kback=1.5                  !WATTS/CM-DEG C THERMAL CONDUCTIVITY BACK SURFACE
770    Tpipe=100                  !TEMPERATURE DEG C OF HEAT PIPE    (ASSUMED TEMP
780                               !OF HEAT PIPE LOWER TEMPERATURE
790    Lambda=1.06                !LASER WAVELENGTH IN MICRONS
800    Re=.05                     !REFLECTION COEFFICIENT FOR ILLUMINATED SURFACE
810    Rs=0.                      ! SOLAR CELL SERIES RESISTANCE IN OHMS
820    Rsh=1.0E+6                 !SHUNT RESISTANCE IN OHMS
830    Epso=11.6                  ! Si PERMITIVITY COEFFICIENT (DIMENSIONLESS)
840    H=4.500E-1                 !SOLAR CELL HEIGHT IN CM
850    Xj=5.0E-4                  !JUNCTION DEPTH IN CM
860    !******************************************************************
870    !
880    !          BEGIN CALCULATIONS FOR THE SPECTRAL RESPONSE
890    !
900    !******************************************************************
910    !ESTIMATE ABSORPTION COEFFICIENT ALPHA
920    T=273+Tpipe+1000*Wo*(1-Re)/Hh2   !ESTIMATE SOLAR CELL TEMP DEG K
930    Ener=1.2402/Lambda   ! ENERGY IN EV FOR WAVELENGTH LAMBDA
940    Egt=Eggo-Alphao*T*T/(T+Betao)    !BANDGAP FOR THIS TEMPERATURE
941    IF (Ener<=1.7) THEN Xkko=(1.3*Ener-1)*1.0E-3
950    Dele=2*Xkko*(T-T0)
960    E=Ener+Dele
970    Alpha=FNAbsorp(Nsi,Esi(*),Asi(*),E)               !APPROXIMATION OF AlPHA
980    !CALCULATE TEMPERATURE OF SOLAR CELL AT LASER SURFACE INTERFACE
990    Yy1=Alpha*H
1000   Yy2=0
1010   IF (Yy1<220) THEN Yy2=EXP(-Yy1)
1020   T=Tpipe+(Wo*1000*(1-Re)/Kback)*((Kback/Hh2)-1/Alpha)*(1-Yy2)
1030   IF (T<Tpipe) THEN T=Tpipe
1040   T=T+273        !CONVERT TO DEG K
1050   Kbtg=Kb*T                  ! BOLTZMANN'S CONSTANT TIMES TEMPERATURE
1060   Egt=Eggo-Alphao*T*T/(T+Betao)     ! BANDGAP CALCULATION
1070   Tn=Tn0/(1+Na/B)                 ! LIFETIME CALCULATION
1080   Tp=Tp0/(1.+Nd/B)                ! LIFETIME CALCULATION
1090   Mun=FNMun(Na,T,A0,A1,A2,A3)    ! MOBILITY CALCULATION -SEE BELOW FOR FN
1100   Mup=FNMup(Nd,T,B0,B1,B2,B3)  !  MOBILITY CALCULATION -SEE BELOW FOR FN
1110   Dn=Kbtg*Mun                     ! DIFFUSION COEFFICIENT CALCULATION
1120   Dp=Kbtg*Mup                     ! DIFFUSION COEFFICIENT CALCULATION
1130   Phio=Wo*Lambda*5.03306E+21     !PHOTONS/CM2-S
1140   Ni=(Nia1)*(Nia2)*(T^1.5)*EXP(-Egt/(Kbtg*2)) !INTRINSIC CARRIER DENSITY
1150   Vbi=Kbtg*LOG(Na*Nd/(Ni*Ni)) ! BUILT IN VOLTAGE
1160   W2=(2.*Epso*(8.85E-14)/Q)*Vbi*(1./Nd+1./Na)
1170   W=SQR(W2)        !SPACE CHARGE REGION WIDTH
1180   Hp=H-Xj-W        ! DEPTH OF BOTTOM SECTION (P REGION)
1190   Lp=SQR(Dp*Tp)  ! DIFFUSION LENGTH CALCULATION
1200   Ln=SQR(Dn*Tn)    ! DIFFUSION LENGTH CALCULATION
1210   Dl=.075          ! WAVELENGTH INCREMENT FOR SPECTRAL RESPONSE CURVE
```

```
1220   !*****************************************************************
1230   !
1240   !PLOT SPECTRAL RESPONSE AND THEN PAUSE TO LOOK AT IT
1250   !
1260   !*******************************************************************
1270   FOR J=1 TO 50
1280   X(J)=1.115+(J-1)*DI   !THIS IS ENERGY IN EV
1290   Xx(J)=1.2402/X(J)     !THIS IS WAVELENGTH IN MICRONS
1300   Ener=X(J)
1310   Engo=X(J)
1320   IF (Ener>1.7) THEN Xkk=Xkko
1330   IF (Ener<1.7) THEN Xkk=(Xkk1*Ener-1)*1.0E-3
1340   Dele=2*Xkk*(T-T0)
1350   Ene=Ener+Dele
1360   Alpha=FNAbsorp(Nsi,Esi(*),Asi(*),Ene)
1370   !PRINT T,Ener,Alpha,Dele
1380   Aa1=Sp*Lp/Dp
1390   Aa2=Xj/Lp
1400   Y1=Alpha*Lp
1410   Aa0=Aa1+Y1
1420   Y2=Y1/(Y1*Y1-1)
1430   Fj=FNJ(Aa1,1.,Aa2)
1440   Z1=Alpha*Xj
1450   Z2=Alpha*(Xj+W)
1460   Z3=Alpha*W
1470   Z4=Alpha*(Hp)
1480   IF (Z1<200) THEN GOTO L53
1490   Y1z=0
1500   GOTO L63
1510 L53: Y1z=EXP(-Z1)
1520 L63:  IF (Z2<200) THEN GOTO L54
1530       Y2z=0
1540       GOTO L64
1550 L54:Y2z=EXP(-Z2)
1560 L64:IF (Z3<200) THEN GOTO L55
1570     Y3z=0
1580     GOTO L65
1590 L55:Y3z=EXP(-Z3)
1600 L65:   IF (Z4<200) THEN GOTO L56
1610        Y4z=0
1620        GOTO L66
1630 L56:       Y4z=EXP(-Z4)
1640 L66:           Y3=Aa0-Fj*Y1z
1650                Y4=FNH(Aa1,1.,Aa2)
1660                Y5=Y1*Y1z
1670                Aa(J,1)=Y2*((Y3/Y4)-Y5)  !TOP OF JUNCTION
1680   Aa3=Sn*Ln/Dn
1690   Aa4=Alpha*Ln
1700   Aa5=Hp/Ln
1710   Aa6=Aa4-Aa3
1720   Y6=Aa4/(Aa4*Aa4-1)
1730   Y7=Aa6*Y4z
1740   Fj=FNJ(Aa3,1.,Aa5)
1750   Y7=Y7+Fj
1760   Y8=FNH(Aa3,1.,Aa5)
1770   Aa(J,2)=Y6*Y2z*(Aa4-Y7/Y8)
1780   Aa(J,3)=Y1z*(1.-Y3z)
1790   Aa(J,4)=Aa(J,1)+Aa(J,2)+Aa(J,3)
1800   NEXT J
1810   !***************************************************************
```

```
1820  !
1830  !          GRAPHICS FOR SPECTRAL RESPONSE CURVE
1840  !
1850  !*****************************************************************
1860  GINIT
1870  GRAPHICS ON
1880  DUMP DEVICE IS 701    !FOR LARGE GRAPHS USE 701,EXPANDED
1890  WINDOW -.25,1.60,-.1,1.1   ! XMIN,XMAX,YMIN,YMAX FOR GRAPH
1900  FRAME                 ! DRAW A BOX AROUND GRAPH
1910  AXES .10,.10,0.,0,5,2,6    !XTIC,YTIC,ORIGIN,POSITION OF MAJOR TICS
1920  !*****************************************************************
1930  !
1940  ! NOW TO LABEL THE AXES---X AXIS FIRST
1950  !
1960  !******************************************************************
1970  CSIZE 4
1980  LORG 6
1990  FOR X_label=0. TO 1.5 STEP .5
2000  MOVE X_label,-.045
2010  LABEL X_label
2020  NEXT X_label
2030  LORG 8
2040  FOR Y_label=0 TO 1 STEP .1
2050  MOVE -.03,Y_label
2060  LABEL Y_label
2070  NEXT Y_label
2080  LORG 6
2090  !***************************************************************
2100  !
2110  !LABEL THE AXES WITH NAMES
2120  !
2130  !***************************************************************
2140  DEG                   !THIS SETS ANGLES TO DEGREES
2150  LDIR 0                !ZERO ROTATION FOR DIRECTION OF LABELS
2160  MOVE (.75),-.01
2170  LABEL "WAVELENGTH(MICRONS)" !WRITE LABEL IN CENTER OF AXES
2180  LDIR 90     ! GET READY FOR A 90 DEG ROTATION OF LABEL
2190  MOVE -.18,.5   ! MOVE TO CENTER OF Y AXIS
2200  LABEL "SPECTRAL RESPONSE"
2210  !****************************************************************
2220  !
2230  !          PLOT THE SPECTRAL RESPONSE CURVES FOR
2240  !
2250  !          CONTRIBUTION: FROM FRONT;BACK;DEPLETION REGION;TOTAL
2260  !
2270  !*****************************************************************
2280  FOR I=1 TO 4
2290      FOR J=1 TO 50
2300      Z(J)=Aa(J,I)
2310      NEXT J
2320      MOVE Xx(1),Z(1)
2330      FOR K=1 TO 50
2340      DRAW Xx(K),Z(K)
2350      NEXT K
2360   NEXT I
2370   LDIR 0
2380   CSIZE 3.8
2390   LORG 3
2391   MOVE -.15,-.05
2392   LABEL "Si"
```

```
010    J01=(Q*Dp/Lp)*(Ni*Ni/Nd)*(Z1/Z2)
020    J02=(Q*Dn/Ln)*(Ni*Ni/Na)*(Z3/Z4)
030    J0=J01+J02
040    Z3=Alpha*Lp
050    Z4=Alpha*Ln
060    R1=Q*Phi0*(1-Re)*Z3/(Z3*Z3-1)
070    R2=Aa1+Z3
080    R3=EXP(-Alpha*Xj)
090    Jp=R1*(((R2-R3*Z1)/Z2)-Z3*R3)
100    R4=EXP(-Alpha*(Xj+W))
110    R5=Q*Phio*(1-Re)*Z4*R4/(Z4*Z4-1)
120    R6=FNCosh(X2)
130    Yy1=Alpha*Hp
140    Yy2=0
150    IF (Yy1<220) THEN Yy2=EXP(-Yy1)
160    R7=Z4*Yy2
170    R8=Z4-(Aa3*(R6-Yy2)+FNSinh(X2)+R7)/FNH(Aa3,1.,X2)
180    Jn=R5*R8
190    Jdr=Q*Phio*(1-Re)*EXP(-Alpha*Xj)*(1.-EXP(-Alpha*W))
200    Jsc=Jp+Jn+Jdr
210    !**************************************************************
220    !
230    !         VOLTAGE GOES FROM 0 TO ITS OPEN CIRCUIT VALUE
240    !       AND WE CALCULATE THE CORRESPONDING CURRENT
250    !*****************************************************************
260          I=Jsc
270 Begin:          X1x=V+I*Rs
290                 Jrec=FNRec(Ni,W,X1x,Kb,T,Vbi,Tn,Tp)
300                 IF (Rs=0) THEN GOTO Skiper
310       I=FNN1(Rs,V,T,J0,Jsc,Jrec,Kb,Rsh)
320       GOTO End
330 Skiper:   I=Jsc-J0*(EXP(V/(Kb*T))-1)-Jrec-V/Rsh
380 End:            ! SAVE RESULTS FOR PLOTTING
390    Volts(Icount)=V*1000.      !MILLIVOLTS
400    Amps(Icount)=I*1000.       !MILLIAMPS
410    P=V*I              !POWER IN WATTS
420    IF (P>Pmax) THEN Pmax=P
430    IF (Amps(Icount)>Max) THEN Max=Amps(Icount)
440    IF (Amps(Icount)<0) THEN GOTO Stop
450    GOTO Start
460 Stop:  !GRAPH CURRENT-VOLTAGE RELATIONSHIP
470        Amps(Icount)=0
480    !****************************************************************
490    !
500    !               GRAPH OF CURRENT VOLTAGE RELATIONSHIP FOLLOWS
510    !
520    !****************************************************************
530        GCLEAR
540        CSIZE 4
550        Maxy=1.2*Max
560        Y1=DROUND(.1*Maxy,2)
570        Dely=Maxy/10
580        WINDOW -150,1000,-Y1*1.6,Maxy+.2*Y1
590        FRAME
600        DEG
610        AXES 10,(Dely),0,0,10,2,6
620    !   LABEL AXES
630    LORG 6
640    LDIR -90
650    FOR X_label=100 TO 1000 STEP 100
```

```
3660    MOVE X_label,-12*Y1/16
3670    LABEL X_label
3680    NEXT X_label
3690    LORG 8
3700    LDIR 0
3710    FOR Y_label=0 TO Maxy STEP Dely
3720    MOVE 0,Y_label
3730    LABEL DROUND(Y_label,2)
3740    NEXT Y_label
3750    LORG 5
3760    MOVE 350,-Y1*1.3
3770    LDIR 0
3780    LABEL "MILLIVOLTS"
3790    MOVE -100,Maxy/2
3800    LDIR 90
3810    LABEL "MILLIAMPS"
3820    CSIZE 4
3830    LDIR 0
3840    MOVE Volts(1),Amps(1)
3850    FOR Ij=1 TO Icount
3860    DRAW Volts(Ij),Amps(Ij)
3870    NEXT Ij
3880    CSIZE 4
3890    Xpo=300
3900    Ypo=.7
3910    LORG 5
3911    MOVE 400,.95*Maxy
3912    LABEL "CONVENTIONAL Si PHOTOCONVERTER"
3920    MOVE Xpo,(Ypo)*Maxy
3930    LABEL "Rs=";Rs
3940    MOVE Xpo,(Ypo-.04)*Maxy
3950    LABEL "T =";DROUND(T-273,4);"DEG C"
3960    MOVE Xpo,(Ypo-.08)*Maxy
3970    LABEL "Sn=";Sn;" Ln=";DROUND(Ln,5)
3980    MOVE Xpo,(Ypo-.12)*Maxy
3990    LABEL "Sp=";Sp;" Lp=";DROUND(Lp,5)
4000    MOVE Xpo,(Ypo-.16)*Maxy
4010    LABEL "Na=";Na;" Mun=";DROUND(Mun,5)
4020    MOVE Xpo,(Ypo-.2)*Maxy
4030    LABEL "Nd=";Nd;" Mup=";DROUND(Mup,5)
4040    MOVE Xpo,(Ypo-.24)*Maxy
4050    LABEL "Xj=";Xj
4060    MOVE Xpo,(Ypo-.28)*Maxy
4070    LABEL "H =";H
4080    MOVE Xpo,(Ypo-.32)*Maxy
4090    LABEL "Rsh =";Rsh
4100    MOVE Xpo,(Ypo-.36)*Maxy
4110    LABEL "Wo =";Wo
4120    MOVE Xpo,(Ypo-.4)*Maxy
4130    LABEL "Pout=";DROUND(Pmax,5)
4140    MOVE Xpo,(Ypo-.44)*Maxy
4150    LABEL "Eff= ";DROUND(100*Pmax/(Wo*1000),5)
4160    MOVE Xpo,(Ypo-.48)*Maxy
4170    LABEL "Alpha=";Alpha
4180    MOVE Xpo,(Ypo-.52)*Maxy
4190    LABEL "Lambda=";Lambda
4200    MOVE Xpo,(Ypo-.56)*Maxy
4210    LABEL "Jsc=";Jsc
4220    !*******************************************************************
4230    !
4240    !        PAUSE LOOK AT GRAPH IF YOU LIKE IT TYPE --- DUMP GRAPHICS
```

```
1250    !
1260    !******************************************************************
1270    !
1280    !          TYPE   GCLEAR     TO CLEAR THE SCREEN
1290    !
1300    !********************************************************************
1310    PAUSE
1320    GCLEAR      !CLEARS THE GRAPHICS SCREEN
1330    LORG 5
1340    CSIZE 9
1350    WINDOW 0,100,0,100
1360    MOVE 50,50
1370    LABEL "THE PROGRAM IS OVER"
1380    FOR I=1 TO 3000
1390    NEXT I
1400    GCLEAR
1410    END
1420    !*********************************************************************
1430    def FNAbsorp(Nsi,Esi(*),Asi(*),Energ)
1440    I=0
1450    IF (Energ<Esi(1)) THEN Alpha=0
1460    IF (Energ<Esi(1)) THEN Stop3
1470 St3:    I=I+1
1480    IF (I>Nsi) THEN Last3
1490    IF (Esi(I)<=Energ) AND (Esi(I+1)>=Energ) THEN Ratio3
1500    GOTO St3
1510 Last3:        Alpha=Asi(Nsi)
1520               GOTO Stop3
1530 Ratio3:  Alpha=Asi(I)+(Asi(I+1)-Asi(I))*(Energ-Esi(I))/(Esi(I+1)-Esi(I))
1540 Stop3:       !
1550    RETURN Alpha
1560    FNEND
1570    !***************************************************************
1580    def FNJ(A1,A3,A2)
1590    Y=A1*FNCosh(A2)+A3*FNSinh(A2)
1600    RETURN Y
1610    FNEND
1620    !**************************************************************
1630    def FNCosh(X)
1640    Y=(EXP(X)+EXP(-X))/2.
1650    RETURN Y
1660    FNEND
1670    !***************************************************************
1680    def FNSinh(X)
1690    Y=(EXP(X)-EXP(-X))/2.
1700    RETURN Y
1710    FNEND
1720    !***************************************************************
1730    def FNH(A,B,C)
1740    Y=A*FNSinh(C)+B*FNCosh(C)
1750    RETURN Y
1760    FNEND
1770    !****************************************************************
1780    DEF FNMun(Nd,T,A0,A1,A2,A3)
1790    Bb1=A1*T*T/(Nd^(2./3.))
1800    D=Nd*Bb1*(1.-.5*Bb1)
1810    X1=A0*(T^1.5)/D
1820    X2=A2*EXP(-A3*LOG(T))
1830    R=1./X2+1./X1
1840    RETURN 1./R
```

```
850    FNEND
860    !*********************************************************************
870    def FNMup(Na,T,B0,B1,B2,B3)
880    X1=B2*EXP(-B3*LOG(T))
890    Bb1=B1*T*T/(Na^(2./3.))
900    D=Na*Bb1*(1.-.5*Bb1)
910    X2=B0*(T^1.5)/D
920    R=1./X2+1./X1
930    RETURN 1./R
940    FNEND
950    !*********************************************************************
960    def FNRec(Ni,W,V,Kb,T,Vbi,Tn,Tp)
970    J1=(1.6E-19)*Ni*W*PI*FNSinh(V/(2*Kb*T))
980    J2=SQR(Tp*Tn)*(Vbi-V)/(Kb*T)
990    Jrec=J1/J2
000    RETURN Jrec
010    FNEND
020    DEF FNNl(Rs,V,T,Io,Isc,Irec,Kb,Rsh)    !NONLINEAR EQ SOLVER
030    Ib=Isc-Irec-V/Rsh+Io
040    Kbtg=Kb*T
050    U=.9999
060 Starter:  U1=1+Rs/Rsh
070      F=Ib*U*U1-Ib+Io*EXP((V+U*Ib*Rs)/Kbtg)
080      Fp=Ib*U1+Io*EXP((V+Ib*U*Rs)/Kbtg)*(Rs*Ib/Kbtg)
090      U1=U-F/Fp
100      Error=ABS(U1-U)
110      IF (Error<1.0E-6) THEN GOTO Ender
120      U=U1
130      GOTO Starter
140 Ender:    RETURN U1*Ib
150      FNEND
```

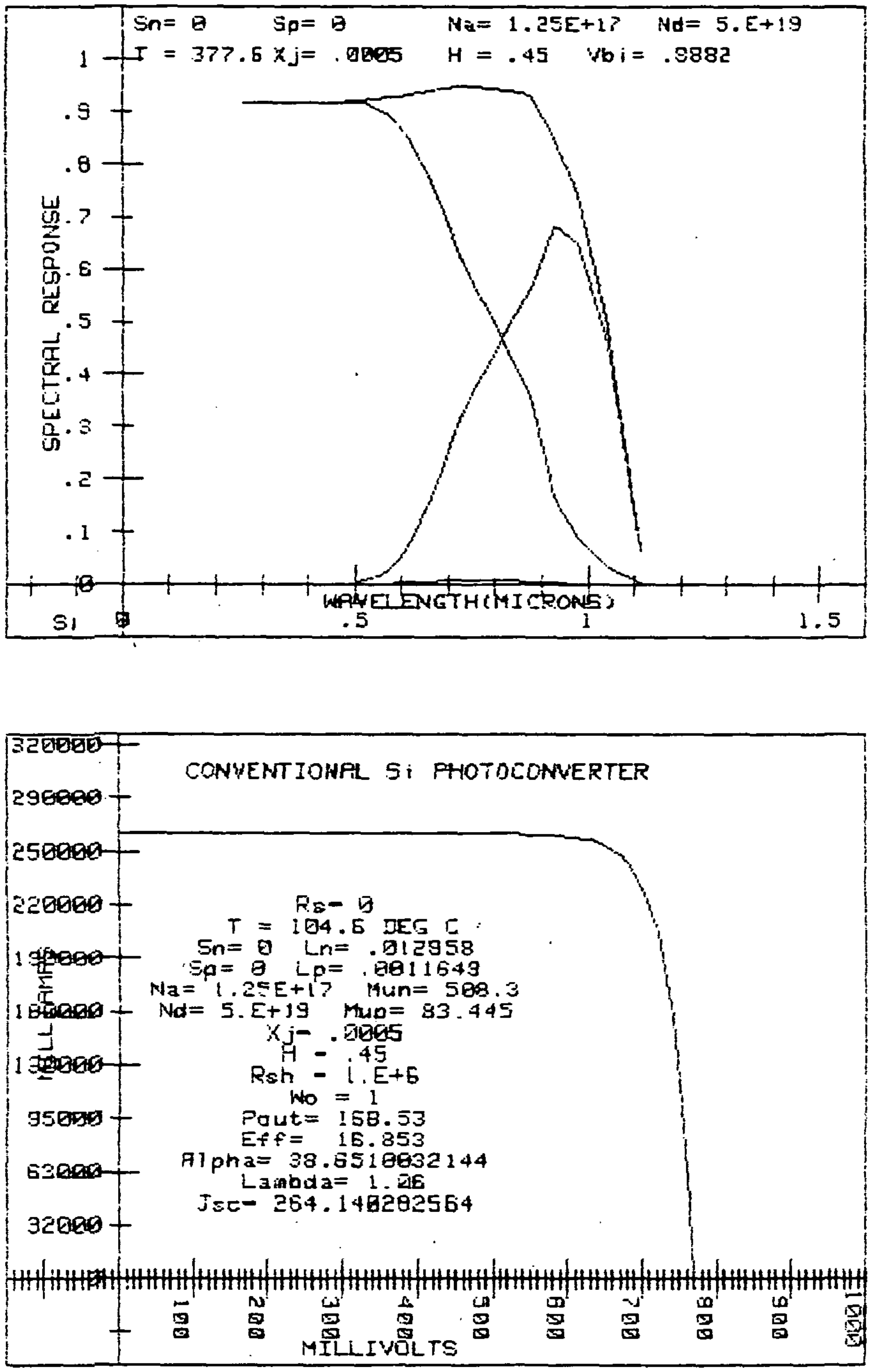


FIGURE A1. Representative output from the program "CONVEN" illustrating spectral response and current voltage relationship for conventional photoconverter.

APPENDIX B

BASIC COMPUTER PROGRAM FOR ONE-DIMENSIONAL VERTICAL JUNCTION PHOTOCONVERTER

```
10    OPTION BASE 1
20    !**************************************************************
30    !
40    !      PROGRAM VJSCP
50    !
60    !VERTICAL JUNCTION SOLAR CELL PROGRAM
70    !
80    REM   VERTICAL JUNCTION SOLAR CELL PROGRAM CONSTANT TEMPERATURE
90    !
100   !**************************************************************
110   DIM Volts(100),Amps(100),Yisc(201),Yidark(201),Yrec(201)
120   DIM Aa(100,3),Z(100),X(100),Xx(100)
130   DIM Esi(20),Asi(20)
140   !**************************************************************
150   !
160   !     Si    ENERGY(EV), ABSORPTION COEFFICIENT (CM-1) DATA
170   !
180   !**************************************************************
190   Nsi=20
200   FOR I=1 TO Nsi
210   READ Esi(I),Asi(I)
220   NEXT I
230   DATA 1.1,1,1.15,10,1.24,100,1.378,350,1.46,950,1.77,2000
240   DATA 2.067,4500,2.48,1E4,2.76,2E4,3.1,5E4,3.26,1E5
250   DATA 3.5,1E6,3.6,1.1E6,4,1.8E6,4.2,2.5E6,5,1.9E6,5.2,2E6
260   DATA 6,1.5E6,8,1.3E6,10,1.1E6
270   !**************************************************************
280   GINIT                            !INITIALIZE GRAPHICS
290   GRAPHICS ON
300   DUMP DEVICE IS 701
310   WINDOW 0,100,0,100
320   LORG 5
330   MOVE 50,50
340   LABEL "SPECTRAL RESPONSE"
350   !**************************************************************
360   !
370   !                SOLAR CELL PARAMETERS
380   !
390   !****************************************************************
400 Parameters:  !
410   Wo=1.0            !LASER POWER IN KW/CM2
420                     !TEMPERATURE CALCULATED BELOW BASED ON THIS POWER
430   Re=.05            !REFLECTION COEFFICIENT
440   Lambda=1.06         !WAVELENGTH IN MICRONS
450   Rs=0.               ! SERIES RESISTANCE IN OHMS
460   Rsh=1.0E+6          !SHUNT RESISTANCE IN OHMS
470   Sn=0.               ! SURFACE RECOMBINATION VELOCITIES CM/S
480   Sp=0.
490   Na=1.25E+17         ! DOPING DENSITIES CM-3
500   Nd=5.0E+19          !DOPING DENSITY CM-3 IN N REGION
510   B1=7.1E+15          ! CONSTANT FOR Si LIFETIMES SEE Taun AND Taup BELOW
520   Eggo=1.16           !FOR Si;USE 1.522 FOR GaAs ;USE .741 FOR Ge
530   Alphao=7.02E-4      !FOR Si;USE 5.8E-4 FOR GaAs;USE 4.56E-4 FOR Ge
540   Betao=1108.         !FOR Si;USE 300 FOR GaAs; USE 210 FOR Ge
550   ! SOLAR CELL DIMENSIONS
560   A=1.0               !CM    Y=A IS TOP, Y=0 IS BOTTOM
570   B=.002              !CM  X=0 IS LEFT, X=B IS RIGHT SIDE OF SOLAR CELL
580   Xj=.001             !CM    JUNCTION LINE AT X=Xj
590   IF (Xj>B) THEN PRINT "PLEASE MAKE JUNCTION INSIDE OF CELL-THANK YOU"
600   Kback=1.5           !WATTS/CM-DEG C   THERMAL CONDUCTIVITY FOR Si
```

```
610   Hh2=100.          !WATTS/CM2-DEG C   HEAT TRANSFER COEFFICIENT
620   Tpipe=20.         !TEMP DEG C OF HEAT PIPE
630   Absorpo=1.6955E+3  !ABSORPTION COEFFICIENT FOR Si SEE Alpha BELOW
640   Xkk=1.2E-3         !CONSTANT FOR ABSORPTION COEFFICIENT SEE Dele BELOW
650   Xkko=1.2E-3
660   Xkk1=1.4
670   Nia0=4.9E+15       !INTRINSIC CARRIER DENSITY COEFFICIENT SEE Ni BELOW
680   Nia1=1.610         !ANOTHER CONSTANT FOR Si INTRINSIC CARRIER DENSITY
690   Epso=11.6          !PERMITIVITY FOR Si    DIMENSIONLESS
700   !CONSTANTS FOR Si MOBILITY Mun
710   Ab0=65.02    ! FOR GaAs USE 5076.11   ; FOR Ge USE 458.68
720   Ab1=5.72E-9  ! FOR GaAs USE 6.03E-88  ;FOR Ge USE 7.92E-9
730   Ab2=2.49E+9  ! FOR GaAs USE 2.13E6    ; FOR Ge USE 6.08E7
740   Ab3=2.5      ! FOR GaAs USE 1.0       ; FOR Ge USE 1.66
750   !CONSTANTS FOR Si MOBILITY Mup
760   Ba0=54.46    ! FOR GaAs USE 37.33     ; FOR Ge USE 3140.27
770   Ba1=6.76E-9  ! FOR GaAs USE 8.51E-9   ; FOR Ge USE 1.79E-7
780   Ba2=2.93E+9  ! FOR GaAs USE 6.05E7    ; FOR Ge USE 1.18E9
790   Ba3=2.7      ! FOR GaAs USE 2.1       ; FOR Ge USE 2.33
800   !**************************************************************
810   !
820   !        END OF SOLAR CELL PARAMETERS
830   !
840   !****************************************************************
850   !APPROXIMATE THE TEMPERATURE
860   T=273+Tpipe+1000*(1-Re)*Wo/Hh2
870   Egt=Eggo-Alphao*T*T/(T+Betao)
880   T0=300                              !CONSTANT REFERENCE TEMPERATURE
890   Engo=1.2402/Lambda
900   IF (Engo<=1.7) THEN Xkk=(1.3*Engo-1)*1.0E-3
910   Dele=Xkk*(T-T0)
920   E=Engo+Dele
930   Alpha=FNAbso(Nsi,Esi(*),Asi(*),E)
940   Ff2=0
950   IF (Alpha*A<700) THEN Ff2=EXP(-Alpha*A)
960   T=Tpipe+Wo*((1-Re)*1000/Kback)*(Kback/Hh2-1./Alpha)*(1-Ff2)
970   IF (T<Tpipe) THEN T=Tpipe
980   T=T+273        ! THIS IS THE TEMPERATURE DEG K DUE TO POWER Wo
990   Kb=8.6172E-5                        ! BOLTZMANN'S CONSTANT EV/K
1000  Q=1.6E-19                           ! ELECTRON CHARGE  COULOMBS
1010  Tno=1.86E-4                         !LIFETIME CONSTANT
1020  Tpo=3.52E-3
1030  Taun=Tno/(1.+Na/B1)                 !CALCULATION OF LIFETIMES
1040  Taup=Tpo/(1.+Nd/B1)
1050  Ego=Eggo-(Alphao)*T0*T0/(T0+Betao)  ! 1.12 EV AT 300 DEG K
1060     Egt=Eggo-(Alphao)*T*T/(T+Betao)  !BANDGAP IN EV
1070  Phi0=Wo*Lambda*5.03306E+21          !PHOTONS/CM2-S
1080  Engo=1.2402/Lambda                  !ENERGY IN EV
1090  IF (Engo<=1.7) THEN Xkk=(1.3*Engo-1.)*1.0E-3 !SEE ABOVE FOR Xkk
1100  Dele=Xkk*(T-T0)                     ! SHIFT IN BANDGAP DUE TO TEMP
1110  E=Engo+Dele
1120  Alpha=FNAbso(Nsi,Esi(*),Asi(*),E)   !  ABSORPTION COEFFICIENT CM-1
1130  Icount=0                            !INITIALIZE COUNTER
1140  Xstep=.01                           !VOLTAGE STEP SIZE
1150  IF (A>.02) THEN Delz=A/200            !DEPTH BELOW SURFACE STEP SIZE
1160  IF (A<=.02) THEN Delz=.02/200
1170  Max=0                               ! DUMMY MAXIMUM CURRENT
1180  Delvo=.05                           !CHANGE IN VOLTAGE
1190  V=-Delvo                            !INITIALIZE VOLTAGE
1200!*******************************************************************
```

```
210!             SPECTRAL RESPONSE CURVES
220!*******************************************************************************
230 Kbtg=Kb*T                                      !BOLTZMANN'S CONSTANT*TEMP
240 Egt=Eggo-Alphao*T*T/(T+Betao)                  !BANDGAP
250 Tn=Tno/(1+Na/B1)                               !LIFETIME
260 Tp=Tpo/(1+Nd/B1)
270 Mun=FNMun(Na,T,Ab0,Ab1,Ab2,Ab3)                !MOBILITIES
280 Mup=FNMup(Nd,T,Ba0,Ba1,Ba2,Ba3)
290 Dn=Kbtg*Mun                                    !DIFFUSION COEFFICIENTS
300 Dp=Kbtg*Mup
310 Phio=Wo*Lambda*5.0330E+21                      !PHOTONS/CM2-S
320 Ni=Nia0*Nia1*(T^1.5)*EXP(-Egt/(Kbtg*2))       !INTRINSIC CARRIER DENSITY
330 Vbi=Kbtg*LOG(Na*Nd/(Ni*Ni))                    !BUILT IN VOLTAGE
340 W2=(2.*Epso*(8.85E-14)/Q)*Vbi*(1./Nd+1./Na)  !SQUARE OF DEPLETION WIDTH
350 W=SQR(W2)                                       !DEPLETION WIDTH
360 Lp=SQR(Dp*Tp)                                   !DIFFUSION LENGTH
370 Ln=SQR(Dn*Tn)
380 Xn=W*Na/(Na+Nd)                                 !DISTANCE INTO N REGION
390 Xp=W-Xn                                         !DISTANCE INTO P REGION
400 U1=(Xj-Xp)/Ln
410 U2=Dn/Ln
420 U4=Dp/Lp
430 F1=FNRatio(U1,Sn,U2)
440 U3=(B-Xj-Xn)/Lp
450 F2=FNRatio(U3,Sp,U4)
460 Pin=B*Wo*1000                          !POWER INTO CELL B by 1 CM (WATTS)
470 Imax=0
480 Kmax=60
490 FOR J=1 TO Kmax
500 X(J)=1.000+(J-1)*.03                             ! ENERGY IN EV
510 Xx(J)=1.2402/X(J)                                !WAVELENGTH IN MICRONS
520 Phio=Wo*Xx(J)*5.033E+21
530 Ener=X(J)
540 IF (Ener>1.7) THEN Xkk=Xkko
550 IF (Ener<1.7) THEN Xkk=(Xkk1*Ener-1)*1.0E-3
560 Del=Xkk*(T-T0)
570 E=Ener+Del
580 Alpha=FNAbso(Nsi,Esi(*),Asi(*),E)              !ABSORPTION COEFFICIENT
590 !PRINT "ALPHA =";Alpha
600 Zz1=Alpha*A
610 Yyy1=0
620 IF (Zz1<700) THEN Yyy1=EXP(-Zz1)          !NO NUMERICAL INTEGRATION
630 In=-Ln*F1*Q*Phio*(1-Re)*(1-Yyy1) !CURRENT FROM RIGHT SIDE AMPS
640 Ip=-Lp*F2*Q*Phio*(1-Re)*(1-Yyy1) !CURRENT FROM LEFT SIDE AMPS
650 Isr=(In+Ip)/Pin
660 IF (Isr>Imax) THEN Imax=Isr
670 !PRINT In,Ip                               !OPTIONAL PRINT STATEMENT
680 Aa(J,1)=In/Pin       !SPECTRAL RESPONSE FROM RIGHT,
690 Aa(J,2)=Ip/Pin       !LEFT
700 Aa(J,3)=Isr          !TOTAL RESPONSE
710 NEXT J
720 !**************************************************************************
730 !
740 !            PLOT SPECTRAL RESPONSE CURVES
750 !
760 !**************************************************************************
770 GCLEAR
780 WINDOW -.25,1.3,-.2,1.1
790 FRAME
800 !**************************************************************************
```

```
1810 !       DRAW AND LABEL AXES
1820 !*************************************************************************
1830 AXES .1,.1,0.,0,5,5,6
1840 CSIZE 4
1850 LORG 6
1860 FOR X_label=.5 TO 1.5 STEP .5
1870 MOVE X_label,-.0125
1880 LABEL X_label
1890 NEXT X_label
1900 LORG 8
1910 FOR Y_label=0 TO 1. STEP .1
1920 MOVE (-.005),Y_label
1930 LABEL Y_label
1940 NEXT Y_label
1950 ! *************************************************************************
1960 !   PUT LABELS ON THE AXES
1970 !**************************************************************************
1980 LORG 6
1990 DEG
2000 LDIR 0
2010 MOVE .75,-.1
2020 LABEL "WAVELENGTH(MICRONS)"
2030 LDIR 90
2040 MOVE -.19,.5
2050 LABEL "NORMALIZED SPECTRAL RESPONSE"
2060 !**************************************************************************
2070 !
2080 !           DRAW THE SPECTRAL RESPONSE CURVES
2090 !
2100 !**************************************************************************
2110 FOR I=1 TO 3
2120 FOR J=1 TO Kmax
2130 Z(J)=Aa(J,I)/Imax
2140 NEXT J
2150 MOVE Xx(1),Z(1)
2160 FOR K=1 TO Kmax
2170 DRAW Xx(K),Z(K)
2180 NEXT K
2190 NEXT I
2200 LDIR 0
2210 MOVE -.15,-.05
2220 LABEL "Si"
2230 !***************************************************************************
2240 !
2250 !              PAUSE
2260 !         TYPE      DUMP GRAPHICS        FOR HARD COPY
2270 !**************************************************************************
2280 !
2290 PAUSE
2300 !
2310 !*************************************************************************
2320 LDIR 0
2330 GCLEAR                       !PUT A LABEL ON THE SCREEN
2340 WINDOW 0,100,0,100
2350 LORG 5
2360 MOVE 50,25
2370 LABEL "CURRENT-VOLTAGE"
2380 MOVE 50,20
2390 LABEL "CURVE IS NEXT"
2400 MOVE 50,15
2410 LABEL "CALCULATIONS TAKE 5 MINUTES "
```

```
2420!*****************************************************************************
2430!
2440 PRINT " Isc                    Io                 Irec         Volts" !OPTIONAL
2450!
2460!*****************************************************************************
2470!TEMPERATURE DISTRIBUTION FROM TOP TO BOTTOM AS FUNCTION OF Z IS CONSTANT
2480        Mun=FNMun(Na,T,Ab0.Ab1,Ab2,Ab3) !MOBILITIES AS FUNCTION OF T
2490        Mup=FNMup(Nd,T,Ba0,Ba1,Ba2,Ba3)
2500        Kbtg=Kb*T      !BOLTZMANN'S CONSTANT TIMES TEMPERATURE
2510        Egt=Eggo-(Alphao)*T*T/(T+Betao)  !BANDGAP IN EV
2520        Dn=Kbtg*Mun    !DIFFUSION COEFFICIENT (CM**2)/S
2530        Dp=Kbtg*Mup
2540  Ni=(Nia0)*(Nia1)*(T^1.5)*EXP(-Egt/(Kbtg*2))     !INTRINSIC DENSITY
2550  Vbi=Kb*T*LOG(Na*Nd/(Ni*Ni))    !BUILT IN VOLTAGE (VOLTS)
2560  Lp=SQR(Dp*Taup)   !DIFFUSION LENGTHS  (CM)
2570  Ln=SQR(Dn*Taun)
2580  U2=Dn/Ln              !CM/S
2590  U4=Dp/Lp              !CM/S
2600  Ppo=Na      ! DOPING DENSITY   CM-3
2610  Nno=Nd        !                CM-3
2620  Npo=Ni*Ni/Ppo      !           CM-3
2630  Pno=Ni*Ni/Nno      !           CM-3
2640 U7=Sp/U4            !      NO DIMENSIONS
2650 U9=Sn/U2            !      NO DIMENSIONS
2660 !****************************************************************************
2670 !
2680 !       CALCULATE CURRENT VOLTAGE RELATIONSHIP
2690 !
2700 !****************************************************************************
2710 Pmax=0
2720 Maxy=0
2730  Phi0=Wo*Lambda*5.03306E+21    !PHOTONS/CM2-S
2740  Engo=1.2402/Lambda     !ENERGY IN EV
2750  IF (Engo<=1.7) THEN Xkk=(1.3*Engo-1.)*1.0E-3 !SEE ABOVE FOR Xkk
2760  Dele=Xkk*(T-T0)       ! SHIFT IN BANDGAP DUE TO TEMP
2770  E=Engo+Dele           ! EV
2780  Alpha=FNAbso(Nsi,Esi(*),Asi(*),E) !  ABSORPTION COEFFICIENT CM-1
2790 Start:  V=V+Delvo    !(VOLTS)
2800        Icount=Icount+1
2810        Volts(Icount)=V*1.0E+3                          ! MILLIVOLTS
2820        IF (Volts(Icount)>Max) THEN Max=Volts(Icount)
2830        Ii=0
2840 Again: Ii=Ii+1
2850        Z2=(Ii-1)*Delz            ! CM
2860        Z1=Z2+Delz/2              ! CM
2870  IF (Z1>A) THEN GOTO Over
2880 W2=(2*Epso*(8.85E-14)/Q)*(Vbi-V)*(1./Nd+1./Na)             ! CM**2
2890 W=SQR(W2)                                                  ! CM
2900 Xn=W*Na/(Na+Nd)                  ! CM
2910 Xp=W-Xn                          ! CM
2920 U1=(Xj-Xp)/Ln                   !NO DIMENSIONS
2930 F1=FNRatio(U1,Sn,U2)            !NO DIMENSIONS
2940 U3=(B-Xj-Xn)/Lp                 !NO DIMENSIONS
2950  F2=FNRatio(U3.Sp,U4)           !NO DIMENSIONS
2960  In=-Ln*F1                       !CM
2970  Ip=-Lp*F2                       !CM
2980  !SHORT CIRCUIT CURRENT
2990  Yy1=Alpha*Z1                   !NO DIMENSIONS
3000  Yy2=0
3010  IF (Yy1<700) THEN Yy2=EXP(-Yy1)
```

```
3020  Isc=(In+Ip)*Phi0*(1-Re)*Alpha*Yy2*Q                    !AMPS/CM2
3030  Y8=FNA(V,Ni,W,Kb,T,Vbi,Taun,Taup)
3040  Irec=Y8    ! RECOMBINATION CURRENT     AMPS/CM2
3050  !*********************************************************************
3060  !
3070 !PRINT Y8;V;Ni;W;Kb;T;Vbi;Taun;Taup    ! OPTIONAL PRINT STATEMENT
3080 !
3090 !**********************************************************************
3110  R32=FNCur(U3,U7)            ! NO DIMENSIONS
3120  Ipd=R32*Pno*Q*U4            !  AMPS/CM**2
3129  U8=(Xj-Xp)/Ln               ! NO DIMENSIONS
3130  R33=FNCur(U8,U9)            ! NO DIMENSIONS
3140  Ind=R33*Npo*Q*U2            !  AMPS/CM**2
3150  Io=(Ipd+Ind)           !     AMPS/CM2
3160  Yisc(Ii)=Isc           !AMPS/CM2
3170  Yidark(Ii)=Io          !AMPS/CM2
3180  Yrec(Ii)=Irec          !AMPS/CM2
3190  GOTO Again
3200  !******************************************************************
3210  !
3220  !      NUMERICAL INTEGRATION OF PREVIOUS RESULTS
3230  !
3240  !*******************************************************************
3250 Over: Irec=0                        !AMPS/CM2
3260  Isc=0                         !AMPS/CM2
3270  Io=0                          !AMPS/CM2
3280  Jki=Ii-2
3290  FOR Ii=1 TO Jki STEP 2
3300  Isc=Isc+(Delz/3.)*(Yisc(Ii)+4*Yisc(Ii+1)+Yisc(Ii+2))
3310  Io=Io+(Delz/3.)*(Yidark(Ii)+4*Yidark(Ii+1)+Yidark(Ii+2))
3320  Irec=Irec+(Delz/3.)*(Yrec(Ii)+4*Yrec(Ii+1)+Yrec(Ii+2))
3330  NEXT Ii
3340  !WE INTEGRATE OVER THE HEIGHT OF CELL--UNITS ARE NOW AMPS FOR ALL I'S
3350  !**********************************************************************
3360  U6=V/(Kb*T)                      ! NO DIMENSIONS
3370 !**********************************************************************
3380 !
3390  PRINT Isc;Io;Irec;V                     !OPTIONAL PRINT STATEMENT
3400 !
3410 !***********************************************************************
3420 IF (Rs=0) THEN GOTO Skip  !TEST TO SEE IF SERIES RESISTANCE IS ZERO
3430 I=FNNl(Rs,V,T,Io,Isc,Irec,Kb,Rsh)    !NONLINEAR CALCULATION OF CURRENT
3440 GOTO Ready
3450 Skip: I=Isc-Io*(EXP(U6)-1)-Irec-V/(Rsh)         ! TOTAL CURRENT  AMPS
3460 Ready: !
3470 Amps(Icount)=I*1000 !SAVE FOR PLOTTING  CONVERT TO MILLIAMPS
3480 P=I*V          !POWER (WATTS)
3490 !*********************************************************************
3500 !                FIND MAXIMUM POWER IN WATTS
3510 IF (P>Pmax) THEN Pmax=P
3520 IF (Amps(Icount)>Maxy) THEN Maxy=Amps(Icount)
3530 IF (I<0) OR (Vbi<V+Delvo) THEN GOTO Finish
3540 IF (V>=.45) THEN Delvo=Xstep
3550 GOTO Start
3560 Finish: Amps(Icount)=0
3570  !*********************************************************************
3580  !
3590  !NOW DO SOME GRAPHICS
3600  !
3610  !*********************************************************************
```

```
3620 GCLEAR
3630 DUMP DEVICE IS 701   ! BE SURE TO TURN THE PRINTING DEVICE ON
3640 Y1=.2*Maxy
3650 Ddy=Maxy/10
3660 WINDOW -(150),(1200),-(Y1),Maxy+Y1
3670 FRAME
3680 DEG
3690 AXES 10,(Ddy),0,0,10,2,6
3700 !**********************************************************************
3710 !LABEL AXES   X-AXIS FIRST
3720 !******************************************
3730 LORG 6
3740 LDIR -90
3750 FOR X_label=0 TO 1200 STEP 100
3760 MOVE X_label,-7*Y1/16
3770 LABEL X_label
3780 NEXT X_label
3790 !******************************************************************
3800 !NOW LABEL Y-AXIS
3810 !******************************************************************
3820 LORG 8
3830 LDIR 0
3840 FOR Y_label=0 TO Maxy STEP Ddy
3850 MOVE 0,Y_label
3860 LABEL DROUND(Y_label,2)
3870 NEXT Y_label
3880 LORG 5
3890 !*******************************************************************
3900 !
3910 !LABEL GRAPH
3920 !
3930 !******************************************************************
3940 MOVE (350),-(Y1*13/16)
3950 LDIR 0
3960 LABEL "MILLIVOLTS"
3970 MOVE -(130),(Maxy/2)
3980 LDIR 90
3990 LABEL "MILLIAMPS"
4000 CSIZE 4
4010 LDIR 0
4020 MOVE (-75),-(13*Y1/16)
4030 LABEL "Wo=";Wo
4040 !*************************************************************
4050 !
4060 !     DRAW THE CURVE
4070 !
4080 !****************************************************************
4090 MOVE Volts(1),Amps(1)
4100 FOR Ij=1 TO Icount
4110 DRAW Volts(Ij),Amps(Ij)
4120 NEXT Ij
4130 MOVE 600,1.05*Maxy
4140 LABEL "SILICON VERTICAL JUNCTION CELL"
4150 MOVE 600,.9*Maxy
4160 LABEL "Rs=";Rs
4170 MOVE 600,.85*Maxy
4180 LABEL "T =";DROUND(T,4)
4190 MOVE 600,.8*Maxy
4200 LABEL "Sn=";Sn
4210 MOVE 600,.75*Maxy
```

```
4220  LABEL "Sp=";Sp
4230  MOVE 500,.7*Maxy
4240  LABEL "Pout=";Pmax
4250  MOVE 500,.65*Maxy
4260  LABEL "Eff=";DROUND(Pmax*100/Pin,4)
4270  MOVE 500,.6*Maxy
4280  LABEL "Lambda=";Lambda
4290  MOVE 500,.55*Maxy
4300  LABEL "Jsc=";DROUND(Isc/B,2);"  AMP/CM2"
4310  MOVE 500,.5*Maxy
4320  LABEL "Isc=";Isc
4330  MOVE 400,.45*Maxy
4340  LABEL "WIDTH=";B;" THICKNESS=";A
4350  MOVE 500,.4*Maxy
4360  LABEL "Xj=";Xj;" Voc=";Volts(Icount)
4370  MOVE 500,.35*Maxy
4380  LABEL "Ln=";DROUND(Ln,5);" Lp=";DROUND(Lp,5)
4390  MOVE 500,.3*Maxy
4400  LABEL "Mun=";DROUND(Mun,5);" Mup=";DROUND(Mup,5)
4410  MOVE 500,.25*Maxy
4420  LABEL "Na=";Na;" Nd=";Nd
4430  !***************************************************************
4440  !
4450  PAUSE       !TYPE 'DUMP GRAPHICS' IF YOU LIKE WHAT YOU SEE
4460  !
4470  !*******************************************************************
4480  GCLEAR
4490  WINDOW 0,100,0,100
4500  LORG 5
4510  MOVE 50,50
4520  LABEL "FINISHED WITH PROGRAM"
4530  FOR K=1 TO 5000       ! PAUSE AND THEN CLEAR THE SCREEN
4540  NEXT K
4550  GCLEAR
4560  end
4570  !*******************************************************************
4580  !
4590  !                  FUNCTIONS USED IN THE PROGRAM
4600  !
4610  !*******************************************************************
4620  def FNMun(N3,T,Ab0,Ab1,Ab2,Ab3)    ! MOBILITY FUNCTION
4630  B1=Ab1*T*T/(N3^.66667)
4640  D=N3*B1*(1.-.5*B1)
4650  X1=Ab0*(T^1.5)/D
4660  X2=Ab2*EXP(-Ab3*LOG(T))
4670  R=1./X2+1./X1
4680  RETURN 1./R
4690  FNEND
4700  !********************************************************************
4710  def FNMup(N4,T,Ba0,Ba1,Ba2,Ba3) ! MOBILITY FUNCTION
4720  X1=Ba2*EXP(-Ba3*LOG(T))
4730  B1=Ba1*T*T/(N4^.66667)
4740  D=N4*B1*(1.-.5*B1)
4750  X2=Ba0*(T^1.5)/D
4760  R=1./X2+1./X1
4770  RETURN 1./R
4780  FNEND
4790  !*********************************************************************
4800  def FNSinh(X)                        !HYPERBOLIC SINE
4810  RETURN (EXP(X)-EXP(-X))/2
4820  FNEND
```

```
4830  !***********************************************************************
4840  def FNCosh(X)                          !HYPERBOLOIC COSINE
4850  RETURN (EXP(X)+EXP(-X))/2
4860  FNEND
4870  !**********************************************************************
4880  def FNRatio(X1,S,X2)                   !SPECIAL FUNCTION
4890  IF (X1>230) THEN GOTO Alternative
4900  F1n=(S/FNCosh(X1))-X2*FNTanh(X1)-S
4910  F1d=X2+S*FNTanh(X1)
4920  F1=F1n/F1d
4930  GOTO Next
4940 Alternative:  F1=-1
4950 Next:   !
4960  RETURN F1
4970  FNEND
4980  !*******************************************************************
4990  def FNTanh(X)                         !HYPERBOLIC TANGENT
5000  IF (X1>230) THEN GOTO Next
5010  F1=(1.-EXP(-2.*X))/(1.+EXP(-2.*X))
5020  GOTO Ret
5030 Next:     F1=1
5040 Ret:           RETURN F1
5050 FNEND
5060 !*********************************************************************
5070 def FNCur(A,B)                  ! ANOTHER RATIO  TYPE FUNCTION
5080 F1=(B+FNTanh(A))/(B*FNTanh(A)+1.)
5090  RETURN F1
5100 FNEND
5110 !*********************************************************************
5120 def FNNl(Rs,V,T,Io,Isc,Irec,Kb,Rsh)   ! NONLINEAR EQUATION SOLVER
5130  Ib=Isc-Irec-V/Rsh+Io                 !INITIAL GUESS AT CURRENT
5140  Kbtg=Kb*T
5150  U=.9999
5160 Start1:   U1=1+Rs/Rsh
5170  F=Ib*U*U1-Ib+Io*EXP((V+U*Ib*Rs)/Kbtg)
5180       Fp=+Ib*U1+Io*EXP((V+Ib*U*Rs)/Kbtg)*(Rs*Ib/Kbtg)
5190       U1=U-F/Fp                       !IMPROVED GUESS BY NEWTONS METHOD
5200       Error=ABS(U1-U)                 !ITERATE UNTIL ERROR IS LESS THAN E-6
5210       IF (Error<1.0E-6) THEN GOTO End
5220       U=U1                  !UPDATE OLD GUESS
5230       GOTO Start1                     !DO EVERYTHING AGAIN
5240 End:           RETURN U1*Ib
5250           FNEND
5260 !******************************************************************
5270  def FNA(X,Ni,W,Kb,T,Vbi,Taun,Taup)        !RECOMBINATION CURRENT
5280  Y1=(1.6E-19)*PI*Ni*W*FNSinh(X/(2*Kb*T))
5290  Y2=SQR(Taup*Taun)*(Vbi-X)/(Kb*T)
5300  Y=Y1/Y2
5310  RETURN Y
5320  FNEND
5330  !******************************************************************
5340  def FNB(X,Ni,W,Kb,T,Vbi,Taun,Taup)   !DERIVATIVE OF ABOVE FUNCTION
5350  Y1=(1.6E-19)*PI*Ni*W*SQR(Taup*Taun)/(Kb*T)
5360  Y2=((Vbi-X)/(Kb*T))*FNCosh(X/(Kb*T))
5370  Y3=FNSinh(X/(Kb*T))
5380  Y4=Taup*Taun*((Vbi-X)/(Kb*T))^2
5390  Y=Y1*(Y2+Y3)/Y4
5400  RETURN Y*1000
5410  FNEND
5420  def FNAbso(Nsi,Esi(*),Asi(*),Energ)
```

```
5430  I=0
5440  IF (Energ<Esi(1)) THEN Alpha=0
5450  IF (Energ<Esi(1)) THEN Stop3
5460 St3:  I=I+1
5470            IF (I>Nsi) THEN Last3
5480            IF (Esi(I)<=Energ) AND (Esi(I+1)>=Energ) THEN Ratio3
5490            GOTO St3
5500 Last3:             Alpha=Asi(Nsi)
5510                    GOTO Stop3
5520 Ratio3: Alpha=Asi(I)+(Asi(I+1)-Asi(I))*(Energ-Esi(I))/(Esi(I+1)-Esi(I))
5530 Stop3:    !
5540 RETURN Alpha
5550 FNEND
```

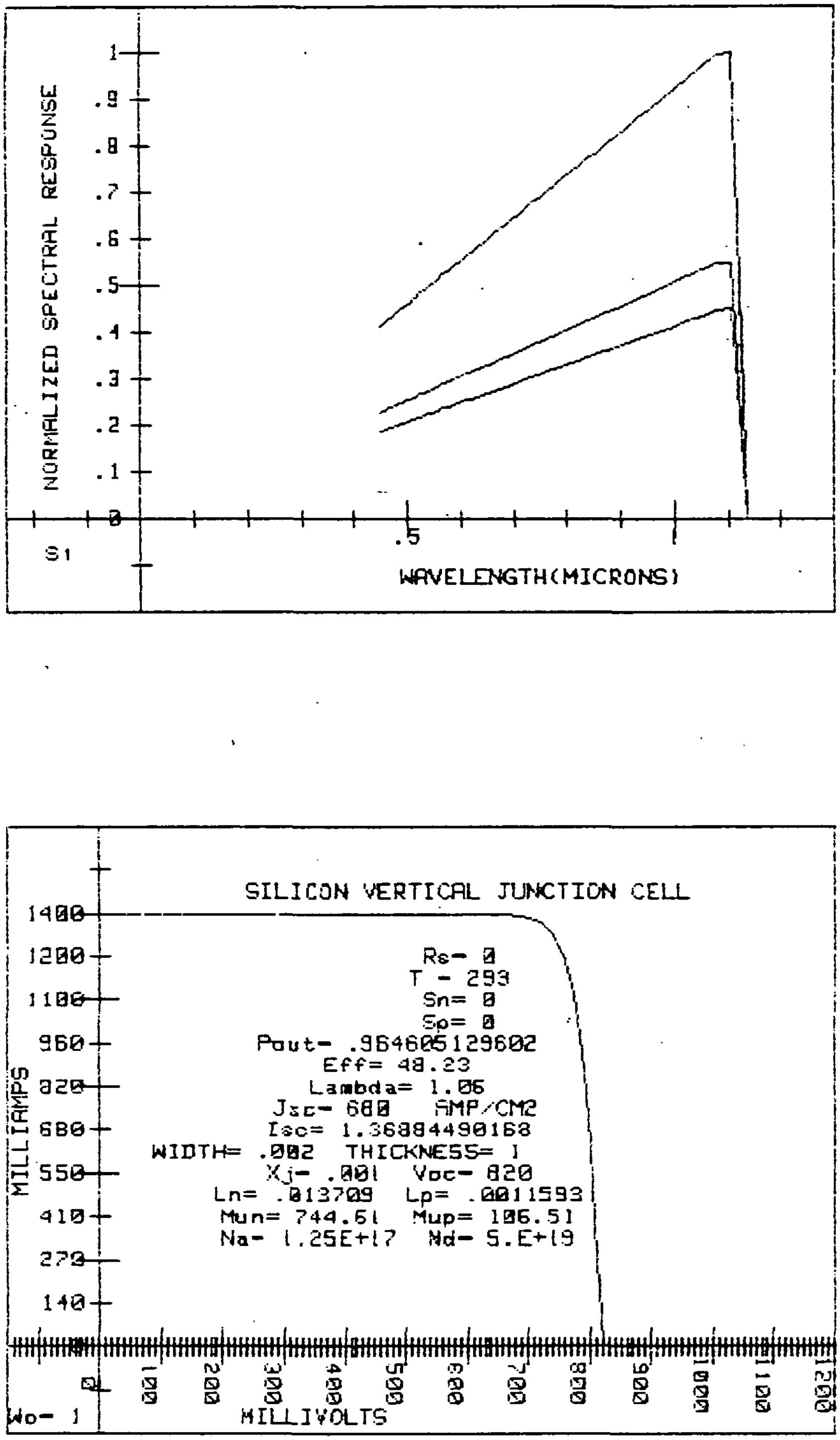


FIGURE B1. Representative output from the program "VJSCP" illustrating spectral response and current-voltage relationship for vertical junction photoconverter.

APPENDIX C

PROGRAM "SC3D" FOR SOLAR CELL
3-DIMENSIONAL

```
      PROGRAM SC3D(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE8)
C
C SC3D=SOLAR CELL 3 DIMENSIONAL (ILLUMINATED FROM TOP Z=0)
C
C GREEN'S FUNCTION SOLUTION - SYMMETRIC IN X AND Y
C
      COMMON/BLK1/NDATA,ENERG(25),ALP(25)
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,S0,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPS0,A0,A1,A2,A3,B0,B1,B2,B3,EGG0,ALPHA0,BETA0
      COMMON/BLK4/XKK0,MUN,MUP,TAUN,TAUP,DN,DP,PHI0,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,T0,NIA1,NIA2,TN0,TP0,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      COMMON/BLK8/VOC,PMAX,EFF,ISC
      DIMENSION  ENERGS(25),ENERGGA(25),ENERGGE(25)
      DIMENSION  ALPS(25),ALPGA(25),ALPGE(25)
C
C
C
      REAL  LAMBDA,NA,ND,NIA1,NIA2,MUN,MUP,KB,KBTG,LN,LP,NI,ISC
      REAL  NIAGE1,NIAGE2,NIAS1,NIAS2,NIAGA1,NIAGA2
C
      CALL PSEUDO
C
C  NAMELIST  VARIABLES
C
      NAMELIST/PARAM/POW,NA,ND,LAMBDA,A,B,H,ZJ,T,RS,RSH,SN,SP,
     1 S0,S1,NEIGV,ITYPE ,ISWITCH
C
C POW = LASER POWER (KW/CM2)
C  NA=DOPING DENSITY (CM-3)
C  ND=DOPING DENSITY (CM-3)
C LAMBDA=WAVELENGTH (MICRONS)
C A=HALF WIDTH OF X-DIRECTION ( -A .LE. X .LE. A)
C B=HALF WIDTH OF Y-DIRECTION ( -B .LE. Y .LE. B)
C H=DEPTH OF CELL IN Z-DIRECTION ( 0 .LE. Z .LE. H)
C ZJ=JUNCTION DEPTH FROM Z=0 (CM)
C T= TEMPERATURE (DEG K)
C RS=SERIES RESISTANCE OHMS
C RSH=SHUNT RESISTANCE OHMS
C SN=SURFACE RECOMBINATION VELOCITY TOP (CM/S)
C SP=SURFACE RECOMBINATION VELOCITY BOTTOM (CM/S)
C S0=SURFACE RECOMBINATION VELOCITY TOP SIDES
C S1=SURFACE RECOMBINATION VELOCITY BOTTOM SIDES
C NEIGV=NUMBER OF EIGENVALUES
C ITYPE = TYPE OF MATERIAL
C             ITYPE = 1 FOR SILICON (SI)
C             ITYPE = 2 FOR GALLIUM ARSENIDE (GAAS)
C             ITYPE = 3 FOR GERMANIUM (GE)
C ISWITCH TURNS CONTOUR PLOT ON AND OFF
C  ISWITCH=0 CONTOUR PLOT IS OFF
C  ISWITCH=1 CONTOUR PLOT IS ON
C
C
```

```
C
C       NOMINAL VALUES FOR NAMELIST VARIABLES
C
      POW=.001          $  RE=.05
      LAMBDA=1.06         $ ITYPE = 1
      TO=300.           $  T=300.
      RS=0.0           $  RSH=1.0E6
      SN=1.0          $  SP=1.0
      SO=1.0          $  S1=1.0
      NA=1.25E17   $   ND=5.0E19
      A=.5              $   B=.5
      H=5.00E-4         $  ZJ=2.5E-4
      NEIGV=10
      ISWITCH=0
C
C
C       SILICON PARAMETERS
      NDATAS=20
      DATA  (ENERGS(K),K=1,8)/1.1,1.15,1.24,1.378,1.46,1.77,2.067,2.48/
      DATA  (ENERGS(K),K=9,15)/2.76,3.1,3.26,3.5,3.6,4.0,4.2/
      DATA (ENERGS(K),K=16,20)/5.0,5.2,6.0,8.0,10.0/
      DATA (ALPS(K),K=1,7)/1.0,10.0,100.0,350.0,950.0,2.E3,4.5E3/
      DATA (ALPS(K),K=8,14)/1.0E4,2.0E4,5.0E4,1.0E5,1.0E6,1.1E6,1.8E6/
      DATA (ALPS(K),K=15,20)/2.5E6,1.9E6,2.0E6,1.5E6,1.3E6,1.1E6/
C CONSTANTS FOR MOBILITIES
        DATA ASO,AS1,AS2,AS3/65.02,5.72E-9,2.49E9,2.5/
        DATA BSO,BS1,BS2,BS3/54.46,6.76E-9,2.93E9,2.7/
C CONSTANTS FOR BANDGAP AS FUNCTION OF TEMPERATURE
       DATA EGGOS,ALPHAOS,BETAOS/1.16,7.02E-4,1108.0/
C CONSTANTS FOR INTRINSIC CARRIER DENSITY
       DATA NIAS1,NIAS2/4.9E15,1.61/
C CONSTANTS FOR LIFETIMES
       DATA TNOS,TPOS,B4/2.79E-4,3.52E-3,7.1E15/
      EPSOS=11.6
C       GALLIUM ARSENIDE PARAMETERS
C ABSORPTION COEFFICIENT CURVE FOR GAAS
      NDATAGA=16
      DATA  (ENERGGA(K),K=1,8)/1.37,1.38,1.4,1.41,1.42,1.43,1.44,1.5/
      DATA  (ENERGGA(K),K=9,16)/1.6,1.8,2.0,2.4,3.0,3.5,4.0,4.5/
      DATA  (ALPGA(K),K=1,8)/18.,32.,119.,175.,2.5E3,4.5E3,6.E3,1.4E4/
      DATA  (ALPGA(K),K=9,16)/1.8E4,3.E4,4.E4,1.E5,2.E5,3.E5,4.E5,5.E5/
C
C CONSTANTS FOR MOBILITIES
      DATA AGAO,AGA1,AGA2,AGA3/5076.11,5.24E-9,6.43E5,1.0/
      DATA BGAO,BGA1,BGA2,BGA3/1477.3,8.59E-8,6.05E7,2.1/
C CONSTANTS FOR BANDGAP
      DATA EGGOGA,ALPHGA,BETGA/1.519,5.4E-4,204./
C CONSTANTS FOR INTRINSIC CARRIER DENSITY
      DATA NIAGA1,NIAGA2/4.9E15,.0488844/
C CONSTANTS FOR LIFETIMES
      DATA TNOGA,TPOGA,B4/8.8179E-7,1.404E-7,7.1E15/
      EPSOGA=13.1
C       GERMANIUM PARAMETERS
C GERMANIUM SOLAR CELL PARAMETERS
      NDATAGE=22
```

```
      DATA   (ENERGGE(K),K=1,8)/.66,.68,.7,.73,.76,.79,.8,.81/
      DATA   (ENERGGE(K),K=9,16)/.83,.85,.875,.9,.97,1.7,2.6,3./
      DATA  (ENERGGE(K),K=17,22)/3.6,4.,4.4,5.0,6.0,8./
      DATA   (ALPGE(K),K=1,8)/1.,10.,20.,60.,100.,600.,1.E3,4.E3/
      DATA   (ALPGE(K),K=9,16)/5.E3,8.E3,8.5E3,9.E3,1.E4,1.E5,7.E5,8.E5/
      DATA  (ALPGE(K),K=17,22)/1.E6,1.4E6,2.0E6,1.3E6,1.2E6,1.0E6/
C
      DATA  AGE0,AGE1,AGE2,AGE3/458.68,7.92E-9,6.08E7,1.66/
      DATA  BGE0,BGE1,BGE2,BGE3/3140.27,1.79E-7,1.18E9,2.33/
      DATA  EGGOGE,ALPHGE,BETGE/.741,4.77E-4,235./
      DATA  NIAGE1,NIAGE2/4.9E15,.33313/
      DATA  TNOGE,TPOGE,B4/2.1022E-5,2.1007E-5,7.1E15/
      EPSOGE=16.
C
C READ IN ANY CHANGES TO THE ABOVE PARAMETERS
C       USE NAMELIST VARIABLES
C
C       LABEL GRAPHICS OUTPUT AND PRINTED OUTPUT
      XGRAPH=0.
100  CONTINUE
      READ(5,PARAM)
      IF(EOF(5))600,601
600  WRITE(6,603)
603 FORMAT(1X,28HEND OF FILE ENCOUNTERED-STOP )
      STOP 1313
601  CONTINUE
C
      WRITE(6,110)
110  FORMAT(//)
      Q=1.6E-19
       XKKO=1.2E-3
       PI=3.1415926536
       PI2=PI*.5
       KB=8.6172E-5
       KBTG=KB*T
C       EPSO IS THE PERMITIVITY
      XGRAPH=XGRAPH+1
C
C       SETUP PARAMETERS FOR CORRECT TYPE OF PHOTOCONVERTER MATERIALS
C       ITYPE  = 1 (SI)
C       ITYPE  = 2 (GAAS)
C       ITYPE  = 3 (GE)
       IF(ITYPE .EQ. 1) WRITE(6,111)
       IF(ITYPE .EQ. 2) WRITE(6,112)
       IF(ITYPE .EQ. 3) WRITE(6,113)
111 FORMAT(1X,25HSILICON PHOTOCONVERTER          ,/)
112  FORMAT(1X,35HGALLIUM ARSENIDE PHOTOCONERTER ,/)
113 FORMAT(1X,25HGERMANIUM PHOTOCONVERTER        ,/)
       IF(ITYPE .EQ. 1) GO TO 10
       IF(ITYPE .EQ. 2) GO TO 20
C       GERMANIUM DATA GOES HERE
       NDATA=NDATAGE
       DO 40 I=1,NDATA
       ENERG(I)=ENERGGE(I)
40   ALP(I)=ALPGE(I)
```

```
      AO=AGEO  $  CzAGE1  $  A2=AGE2  $  A3=AGE3
      BO=BGEO  $  B1=BGE1  $  B2=BGE2  $  B3=BGE3
      EGGO=EGGOGE  $  ALPHAO=ALPHGE  $  BETAO=BETGE
      NIA1=NIAGE1  $  NIA2=NIAGE2
      TNO=TNOGE  $  TPO=TPOGE
      EPSO=EPSOGE
      GO TO 30
10    CONTINUE
C     SILICON PARAMETERS
      NDATA=NDATAS
      DO 41 I=1,NDATA
      ENERG(I)=ENERGS(I)
41    ALP(I)=ALPS(I)
      AO=ASO  $  A1=AS1  $  A2=AS2  $  A3=AS3
      BO=BSO  $  B1=BS1  $  B2=BS2  $  B3=BS3
      EGGO=EGGOS  $  ALPHAO=ALPHAOS  $  BETAO=BETAOS
      NIA1=NIAS1  $  NIA2=NIAS2
      TNO=TNOS  $  TPO=TPOS
      EPSO=EPSOS
      GO TO 30
20    CONTINUE
C     GALLIUM ARSENIDE PARAMETERS
      NDATA=NDATAGA
      DO 42 I=1,NDATA
      ENERG(I)=ENERGGA(I)
42    ALP(I)=ALPGA(I)
      AO=AGAO  $  A1=AGA1  $  A2=AGA2  $  A3=AGA3
      BO=BGAO  $  B1=BGA1  $  B2=BGA2  $  B3=BGA3
      EGGO=EGGOGA  $  ALPHAO=ALPHGA  $  BETAO=BETGA
      NIA1=NIAGA1  $  NIA2=NIAGA2
      TNO=TNOGA  $  TPO=TPOGA
      EPSO=EPSOGA
30    CONTINUE
C     CALCULATE CONSTANTS
      CALL CONST
C     CALCULATE SPECTRAL RESPONSE
      CALL SPEC
C     CALCULATE I-V CURVE
      CALL IV(LAMBDA)
      WRITE(6,199)XGRAPH
199   FORMAT(T20,6HGRAPH  ,F3.0  )
      WRITE(6,200)ISC,VOC,EFF,RSH,DN,NEIGV
200   FORMAT(/,T2,4HISC=,E12.5,T20,4HVOC=,E12.5,T40,4HEFF=,
     1 E12.5,T60,4HRSH=,E12.5,T80,3HDN=,E12.5,T99,8HNEIGV  =  ,I5)
      WRITE(6,201)NA,ND,ZJ,S1,DP,NIA1
201   FORMAT(T2,3HNA=,E12.5,T20,3HND=,E12.5,T40,3HZJ=,E12.5,
     1T60,3HS1=,E12.5,T80,3HDP=,E12.5,T99,7HNIA1  =  ,E12.5)
      WRITE(6,202)TAUN,TAUP,LN,LP,TNO,NIA2
202   FORMAT(T2,5HTAUN=,E12.5,T20,5HTAUP=,E12.5,T40,3HLN=,E12.5,
     1 T60,3HLP=,E12.5,T80,6HTNO  =  ,E12.5,T99,7HNIA2  =  ,E12.5)
      WRITE(6,203)A,B,H,SO,TPO
203   FORMAT(T2,2HA=,E12.5,T20,2HB=,E12.5,T40,2HH=,E12.5,T60,3HSO=,
     1 E12.5,T80,6HTPO  =  ,E12.5)
      WRITE(6,204)MUN,MUP,LAMBDA,POW
204   FORMAT(T2,4HMUN=,E12.5,T20,4HMUP=,E12.5,T40,7HLAMBDA=,F10.4,
```

```
     1T60,4HPOW=,E12.5  )
      WRITE(6,205)T,RS,SN,SP
205  FORMAT(T2,2HT=,E12.5,T20,3HRS=,E12.5,T40,3HSN=,E12.5,
     1  T60,3HSP=,E12.5)
      WRITE(6,206)W,PMAX,NI,VBI,ALPHA
206  FORMAT(T2,2HW=,E12.5,T20,5HPMAX=,E12.5,T40,3HNI=,E12.5,
     1  T60,4HVBI=,E12.5,T80,6HALPHA=,E12.5,///)
C      TEST TO SEE IF CONTOUR PLOT IS WANTED
      IF(ISWITCH.EQ.1) CALL  CONTOUR
      GO TO 100
      END
      SUBROUTINE CONTOUR
C      CONTOUR PLOTS OF CURRENT DENSITY
C      VALUES STORED IN AAA AND BBB ARRAYS
      DIMENSION  AAA(20,20),BBB(20,20)
C AAA IS 20X20 ARRAY OF CURRENT DENSITY VALUES AT X,Y AND Z=ZJ
C BBB IS 20X20 ARRAY OF CURRENT DENSITY VALUES AT X,Y AND Z=ZJ+W
C
      N=20
C CALCULATE JP AND STORE IN AAA.  FIND AMAX AND AMIN VALUES FOR ARRAY
C
      CALL  CDENAB(AAA,BBB,AMAX,AMIN,BMAX,BMIN,N)
C
      FINC=0 $ NSET=0 $ NHI=-1 $ NDOT=0
C CALCULATE JN AND STORE IN BBB.  FIND BMAX AND BMIN VALURS FOR ARRAY
C
C
C       PLOT CONTOUR GRAPH OF AAA
       CALL  CONREC(AAA,N,N,N,AMIN,AMAX,FINC,NSET,NHI,NDOT)
       CALL EZTRN
       CALL NFRAME
C       PLOT CONTOUR GRAPH OF BBB
       CALL  CONREC(BBB,N,N,N,BMIN,BMAX,FINC,NSET,NHI,NDOT)
       CALL EZTRN
       CALL NFRAME
       RETURN
       END
       SUBROUTINE  CDENAB(AAA,BBB,AMAX,AMIN,BMAX,BMIN,N)
C        CALCULATE CURRENT DENSITY AT X,Y COORDINATES SPECIFIED
C        PUT RESULTS IN AAA AND BBB ARRAYS
C        ALSO FIND MAX AND MIN VALUES OF ARRAY ELEMENTS
       DIMENSION  AAA(20,20),BBB(20,20)
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
C       CALCULATE JP(X,Y) AND STORE IN AAA
      REAL NA,ND
C       CALCULATE JN(X,Y) AND STORE IN BBB
       DELX=2.*A/FLOAT(N+1)
       AMIN=5.E5
       YWQ=ZJ+W
       AMAX=0.0
       DELY=2.*B/FLOAT(N+1)
       BMIN=5.0E5
       BMAX=0.0
```

```
      DO 10 J=1,N
      WRITE(6,99)
99    FORMAT(T5,1HX,T15,1HY,T25,2HZJ,T43,2HJP,T55,1HX,
     1 T65,1HY,T75,4HZJ+W,T93,2HJN  )
      DO 20 I=1,N
      X=-A+I*DELX
      Y=-B+J*DELY
      CALL SUMIJ(X,Y,XJP,XJN)
      WRITE(6,100)X,Y,ZJ,XJP,X,Y,YWQ,XJN
100   FORMAT(3F10.4,E15.7,3X,3F10.6,E15.7  )
      AAA(I,J)=4.0*Q*ALPHA*PHIO*(1-RE)*XJP
      BBB(I,J)=4.0*Q*ALPHA*PHIO*(1-RE)*XJN
      IF(AAA(I,J).GT.AMAX)  AMAX=AAA(I,J)
      IF(AAA(I,J).LT.AMIN)  AMIN=AAA(I,J)
      IF(BBB(I,J).GT.BMAX)  BMAX=BBB(I,J)
      IF(BBB(I,J).LT.BMIN)  BMIN=BBB(I,J)
20    CONTINUE
10    CONTINUE
      RETURN
      END
      SUBROUTINE  SUMIJ(X,Y,XJP,XJN)
C       SUM TERMS OF DOUBLE FOURIER SERIES FOR CURRENT
C       DENSITIES JN AND JP
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C       INSERT  COMMON  BLKS  2,4,5,6,7
      REAL  NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2KB,KBTG
C
      XJP=0.0
      XJN=0.0
      DO 10 I=1,NEIGV
      DO 20 J=1,NEIGV
      CALL  TERNIJ(X,Y,I,J,FPIJ,FNIJ)
      XJP=XJP+FPIJ
      XJN=XJN+FNIJ
20    CONTINUE
10    CONTINUE
      RETURN
      END
      SUBROUTINE  TERNIJ(X,Y,I,J,FPIJ,FNIJ)
C       I,J TERM OF DOUBLE FOURIER SERIES
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      REAL  NA,ND,LP,LN,NP,NN,MUN,MUP,NI,NIA1,NIA2,KB,KBTG
      G(Z)=FUN(-ALPHA*Z)
      HH(AA,X)=(ALPHA*COS(AA*X)+AA*SIN(AA*X))/(ALPHA*ALPHA+AA*AA)
      S(AA,X)=HH(AA,X)-G(2*X)*HH(AA,-X)
```

```
      Y1(AA,X)=AA*SINH(X)+COSH(X)
      YI4(AA,B,X)=AA*(B*COSH(X)+SINH(X)-B)
C      FPIJ (TOP REGION)  SOLVE FOR JP
       UJPNOR=A+(SO*A*A/DP)*(COS(XIP(J))/XIP(J))**2
       XMUI=ETAP(I)/B
       XLAMJ=(XIP(J))/A
       DEN2=(XMUI**2)+(XLAMJ**2)
       GIJ2=LP*LP/(1.+LP*LP*DEN2)
       GIJ=SQRT(GIJ2)
       VIPNOR=B+(SO*B*B/DP)*(COS(ETAP(I))/ETAP(I))**2
       NP=SP*GIJ/DP
       XXT=ZJ/GIJ
       SPI1=B*SIN(ETAP(I))/ETAP(I)
       SPI2=A*SIN(XIP(J))/XIP(J)
       SPI3=COS(XLAMJ*X)/UJPNOR
       SPI4=COS(XMUI*Y)/VIPNOR
       SPI6=NP*SINH(XXT)+COSH(XXT)
      ZO=ALPHA*GIJ-1
      XO=(1-EXP(-XXT*ZO))/ZO
      X1=(1+(NP+1)*XO)/SPI6
      X2=X1-EXP(-ALPHA*ZJ)
      X3=1./(1+ALPHA*GIJ)
      GMN=X3*X2
      FPIJ=GIJ*SPI4*SPI3*SPI2*SPI1*GMN
C      CALCULATE FNIJ
       HP=H-(ZJ+W)
       UJNNOR=A+(S1*A*A/DN)*(COS(XIN(J))/XIN(J))**2
       VINNOR=B+(S1*B*B/DN)*(COS(ETAN(I))/ETAN(I))**2
      XMUI=ETAN(I)/B
      XLAMJ=XIN(J)/A
      DEN3=(XLAMJ**2)+(XMUI**2)
      SIJ2=LN*LN/(1.+LN*LN*DEN3)
      SIJ=SQRT(SIJ2)
      NN=SN*SIJ/DN
      XXB=HP/SIJ
      SNI1=B*SIN(ETAN(I))/ETAN(I)
      SNI2=A*SIN(XIN(J))/XIN(J)
      SNI3=COS(XLAMJ*X)/UJNNOR
      SNI4=COS(XMUI*Y)/VINNOR
      SNI5=YI4(SIJ,NN,XXB)
      Z1=EXP(-ALPHA*H)
      Z2=EXP(-ALPHA*(ZJ+W))
      Z3=(ALPHA*SIJ)**2
      Z4=1./(Z3-1)
      Z5=NN-ALPHA*SIJ
      Z6=NN*ALPHA*SIJ-1
      SNI6=COSH(XXB)+NN*SINH(XXB)
      HMN=Z4*(Z1*Z5+Z2*Z6*SINH(XXB)+Z2*(-Z5)*COSH(XXB))
      FNIJ=SIJ*SNI1*SNI2*SNI3*SNI4*HMN/SNI6
      RETURN
      END
      SUBROUTINE CONST
C       CALCULATE CONSTANTS
C
C CALCULATES OTHER CONSTANTS AND PARAMETERS FOR PROBLEM
```

```
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
C
      REAL  MUN,MUP,KBTG,KB,LAMBDA,NA,ND,NIA1,NIA2,NI,LN,LP
C
C
C CONVERT WAVELENGTH (MICRONS) TO ENERGY (EV)
      ENER=1.2402/LAMBDA
C CALCULATE BANDGAP AS FUNCTION OF TEMPERATURE
      EGT=EGGO-ALPHAO*T*T/(T+BETAO)
C CALCULATE ENERGY SHIFT DUE TO TEMPERATURE
      DELE=XKKO*(T-TO)
      E=ENER+DELE
C CALCUALTE ABSORPTION COEFFICIENT
      CALL ABSORP(E,ALPHA1)
      ALPHA=ALPHA1
C CALCULATE LIFETIMES
      TAUN=TNO/(1.+NA/B4)
      TAUP=TPO/(1.+ND/B4)
C CALCULATE MOBILITIES
      CALL MOBIL(Y1,Y2)
      MUN=Y1  $  MUP=Y2
C CALCULATE DIFFUSION COEFFICIENTS
      DN=KBTG*MUN  $  DP=KBTG*MUP
C CALCUALTE DENSITY OF PHOTONS IN PHOTON'S/CM2-S
      PHIO=POW*LAMBDA*5.03306E21
C CALCULATE INTRINSIC CARRIER DENSITY
      POWER=-EGT/(2.*KBTG)
      CALL EXPON(POWER,ANS)
      NI=NIA1*NIA2*(T**1.5)*ANS
C CALCULATE BUILT IN VOLTAGE
      VBI=KBTG*ALOG(NA*ND/(NI*NI))
      VOLTS=0.0
      CALL WIDTH(VOLTS)
C CALCULATE DIFFUSION LENGTHS
      LP=SQRT(DP*TAUP)  $  LN=SQRT(DN*TAUN)
C CALCULATE ALL NECESSARY EIGENVALUES FOR PROBLEM
      CALL ESET
      RETURN
      END
      SUBROUTINE ABSORP(E,ALPHA)
C      CALCULATE THE ABSORPTION COEFFICIENT FOR GIVEN ENERGY E
C
C
      COMMON/BLK1/NDATA,ENERG(25),ALP(25)
C
C
C
      I=0
```

```
      IF(E.LT.ENERG(1))GO TO 10
20   CONTINUE
      I=I+1
      IF(I.GT.NDATA)GO TO 30
      IF((ENERG(I).LE.E).AND.(ENERG(I+1) .GE. E))GO TO 40
      GO TO 20
40   ALPHA=ALP(I)+(ALP(I+1)-ALP(I))*(E-ENERG(I))/(ENERG(I+1)-ENERG(I))
      RETURN
10    ALPHA=0.
      RETURN
30   ALPHA=ALP(NDATA)
      RETURN
      END
      SUBROUTINE EXPON(X,ANS)
C       EXPONENTIAL TERM IN CASE ARGUMENTS GET LARGE
      IF(X.LT.-500) GO TO 10
      IF(X .GT. 700)GO TO 20
       ANS=EXP(X)
      RETURN
10     ANS=0.0
      RETURN
20    WRITE(6,30)
30   FORMAT(1X,29H  ARG TOO LARGE, EXP FUNCTION )
      STOP 444
      END
      SUBROUTINE ESET
C       CALCULATE EIGENVALUES FOR ORTHOGONAL FUNCTIONS
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  MUN,MUP,NI,LN,LP,NIA1,NIA2,KB,KBTG,NA,ND,LAMBDA
C
C CALCULATE EIGENVALUES FOR TOP REGION X-DIRECTION
      R1=SO  $  R2=DP  $  R3=A  $  N4=NEIGV
      CALL  EIGEN(XIP,R1,R2,R3,N4)
C CALCULATE EIGENVALUES FOR TOP REGION Y-DIRECTION
      R1=SO  $  R3=B
      CALL EIGEN(ETAP,R1,R2,R3,N4Z8hP CALCULATE EIGENVALUES FOR BOTTOM R
      R1=S1  $  R2=DN  $  R3=A
      CALL  EIGEN(XIN,R1,R2,R3,N4)
C CALCULATE EIGENVALUES FOR BOJOM REGION
      R1=S1   $   R3=B
      CALL  EIGEN(ETAN,R1,R2,R3,N4)
      RETURN
      END
      SUBROUTINE EIGEN(XX, S,D,H,N)
C       FINDS EIGENVALUES FOR EQUATION TAN(X) = C/X, C=CONSTANT
C
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
C
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
      REAL NIA1,NIA2
C
      DIMENSION XX(200)
      F(Z)=TAN(Z)-C/Z
      FP(Z)=C/(Z*Z)+1./(COS(Z)**2)
C SOLVES EQUATION X*TANX=C
C N MUST BE .LE. 200
      C=S*H/D
      IF(C.EQ.0) GO TO 1001
C GUESS AT FIRST ROOT
      X1=PI/4.
      M=1   $   IC=1
200   Y1=F(X1)
      IF(Y1.GT.0)GO TO 10
C  Y1 IS NEGATIVE
      X2=X1
      Y2=Y1
5    X1=.5*(X2+(2*M-1)*PI2)
      Y1=F(X1)
      IF(Y1.GT.0)GO TO 20
C  Y1 IS NEGATIVE
      X2=X1
      Y2=Y1
      GO TO 5
10    X2=(M-1)*PI+.8*(X1-(M-1)*PI)
      Y2=F(X2)
      IF(Y2.LT.0)GO TO 20
      X1=X2
      Y1=Y2
      GO TO 10
20    X=(X1+X2)/2.
      Y=F(X)
      IF(ABS(Y) .LT. 1.0E-5)GO TO 100
      IF(Y .LT. 0) GO TO 30
      X1=X
      Y1=Y
      GO TO 20
30    X2=X
      Y2=Y
      GO TO 20
100   XX(IC)=X
      M=M+1   $   IC=IC+1
      X1=X+PI
      IF(IC.GT.N) GO TO 300
      GO TO 200
 300  CONTINUE
      RETURN
1001   WRITE(6,234)
234 FORMAT(45HRECOMBINATION VELOCITY OF ZERO NOT ALLOWED          )
      END

      SUBROUTINE MOBIL(XMUN,XMUP)
C       CALCULATE MOBILITIES IN N AND P REGIONS
C
C
```

```
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
C
C
      REAL  LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2
C
C MOBILITY  OF  ELECTRONS
      RQ=2./3.
      BB1=A1*T*T/(NA**RQ)
      D=NA*BB1*(1.-.5*BB1)
      X1=AO*(T**1.5)/D
      ZZ=-A3*ALOG(T)
      CALL  EXPON(ZZ,ANS)
      X2=A2*ANS
      R=1./X2  +  1./X1
      XMUN=1./R
C MOBILITY  OF  HOLES
      ZZZ=-B3*ALOG(T)
      CALL  EXPON(ZZZ,ANS)
      X1=B2*ANS
      BB1=B1*T*T/(ND**RQ)
      D=ND*BB1*(1.-.5*BB1)
      X2=BO*(T**1.5)/D
      R=1./X2  +1./X1
      XMUP=1./R
      RETURN
      END
      SUBROUTINE WIDTH(VOLTS)
C        CALCULATE WIDTH OF DEPLETION REGION
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  KB,KBTG,LAMBDA,LN,LP,MUN,MUP,NA,ND,NI,NIA1,NIA2
C
      ABC=(1./ND  +  1./NA)
      W2=(2.*EPSO*(8.85E-14)/Q)*(VBI-VOLTS)*ABC
      W=SQRT(W2)
      RETURN
      END
      SUBROUTINE SPEC
C        CALCULATE SPECTRAL RESPONSE
C
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
C CALCULATE  SPECTRAL  RESPONSE
C
C
C
      DIMENSION  WAV(200),SP(200),SN(200),SDR(200),SR(200)
```

```
C
      I=0
90    I=I+1
      E=EGG0-.05+.025*(I-1)
      IF((E.GT.5.0).OR.(I.GT.200))GO  TO  100
      WAV(I)=1.2402/E
      CALL  SHORT(S1P,S1N,S1DR,E)
      SN(I)=S1N
      SP(I)=S1P
      SDR(I)=S1DR
      SR(I)=S1N+S1P+S1DR
       WRITE(6,80)I,E,WAV(I),S1P,S1N,S1DR
80   FORMAT(I5,5E15.5)
      GO TO 90
100  CONTINUE
      MAX=I-1
       I=I-1
C      NORMALIZE SPECTRAL RESPONSE
      XMAX=0.
      DO 110 K=1,MAX
      IF(SR(K).GT.XMAX)XMAX=SR(K)
110  CONTINUE
      DO 120 K=1,MAX
      SN(K)=SN(K)/XMAX
      SP(K)=SP(K)/XMAX
      SDR(K)=SDR(K)/XMAX
      SR(K)=SR(K)/XMAX
120  CONTINUE
C  PLOT  GRAPH
      NXL=20 $ SX=10.               $  XOFF=.5
      NYL=28 $ SY=10.               $  YOFF=.5
      ISYM=0   $   XMIN=0.    $   XMAX=1.2
      IEC=0
      CALL  GRAPH(WAV,SN,SP,SDR,SR,I)
      RETURN
      END
      SUBROUTINE  GRAPH(WAV,SN,SP,SDR,SR,I)
C      GRAPHICS OUTPUT OF PREVIOUS RESULTS FOR SPECTRAL RESPONSE
      DIMENSION  WAV(200),SN(200),SP(200),SDR(200),SR(200)
      CALL  CALPLT(1.5,1.0,-3)
      XPG=5.0
      XDV=10.0
      XTIC=.5
      YPG=5.0
      YDV=10.0
      YTIC=.5
      CALL  ASCALE(WAV,XPG,I,1,XDV)
      CALL  ASCALE(SR,YPG,I,1,YDV)
      CALL  AXES(0.,0.,0.,XPG,0.0,WAV(I+2),-XTIC,XDV,
     120HWAVELENGTH (MICRONS) ,.14,-20)
      CALL  AXES(0.,0.,90.,YPG,0.0,.2,-YTIC,YDV,
     1 28HNORMALIZED  SPECTRAL  RESPONSE ,.14,28)
      SFX=1./WAV(I+2)
      SFY=5.0
      CALL  CALPLT(WAV(1)*SFX,SN(1)*SFY,3)
```

```
      DO 100 J=1,I
      CALL CALPLT(WAV(J)*SFX,SN(J)*SFY,2)
100   CONTINUE
      CALL CALPLT(WAV(1)*SFX,SP(1)*SFY,3)
      DO 101 J=1,I
      CALL CALPLT(WAV(J)*SFX,SP(J)*SFY,2)
101   CONTINUE
      CALL CALPLT(WAV(1)*SFX,SDR(1)*SFY,3)
      DO 102 J=1,I
      CALL CALPLT(WAV(J)*SFX,SDR(J)*SFY,2)
102   CONTINUE
      CALL CALPLT(WAV(1)*SFX,SR(1)*SFY,3)
      DO 103 J=1,I
      CALL CALPLT(WAV(J)*SFX,SR(J)*SFY,2)
103   CONTINUE
      CALL CALPLT(0.,6.,-3)
       RETURN
       END
      SUBROUTINE SHORT(S1P,S1N,S1DR,E)
C        SHORT CIRCUIT CURRENT
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,KB,KBTG,NIA1,NIA2
C
C CALCULATES THE SPECTRAL RESPONSE COMPONENTS
C  CALCULATES DOUBLE SUMMATION OVER I,J
      CALL ABSORP(E,ALP1)
      ALPHA=ALP1
      S1P=0  $  S1N=0
      DO 10 I=1,NEIGV
      DO 20 J=1,NEIGV
      CALL NUMBS(I,J,SNIJ,SPIJ)
      S1P=S1P+SPIJ
      S1N=S1N+SNIJ
20    CONTINUE
10    CONTINUE
      CALL EXPON(-ALPHA*ZJ,Q1)
      CALL EXPON(-ALPHA*W,Q2)
      S1DR=Q1*(1.-Q2)*4.*A*B
      RETURN
      END
      SUBROUTINE DCURENT(IO)
C        DARK CURRENT
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
```

```
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  NNO,NPO,LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2
      REAL  KB,KBTG,IO,NN,NP
C
      Y1(X,Z)=Z*COSH(X)+SINH(X)
      Y2(X,Z)=Z*SINH(X)+COSH(X)
      Y3(X,Z)=(Z+TANH(X))/(1+Z*TANH(X))
C  DOPING  DENSITIES
      PPO=NA
      NNO=ND
      NPO=NI*NI/PPO
      PNO=NI*NI/NNO
      SUM1=0  $  SUM2=0
      DO  10  I=1,NEIGV
      DO  20  J=1,NEIGV
       DEN2=(ETAP(J)/B)**2  +(XIP(I)/A)**2
       GIJ2=LP*LP/(1.+LP*LP*DEN2)
       GIJ=SQRT(GIJ2)
      DEN3=(XIN(I)/A)**2  +(ETAN(J)/B)**2
      SIJ2=LN*LN/(1.+LN*LN*DEN3)
      SIJ=SQRT(SIJ2)
      NP=SP*GIJ/DP  $  NN=SN*SIJ/DN
      UJNNORM=A+(SO*A*A/DN)*(COS(XIN(J))/XIN(J))**2
      VINNORM=B+(S1*B*B/DN)*(COS(ETAN(I))/ETAN(I))**2
      F1=SIN(XIN(J))    $   F2=SIN(ETAN(I))
      HP=H-ZJ-W
      F3=16*A*A*B*B*Q*DN*NI*NI/(NA*SIJ)
      F4=(F1/XIN(J))**2   $   F5=(F2/ETAN(I))**2
      F6=1./(UJNNORM*VINNORM)
      TERMN=F3*F4*F5*F6*Y3((HP/SIJ),NN)
      UJPNORM=A+(SO*A*A/DP)*(COS(XIP(J))/XIP(J))**2
      VIPNORM=B+(S1*B*B/DP)*(COS(ETAP(I))/ETAP(I))**2
      F1=SIN(XIP(J))   $  F2=  SIN(ETAP(I))
      G3=16*A*A*B*B*Q*DP*NI*NI/(ND*GIJ)
      G4=(F1/XIP(J))**2   $   G5=(F2/ETAP(I))**2
      G6=1./(UJPNORM*VIPNORM)
      TERMP=G3*G4*G5*G6*Y3((ZJ/GIJ),NP)
      SUM1=SUM1+TERMN
      SUM2=SUM2+TERMP
20    CONTINUE
10    CONTINUE
      IO=SUM1+SUM2
      RETURN
      END
       SUBROUTINE  NUMBS(I,J,SNIJ,SPIJ)
C  I,J  TH  TERM  OF  DOUBLE  FOURIER  SERIES
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
```

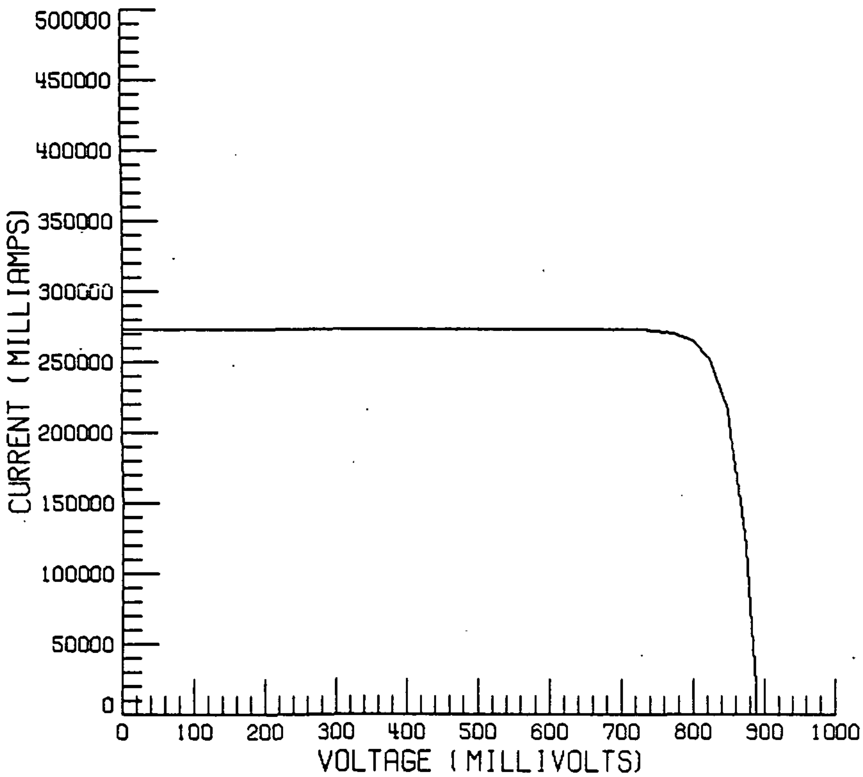
```
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2,KB,KBTG,NN,NP
      EXTERNAL FUN
C
       G(Z)=FUN(-ALPHA*Z)
      Y1(X,Z)=Z*COSH(X)+SINH(X)
      Y2(X,Z)=Z*SINH(X)+COSH(X)
C
C
C
       UJPNOR=A+(SO*A*A/DP)*(COS(XIP(J))/XIP(J))**2
       DEN2=(ETAP(I)/B)**2  +(XIP(J)/A)**2
       GIJ2=LP*LP/(1.+LP*LP*DEN2)
       GIJ=SQRT(GIJ2)
       VIPNOR=B+(SO*B*B/DP)*(COS(ETAP(I))/ETAP(I))**2
      UJNNOR=A+(S1*A*A/DN)*(COS(XIN(J))/XIN(J))**2
      VINNOR=B+(S1*B*B/DN)*(COS(ETAN(I))/ETAN(I))**2
      DEN3=(XIN(J)/A)**2  +(ETAN(I)/B)**2
      SIJ2=LN*LN/(1.+LN*LN*DEN3)
      SIJ=SQRT(SIJ2)
      NP=SP*GIJ/DP      $  NN=SN*SIJ/DN
      TEST=(ALPHA*GIJ-1)
      IF(ABS(TEST).LE..001)GO TO 10
      SPI1=16*ALPHA*A*A*B*B*GIJ/(UJPNOR*VIPNOR*((ALPHA*GIJ)**2-1))
      F4=SIN(XIP(J))          $  F5=SIN(ETAP(I))
      SPI2=((F5/ETAP(I))**2)*((F4/XIP(J))**2)
      SPI3=NP+ALPHA*GIJ-G(ZJ)*Y1((ZJ/GIJ),NP)
      SPI4=(SPI3/Y2((ZJ/GIJ),NP))-ALPHA*GIJ*G(ZJ)
      SPIJ=SPI1*SPI2*SPI4
      GO TO 40
10  SPI1=16*ALPHA*A*A*B*B*GIJ/(UJPNOR*VIPNOR*(ALPHA*GIJ+1))
      F4=SIN(XIP(J))   $  F5=SIN(ETAP(I))
      SPI2=((F5/ETAP(I))**2)*((F4/XIP(J))**2)
      BX=ZJ/GIJ
        SUM=BX  $  XL=BX
20   RATIO=(1+(NP+1)*SUM)/(NP*SINH(BX)+COSH(BX))
      SPI3=RATIO-G(ZJ)
      SPIJ=SPI1*SPI2*SPI3
40   CONTINUE
      HP=H-ZJ-W
      G5=SIN(XIN(J))    $  G6=SIN(ETAN(I))
      SNI1=16*ALPHA*A*A*B*B*SIJ*G((ZJ+W))
      SNI2=(G5/XIN(J))**2
      SNI3=(G6/ETAN(I))**2
      SNI4=1./(UJNNOR*VINNOR)
      TEST=ALPHA*SIJ-1
      IF(ABS(TEST).LE..001)GO TO 50
      SNI5=1./((ALPHA*SIJ)**2  -1.)
      XA=NN*(COSH(HP/SIJ)-G(HP))+SINH(HP/SIJ)
      XB=ALPHA*SIJ*G(HP)
      SNI6=ALPHA*SIJ-(XA+XB)/Y2((HP/SIJ),NN)
      SNIJ=SNI1*SNI2*SNI3*SNI4*SNI5*SNI6
      RETURN
50   CONTINUE
```

```
      BY=HP/SIJ
      SUM=BY
60  RATIO=((NN-1.)*SUM  -  1)*G(HP)/(NN*SINH(BY)+COSH(BY))
      SNI5=(1.+RATIO)/(ALPHA*SIJ+1.)
      SNIJ=SNI1*SNI2*SNI3*SNI4*SNI5
      RETURN
      END
      FUNCTION FUN(X)
      IF(X.LT.-230)GO  TO  10
      FUN=EXP(X)
      RETURN
10    FUN=0
       RETURN
       END
      SUBROUTINE IV(WAVE)
C      CURRENT-VOLTAGE CURVE
C
C CALCULATE  CURRENT-VOLTAGE  CURVE
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(200),XIN(200),XIP(200),ETAP(200)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      COMMON/BLK8/VOC,PMAX,EFF,ISC
C
C
      DIMENSION  AMPS(100),VOLTS(100)
      REAL  IREC,IB,IO,ISC,I
      REAL  LAMBDA,NA,ND,LN,LP,MUP,MUN,NIA1,NIA2,KB,KBTG,NI
C CALCULATE  IV  CURVE
      FFF=Q*PHIO*(1-RE)
      E=1.2402/WAVE
      ICOUNT=0         $  PMAX=-.5
      DELVO=.0125
      DELV=.025
C CALCULATE  ISC  (LIGHT  CURRENT)
      CALL  SHORT(S1P,S1N,S1DR,E)
      ISC=FFF*(S1P+S1N+S1DR)
      V=-DELV
100  CONTINUE
      ICOUNT=ICOUNT+1
      V=V+DELV
      CALL  WIDTH(V)
C CALCULATE  DARK  CURRENT
       CALL  DCURENT(IO)
       IREC=4*A*B*Q*NI*W*PI2*2*SINH(V/(2*KBTG))
       IREC=IREC/((VBI-V)/KBTG)
       IREC=IREC/SQRT(TAUN*TAUP)
C SOLVE  FOR  I
       U1=1+RS/RSH
       U=.999
       IB=ISC-IREC-V/RSH+IO
        VOLTS(ICOUNT)=V*1000
```

```
110   CONTINUE
       Z=(V+U*IB*RS)/KBTG
       F=IB*U*U1-IB+IO*EXP(Z)
       FP=IB*U1+IO*(RS*IB/KBTG)*EXP(Z)
       U2=U-F/FP
       ERROR=ABS(U2-U)
       IF(ERROR.LT.1.0E-6) GO TO 120
       U=U2
       GO TO 110
120    I=U2*IB
      AMPS(ICOUNT)=I*1000
      P=I*V
      IF(P.GT.PMAX)PMAX=P
      IF((I.LT.O).OR.(VBI.LT.(V+DELV)))GO  TO  130
      IF(V.GT..85) DELV=DELVO
      GO TO 100
130  AMPS(ICOUNT)=0.
      PIN=POW*1000*4*A*B
      EFF=PMAX*100/PIN
      VOLTS(ICOUNT)=VOLTS(ICOUNT-1)+DELV/100.
       VOC=VOLTS(ICOUNT)
      N=ICOUNT  $  YMIN=0  $  XMIN=0
      YMAX=1.2*AMPS(1)
      XMAX=1.2*VOLTS(ICOUNT)
      NXL=20
      NYL=19
      ISYM=0  $  SX=5.0  $  SY=5.0
      XOFF=0.75  $  YOFF=0.75
      CALL GRAPHIV(VOLTS,AMPS,ICOUNT)
      CALL NFRAME
      RETURN
      END
      SUBROUTINE  GRAPHIV(X,Y,I)
C      GRAPHICS OF CURRENT-VOLTAGE RESULTS
      DIMENSION  X(100),Y(100)
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      XPG=5.0
      XDV=10.
      XTIC=.5
      YPG=5.0
      YDV=10.0
      YTIC=.5
      CALL  ASCALE(X,XPG,I,1,XDV)
      CALL  ASCALE(Y,YPG,I,1,YDV)
      CALL  AXES(0.,0.,0.,XPG,0.0,X(I+2),-XTIC,XDV,
     1 20HVOLTAGE  (MILLIVOLTS) ,.14,-20)
      CALL  AXES(0.,0.,90.,YPG,0.0,Y(I+2),-YTIC,YDV,
     1 19HCURRENT  (MILLIAMPS)  ,.14,19)
      SFX=1./X(I+2)
      SFY=1./Y(I+2)
      CALL  CALPLT(X(1)*SFX,Y(1)*SFY,3)
      DO  100  J=1,I
      CALL  CALPLT(X(J)*SFX,Y(J)*SFY,2)
100  CONTINUE
      CALL  CALPLT(0.,6.,-3)
```

```
      CALL  CHARACT(0.0,0.0,.1,5HGRAPH,0.0,5)
      CALL  WHERE(XX,YY,IXX)
      CALL  NUMBER(XX+.07,0.,.1,XGRAPH,0.0,-1)
      CALL NFRAME
      RETURN
      END
```

a)



b)

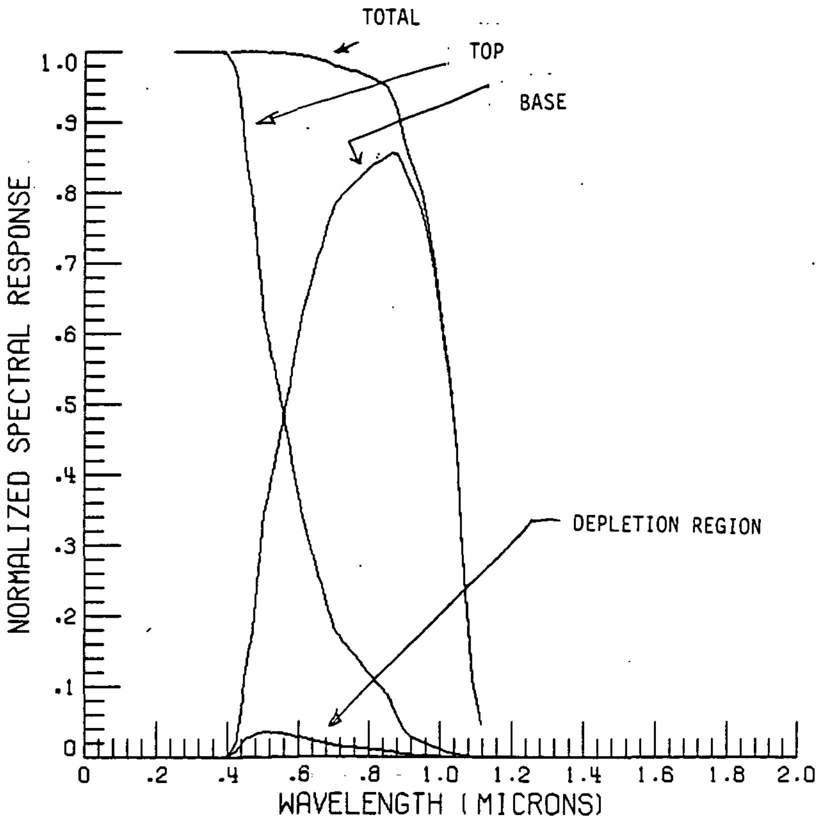


FIGURE C1. Representative output from program "SC3D" illustrating the spectral response, the current-voltage relation and contour plot of current density in the planes $Z=Z_j$ and $Z=Z_j+W$.

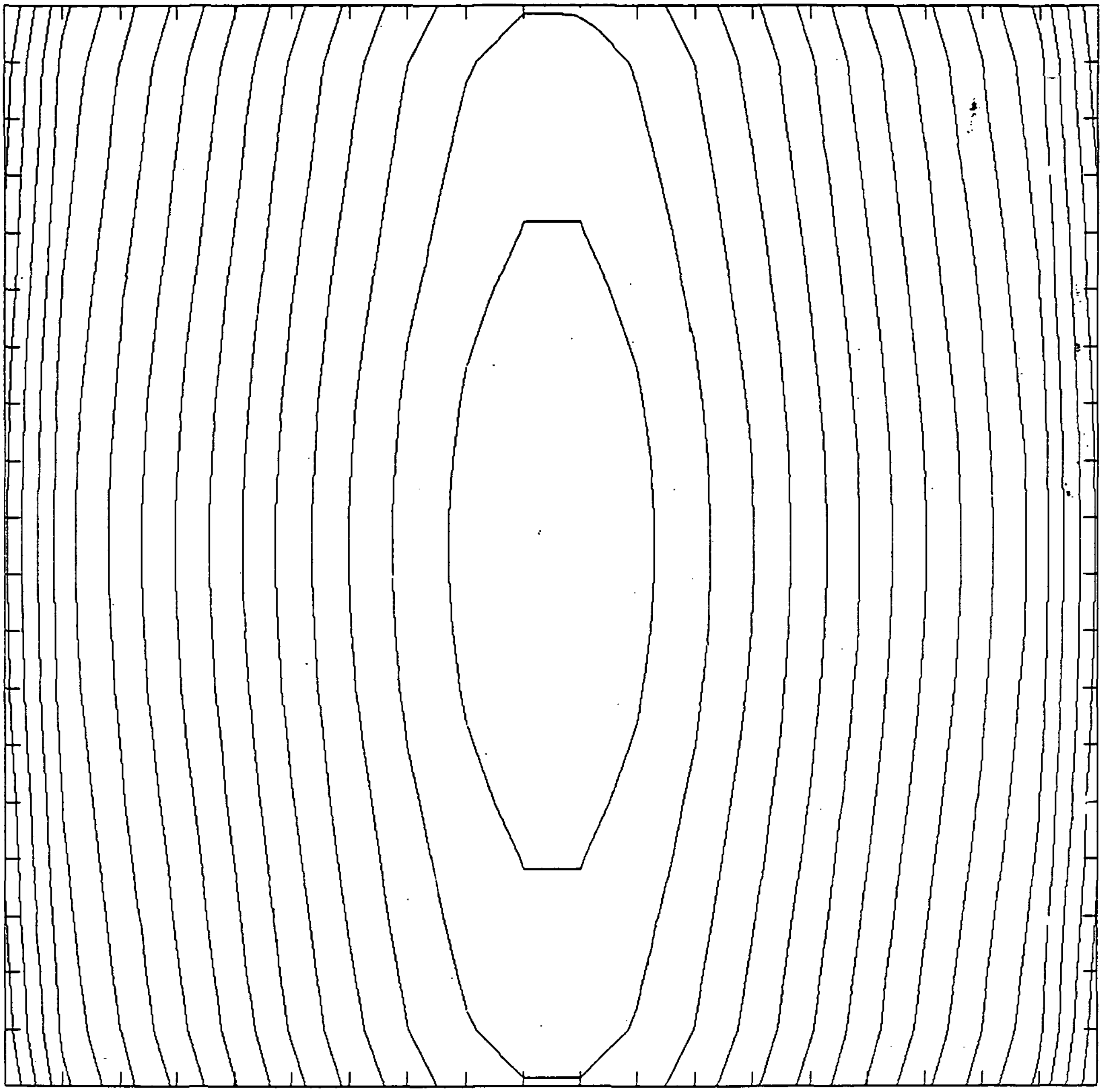


FIGURE C1. (c) Contour plot of $J_p(x, y)$ in plane $Z=Z_j$.

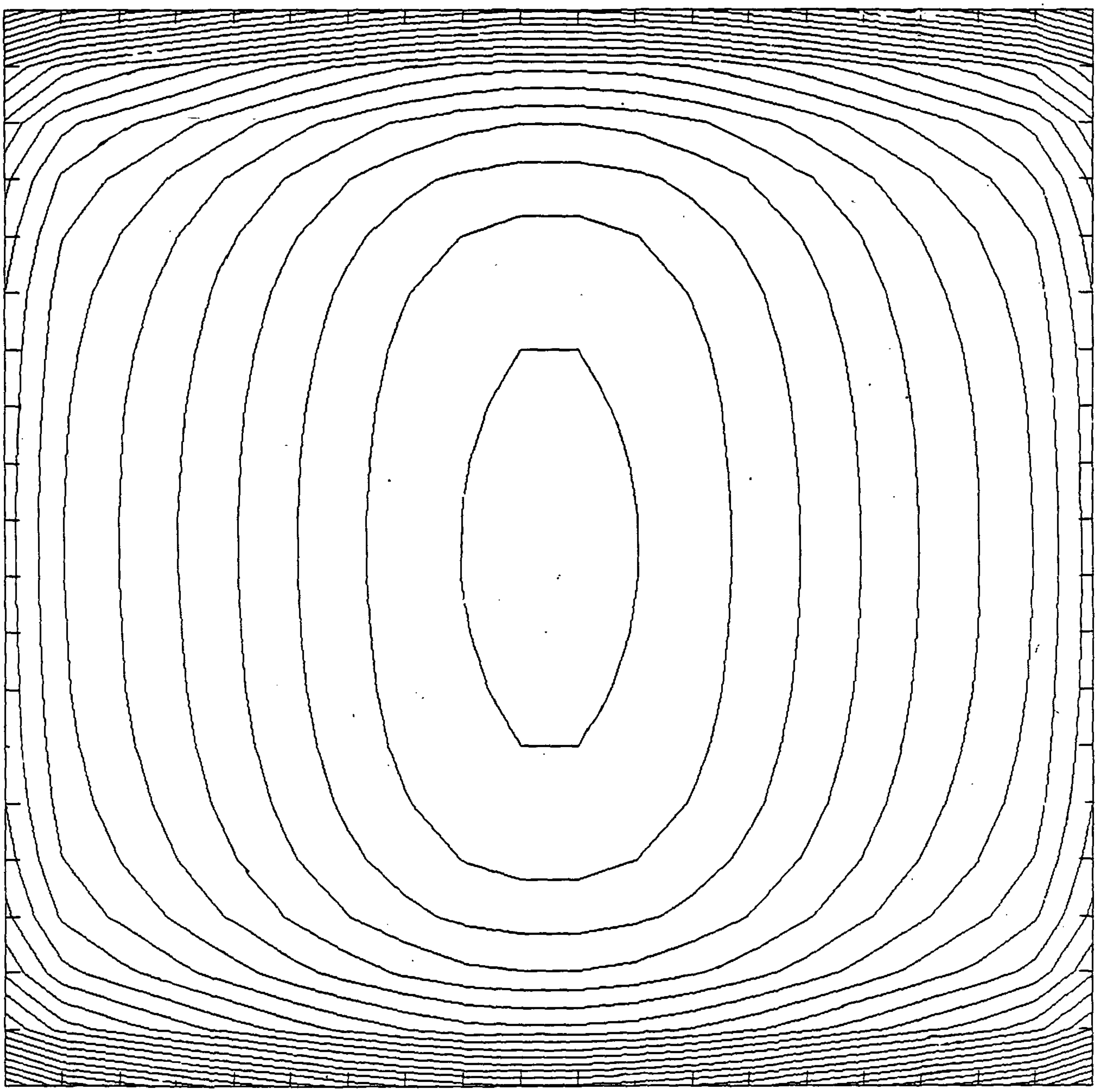


FIGURE C1. (d) Contour plot of $J_n(x,y)$ in plane $Z=Z_j+W$.

APPENDIX D

PROGRAM "VSC3D" FOR VERTICAL JUNCTION SOLAR CELL
3-DIMENSIONAL

```
      PROGRAM VSC3D(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE8)
C
C  SC3D=SOLAR CELL 3 DIMENSIONAL (ILLUMINATED FROM SIDE X=A)
C
C  GREEN'S FUNCTION SOLUTION
C
      COMMON/BLK1/NDATA,ENERG(25),ALP(25)
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(50),XIN(50),XIP(50),ETAP(50),XN(50),XP(50)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      COMMON/BLK8/VOC,PMAX,EFF,ISC
      COMMON/BLK9/SPTOP,SNBOT
      DIMENSION  ENERGS(25),ENERGGA(25),ENERGGE(25)
      DIMENSION  ALPS(25),ALPGA(25),ALPGE(25)
C
C
C
      REAL  LAMBDA,NA,ND,NIA1,NIA2,MUN,MUP,KB,KBTG,LN,LP,NI,ISC
      REAL  NIAS1,NIAS2,NIAGA1,6[>Ics.TTC'IAGE25*P&K  -,+I

C
      CALL PSEUDO
C
C  NAMELIST  VARIABLES
C
      NAMELIST/PARAM/POW,NA,ND,LAMBDA,A,B,H,ZJ,T,RS,RSH,SN,SP,
     1  SO,S1,NEIGV,ITYPE,ISWITCH
C
C  POW = LASER POWER (KW/CM2)
C  NA=DOPING  DENSITY  (CM-3)
C  ND=DOPING  DENSITY  (CM-3)
C  LAMBDA=WAVELENGTH  (MICRONS)
C  A=HALF  WIDTH  OF  X-DIRECTION  ( -A  .LE.  X  .LE.  A)
C  B=HALF  WIDTH  OF  Y-DIRECTION  ( -B  .LE.  Y  .LE.  B)
C  H=DEPTH  OF  CELL  IN  Z-DIRECTION  ( O  .LE.  Z  .LE.  H)
C  ZJ=JUNCTION  DEPTH  FROM  Z=O  (CM)
C  T=  TEMPERATURE  (DEG  K)
C  RS=SERIES  RESISTANCE  OHMS
C  RSH=SHUNT  RESISTANCE  OHMS
C  SN=SURFACE  RECOMBINATION  VELOCITY  TOP  (CM/S)
C  SP=SURFACE  RECOMBINATION  VELOCITY  BOTTOM  (CM/S)
C  SO=SURFACE  RECOMBINATION  VELOCITY  TOP  SIDES
C  S1=SURFACE  RECOMBINATION  VELOCITY  BOTTOM  SIDES
C  NEIGV=NUMBER  OF  EIGENVALUES
C  ITYPE  =  TYPE  OF  MATERIAL
C               ITYPE  =  1  FOR  SILICON  (SI)
C               ITYPE  =  2  FOR  GALLIUM  ARSENIDE  (GAAS)
C               ITYPE  =  3  FOR  GERMANIUM  (GE)
C ISWITCH TURNS CONTOUR PLOT ON AND OFF
C ISWITCH=O          CONTOUR PLOT IS OFF
C ISWITCH=1          CONTOUR PLOT IS ON
```

```
C

C
C       NOMINAL VALUES FOR NAMELIST VARIABLES
C
      POW=.001          $  RE=.05
      LAMBDA=.8         $  ITYPE = 1
      TO=300.           $  T=300.
      RS=0.0            $  RSH=1.0E6
      SN=1.0            $  SP=1.0
      SO=1.0            $  S1=1.0
      NA=1.25E17        $  ND=5.0E19
      A=.5              $  B=.500
      H=5.00E-4         $  ZJ=2.5E-4
      NEIGV=15
      ISWITCH=1

C
C       SILICON PARAMETERS
      NDATAS=20
      DATA  (ENERGS(K),K=1,8)/1.1,1.15,1.24,1.378,1.46,1.77,2.067,2.48/
      DATA  (ENERGS(K),K=9,15)/2.76,3.1,3.26,3.5,3.6,4.0,4.2/
      DATA (ENERGS(K),K=16,20)/5.0,5.2,6.0,8.0,10.0/
      DATA (ALPS(K),K=1,7)/1.0,10.0,100.0,350.0,950.0,2.E3,4.5E3/
      DATA (ALPS(K),K=8,14)/1.0E4,2.0E4,5.0E4,1.0E5,1.0E6,1.1E6,1.8E6/
      DATA (ALPS(K),K=15,20)/2.5E6,1.9E6,2.0E6,1.5E6,1.3E6,1.1E6/
C CONSTANTS FOR MOBILITIES
        DATA  ASO,AS1,AS2,AS3/65.02,5.72E-9,2.49E9,2.5/
        DATA  BSO,BS1,BS2,BS3/54.46,6.76E-9,2.93E9,2.7/
C CONSTANTS FOR BANDGAP AS FUNCTION OF TEMPERATURE
       DATA EGGOS,ALPHAOS,BETAOS/1.16,7.02E-4,1108./
C CONSTANTS FOR INTRINSIC CARRIER DENSITY
       DATA NIAS1,NIAS2/4.9E15,1.61/
C CONSTANTS FOR LIFETIMES
       DATA TNOS,TPOS,B4/1.86E-4,3.52E-3,7.1E15/
      EPSOS=11.6
C       GALLIUM ARSENIDE PARAMETERS
C ABSORPTION COEFFICIENT CURVE FOR GAAS
      NDATAGA=16
      DATA  (ENERGGA(K),K=1,8)/1.37,1.38,1.4,1.41,1.42,1.43,1.44,1.5/
      DATA  (ENERGGA(K),K=9,16)/1.6,1.8,2.0,2.4,3.0,3.5,4.0,4.5/
      DATA  (ALPGA(K),K=1,8)/18.,32.,119.,175.,2.5E3,4.5E3,6.E3,1.4E4/
      DATA  (ALPGA(K),K=9,16)/1.8E4,3.E4,4.E4,1.E5,2.E5,3.E5,4.E5,5.E5/
C
C CONSTANTS FOR MOBILITIES
      DATA  AGA0,AGA1,AGA2,AGA3/5076.11,5.24E-9,6.43E5,1.0/
      DATA  BGA0,BGA1,BGA2,BGA3/1477.3,8.59E-8,6.05E7,2.1/
C CONSTANTS FOR BANDGAP
      DATA EGGOGA,ALPHGA,BETGA/1.519,5.4E-4,204./
C CONSTANTS FOR INTRINSIC CARRIER DENSITY
      DATA NIAGA1,NIAGA2/4.9E15,.0488844/
C CONSTANTS FOR LIFETIMES
      DATA TNOGA,TPOGA,B4/8.8179E-7,1.404E-7,7.1E15/
      EPSOGA=13.1
C       GERMANIUM PARAMETERS
```

```
C GERMANIUM SOLAR CELL PARAMETERS
      NDATAGE=22
      DATA  (ENERGGE(K),K=1,8)/.66,.68,.7,.73,.76,.79,.8,.81/
      DATA  (ENERGGE(K),K=9,16)/.83,.85,.875,.9,.97,1.7,2.6,3./
      DATA  (ENERGGE(K),K=17,22)/3.6,4.,4.4,5.0,6.0,8./
      DATA  (ALPGE(K),K=1,8)/1.,10.,20.,60.,100.,600.,1.E3,4.E3/
      DATA  (ALPGE(K),K=9,16)/5.E3,8.E3,8.5E3,9.E3,1.E4,1.E5,7.E5,8.E5/
      DATA  (ALPGE(K),K=17,22)/1.E6,1.4E6,2.0E6,1.3E6,1.2E6,1.0E6/
C
      DATA  AGE0,AGE1,AGE2,AGE3/458.68,7.92E-9,6.08E7,1.66/
      DATA  BGE0,BGE1,BGE2,BGE3/3140.27,1.79E-7,1.18E9,2.33/
      DATA  EGGOGE,ALPHGE,BETGE/.741,4.77E-4,235./
      DATA  NIAGE1,NIAGE2/4.9E15,.33313/
      DATA  TNOGE,TPOGE,B4/2.1022E-5,2.1007E-5,7.1E15/
      EPSOGE=16.
C
C READ IN ANY CHANGES TO THE ABOVE PARAMETERS
C
      XGRAPH=0.
100   CONTINUE
      READ(5,PARAM)
      IF(EOF(5))600,601
600   WRITE(6,603)
603   FORMAT(1X,28HEND OF FILE ENCOUNTERED-STOP )
      STOP 1313
601   CONTINUE
C
      WRITE(6,110)
110   FORMAT(//)
      Q=1.6E-19
       XKKO=1.2E-3
       PI=3.1415926536
       PI2=PI*.5
       KB=8.6172E-5
       KBTG=KB*T
C      EPSO IS THE PERMITIVITY
      XGRAPH=XGRAPH+1
C
C      SETUP PARAMETERS FOR CORRECT TYPE OF PHOTOCONVERTER MATERIALS
C      ITYPE = 1 (SI)
C      ITYPE = 2 (GAAS)
C      ITYPE = 3 (GE)
       IF(ITYPE .EQ. 1) WRITE(6,111)
       IF(ITYPE .EQ. 2) WRITE(6,112)
       IF(ITYPE .EQ. 3) WRITE(6,113)
111 FORMAT(1X,25HSILICON PHOTOCONVERTER          ,/)
112 FORMAT(1X,35HGALLIUM ARSENIDE PHOTOCONVERTER ,/)
113 FORMAT(1X,25HGERMANIUM PHOTOCONVERTER        ,/)
       IF(ITYPE .EQ. 1) GO TO 10
       IF(ITYPE .EQ. 2) GO TO 20
C      GERMANIUM DATA GOES HERE
       NDATA=NDATAGE
       DO 40 I=1,NDATA
       ENERGE(I)=ENERGGE(I)
40    ALP(I)=ALPGE(I)
```

```
      AO=AGEO  $  A1=AGE1  $  A2=AGE2  $  A3=AGE3
      BO=BGEO  $  B1=BGE1  $  B2=BGE2  $  B3=BGE3
      EGGO=EGGOGE  $  ALPHAO=ALPHGE  $  BETAO=BETGE
      NIA1=NIAGE1  $  NIA2=NIAGE2
      TNO=TNOGE  $  TPO=TPOGE
      EPSO=EPSOGE
      GO TO 30
10    CONTINUE
C       SILICON PARAMETERS
      NDATA=NDATAS
      DO 41 I=1,NDATA
      ENERG(I)=ENERGS(I)
41    ALP(I)=ALPS(I)
      AO=ASO  $  A1=AS1  $  A2=AS2  $  A3=AS3
      BO=BSO  $  B1=BS1  $  B2=BS2  $  B3=BS3
      EGGO=EGGOS  $  ALPHAO=ALPHAOS  $  BETAO=BETAOS
      NIA1=NIAS1  $  NIA2=NIAS2
      TNO=TNOS  $  TPO=TPOS
      EPSO=EPSOS
      GO TO 30
20    CONTINUE
C       GALLIUM ARSENIDE PARAMETERS
      NDATA=NDATAGA
      DO 42 I=1,NDATA
      ENERG(I)=ENERGGA(I)
42    ALP(I)=ALPGA(I)
      AO=AGAO  $  A1=AGA1  $  A2=AGA2  $  A3=AGA3
      BO=BGAO  $  B1=BGA1  $  B2=BGA2  $  B3=BGA3
      EGGO=EGGOGA  $  ALPHAO=ALPHGA  $  BETAO=BETGA
      NIA1=NIAGA1  $  NIA2=NIAGA2
      TNO=TNOGA  $  TPO=TPOGA
      EPSO=EPSOGA
30    CONTINUE
C       CALCULATE CONSTANTS
      CALL CONST
C       CALCULATE SPECTRAL RESPONSE
      CALL SPEC
C       CALCULATE I-V CURVE
      CALL IV(LAMBDA)
      WRITE(6,199)XGRAPH
199   FORMAT(T20,6HGRAPH  ,F3.0 )
      WRITE(6,200)ISC,VOC,EFF,RSH,DN,NEIGV
200   FORMAT(/,T2,4HISC=,E12.5,T20,4HVOC=,E12.5,T40,4HEFF=,
     1 E12.5,T60,4HRSH=,E12.5,T80,3HDN=,E12.5,T99,8HNEIGV  =  ,I5)
      WRITE(6,201)NA,ND,ZJ,S1,DP,NIA1
201   FORMAT(T2,3HNA=,E12.5,T20,3HND=,E12.5,T40,3HZJ=,E12.5,
     1T60,3HS1=,E12.5,T80,3HDP=,E12.5,T99,7HNIA1  =  ,E12.5)
      WRITE(6,202)TAUN,TAUP,LN,LP,TNO,NIA2
202   FORMAT(T2,5HTAUN=,E12.5,T20,5HTAUP=,E12.5,T40,3HLN=,E12.5,
     1 T60,3HLP=,E12.5,T80,6HTNO  =  ,E12.5,T99,7HNIA2  =  ,E12.5)
      WRITE(6,203)A,B,H,SO,TPO
203   FORMAT(T2,2HA=,E12.5,T20,2HB=,E12.5,T40,2HH=,E12.5,T60,3HSO=,
     1 E12.5,T80,6HTPO  =  ,E12.5)
      WRITE(6,204)MUN,MUP,LAMBDA,POW,SPTOP
204   FORMAT(T2,4HMUN=,E12.5,T20,4HMUP=,E12.5,T40,7HLAMBDA=,F10.4,
```

```
     1T60,4HPOW=,E12.5  ,T80,6HSPTOP=  ,E12.5  )
      WRITE(6,205)T,RS,SN,SP,SNBOT
205  FORMAT(T2,2HT=,E12.5,T20,3HRS=,E12.5,T40,3HSN=,E12.5,
     1  T60,3HSP=,E12.5,T80,6HSNBOT=  ,E12.5  )
      WRITE(6,206)W,PMAX,NI,VBI,ALPHA
206  FORMAT(T2,2HW=,E12.5,T20,5HPMAX=,E12.5,T40,3HNI=,E12.5,
     1  T60,4HVBI=,E12.5,T80,6HALPHA=,E12.5,///)
      IF(ISWITCH .EQ. 1) CALL CONTOUR
      GO TO 100
      END

      SUBROUTINE CONTOUR
      DIMENSION  AAA(40,40),BBB(40,40)
C AAA IS 40X40 ARRAY OF CURRENT DENSITY VALUES AT X,Y AND Z=ZJ
C BBB IS 40X40 ARRAY OF CURRENT DENSITY VALUES AT X,Y AND Z=ZJ+W
C
      N=40
C CALCULATE JP AND STORE IN AAA.  FIND AMAX AND AMIN VALUES FOR ARRAY
C
      CALL  CDENAB(AAA,BBB,AMAX,AMIN,BMAX,BMIN,N)
C
C CALCULATE JN AND STORE IN BBB.  FIND BMAX AND BMIN VALURS FOR ARRAY
C
C        AAA ARE VALUES OF XJP
C        BBB ARE VALUES OF XJN
C
C
C
C       PLOT CONTOUR GRAPH OF AAA
       CALL  CONREC(AAA,N,N,N,AMIN,AMAX,0,0,-1,0)
       CALL EZTRN
       CALL NFRAME
       WRITE(6,199)
199  FORMAT(////)
C       PLOT CONTOUR GRAPH OF BBB
C
       CALL  CONREC(BBB,N,N,N,BMIN,BMAX,0,0,-1,0)
       CALL EZTRN
       CALL NFRAME
       RETURN
       END

       SUBROUTINE  CDENAB(AAA,BBB,AMAX,AMIN,BMAX,BMIN,N)
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      REAL  NA,ND,LAMBDA,LN,LP,MUN,MUP,NI,NIA1,NIA2
       DIMENSION  AAA(40,40),BBB(40,40)
C      CALCULATE JP(X,Y) AND STORE IN AAA
C      CALCULATE JN(X,Y) AND STORE IN BBB
       DELX=2.*A/FLOAT(N+1)
       AMIN=5.E5
       AMAX=0.0
       DELY=2.*B/FLOAT(N+1)
        YWQ=ZJ+W
```

```
      WRITE(6,99)
99   FORMAT(T5,1HX,T15,1HY,T25,2HZJ,T43,2HJP,T55,1HX,
    1 T65,1HY,T75,4HZJ+W,T93,2HJN )
      BMIN=5.0E5
      BMAX=0.0
      DO  10  J=1,N
      DO  20  I=1,N
      X=-A+I*DELX
      Y=-B+J*DELY
      CALL  SUMIJ(X,Y,XJP,XJN)
      AAA(I,J)=2.0*Q*ALPHA*PHIO*(1-RE)*XJP
      BBB(I,J)=2.0*Q*ALPHA*PHIO*(1-RE)*XJN
      WRITE(6,100)X,Y,ZJ,AAA(I,J),X,Y,YWQ,BBB(I,J)
100   FORMAT(1X,3F10.4,E15.7,3X,3F10.6,E15.7)
      IF(AAA(I,J).GT.AMAX)  AMAX=AAA(I,J)
      IF(AAA(I,J).LT.AMIN)  AMIN=AAA(I,J)
      IF(BBB(I,J).GT.BMAX)  BMAX=BBB(I,J)
      IF(BBB(I,J).LT.BMIN)  BMIN=BBB(I,J)
20   CONTINUE
10   CONTINUE
      RETURN
      END

      SUBROUTINE  SUMIJ(X,Y,XJP,XJN)
C
     COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
     COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
     COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
     REAL  NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2,KB,KBTG,LAMBDA
C
      XJP=0.0
      XJN=0.0
      DO  10  I=1,NEIGV
      DO  20  J=1,NEIGV
      CALL   TERNIJ(X,Y,I,J,FPIJ,FNIJ)
      XJP=XJP+FPIJ
      XJN=XJN+FNIJ
20   CONTINUE
10   CONTINUE
      RETURN
      END

      SUBROUTINE  TERNIJ(X,Y,I,J,FPIJ,FNIJ)
     COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
     COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
     COMMON/BLK5/ETAN(50),XIN(50),XIP(50),ETAP(50),XN(50),XP(50)
     COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
     COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
     REAL  NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2,KB,KBTG
     REAL LAMBDA
     EXTERNAL FUN
C
      G(Z)=FUN(-ALPHA*Z)
C     FPIJ  (TOP  REGION)   N-REGION
      WJPNOR=.5*ZJ-.25*SIN(2*XP(J))*ZJ/XP(J)
```

```
 XMUI=ETAP(I)/B
 XLAMJ=(XP(J))/ZJ
 DEN2=(XMUI**2)+(XLAMJ**2)
 GIJ2=LP*LP/(1.+LP*LP*DEN2)
 GIJ=SQRT(GIJ2)
CC=ALPHA*ALPHA*GIJ2-1
 VIPNOR=B+(SO*B*B/DP)*(COS(ETAP(I))/ETAP(I))**2
 SPI1=B*SIN(ETAP(I))/ETAP(I)
 SPI2=ZJ*(1.-COS(XP(J)))/XP(J)
 SPI3=XLAMJ/WJPNOR
 SPI4=COS(XMUI*Y)/VIPNOR
CALL  SUB1(X,A,GIJ,SO,DP,ALPHA,CC,SPI5)
 FPIJ=SPI1*SPI2*SPI3*SPI4*SPI5
C       CALCULATE FNIJ BOTTOM REGION (P-REGION) EVALUATE AT Z=ZJ+W
 HP=H-(ZJ+W)
 WJNNOR=.5*HP-.25*SIN(2*XN(J))*HP/XN(J)
 VINNOR=B+(S1*B*B/DN)*(COS(ETAN(I))/ETAN(I))**2
XMUI=ETAN(I)/B
XLAMJ=XN(J)/HP
DEN3=(XLAMJ**2)+(XMUI**2)
SIJ2=LN*LN/(1.+LN*LN*DEN3)
SIJ=SQRT(SIJ2)
EE=ALPHA*ALPHA*SIJ2-1
SNI1=B*SIN(ETAN(I))/ETAN(I)
SNI2=HP*(1.-COS(XN(J)))/XN(J)
SNI3=XLAMJ/WJNNOR
SNI4=COS(XMUI*Y)/VINNOR
 CALL  SUB1(X,A,SIJ,S1,DN,ALPHA,EE,SNI5)
FNIJ=SNI1*SNI2*SNI3*SNI4*SNI5
RETURN
END

 SUBROUTINE  SUB1(X,A,GIJ,SO,DP,ALPHA,CC,SPI5)
EXTERNAL FUN
G2=GIJ*GIJ
G1=SO/DP
AB1=G1-ALPHA
AB2=G1+ALPHA
AO=G2*AB1*EXP(-2.*A*ALPHA)/CC
A1=AO*GIJ*G1
A2=G2*AB2/CC
A3=A2*GIJ*G1
BO=2.*G1
B1=(1./GIJ)+G1*G1*G2
H=ALPHA*(X-A)
Q1=TANH(2.*A/GIJ)
R1=-G2*BO*EXP(H)/CC
R2=(-GIJ*(1+G1*G1*G2)*EXP(H)/CC)*Q1
ARG1=-(X+A)/GIJ
ARG2=(X-3*A)/GIJ
ARG3=(X-A)/GIJ
ARG4=-(X+3*A)/GIJ
DEN=1+FUN(ARG4)
R3=AO*(FUN(ARG1)+FUN(ARG2))/DEN
R4=A1*(FUN(ARG1)-FUN(ARG2))/DEN
```

```
      R5=A2*(FUN(ARG3)+FUN(ARG4))/DEN
      R6=A3*(FUN(ARG3)-FUN(ARG4))/DEN
      SPI5=(R1+R2+R3+R4+R5+R6)/(BO+B1*Q1)
      RETURN
      END

      SUBROUTINE CONST
C
C CALCULATES OTHER CONSTANTS AND PARAMETERS FOR PROBLEM
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
C
      REAL  MUN,MUP,KBTG,KB,LAMBDA,NA,ND,NIA1,NIA2,NI,LN,LP
C
C
C  CONVERT  WAVELENGTH  (MICRONS)  TO  ENERGY  (EV)
      ENER=1.2402/LAMBDA
C CALCULATE  BANDGAP  AS  FUNCTION  OF  TEMPERATURE
      EGT=EGGO-ALPHAO*T*T/(T+BETAO)
C CALCULATE  ENERGY  SHIFT  DUE  TO  TEMPERATURE
      DELE=XKKO*(T-TO)
      E=ENER+DELE
C  CALCUALTE  ABSORPTION  COEFFICIENT
      CALL ABSORP(E,ALPHA1)
      ALPHA=ALPHA1
C  CALCULATE  LIFETIMES
      TAUN=TNO/(1.+NA/B4)
      TAUP=TPO/(1.+ND/B4)
C  CALCULATE  MOBILITIES
      CALL  MOBIL(Y1,Y2)
      MUN=Y1  $  MUP=Y2
C  CALCULATE  DIFFUSION  COEFFICIENTS
      DN=KBTG*MUN  $  DP=KBTG*MUP
C  CALCUALTE  DENSITY  OF  PHOTONS  IN  PHOTON'S/CM2-S
      PHIO=POW*LAMBDA*5.03306E21
C  CALCULATE  INTRINSIC  CARRIER  DENSITY
      POWER=-EGT/(2.*KBTG)
      CALL EXPON(POWER,ANS)
      NI=NIA1*NIA2*(T**1.5)*ANS
C  CALCULATE  BUILT  IN  VOLTAGE
      VBI=KBTG*ALOG(NA*ND/(NI*NI))
      VOLTS=0.0
      CALL WIDTH(VOLTS)
C  CALCULATE  DIFFUSION  LENGTHS
      LP=SQRT(DP*TAUP)  $  LN=SQRT(DN*TAUN)
C CALCULATE ALL NECESSARY EIGENVALUES FOR PROBLEM
      CALL ESET
      RETURN
      END
```

```
      SUBROUTINE ABSORP(E,ALPHA)
C
C
      COMMON/BLK1/NDATA,ENERG(25),ALP(25)
C
C
C
      I=0
      IF(E.LT.ENERG(1))GO TO 10
20    CONTINUE
      I=I+1
      IF(I.GE.NDATA)GO TO 30
      IF((ENERG(I).LE.E).AND.(ENERG(I+1) .GE. E))GO TO 40
      GO TO 20
40    ALPHA=ALP(I)+(ALP(I+1)-ALP(I))*(E-ENERG(I))/(ENERG(I+1)-ENERG(I))
      RETURN
10    ALPHA=0.
      RETURN
30    ALPHA=ALP(NDATA)
      RETURN
      END

      SUBROUTINE EXPON(X,ANS)
      IF(X.LT.-500) GO TO 10
      IF(X .GT. 700)GO TO 20
       ANS=EXP(X)
      RETURN
10    ANS=0.0
      RETURN
20    WRITE(6,30)
30    FORMAT(1X,29H ARG TOO LARGE, EXP FUNCTION )
      STOP 444
      END

      SUBROUTINE ESET
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(50),XIN(50),XIP(50),ETAP(50),XN(50),XP(50)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL MUN,MUP,NI,LN,LP,NIA1,NIA2,KB,KBTG,NA,ND,LAMBDA
C
C CALCULATE EIGENVALUES FOR TOP REGION X-DIRECTION
      R1=SO $ R2=DP $ R3=A $ N4=NEIGV
      CALL EIGEN(XIP,R1,R2,R3,N4)
C CALCULATE EIGENVVALUES FOR TOP REGION Z-DIRECTION
      R1=SP $ R2=DP $ R3=ZJ
      CALL EIG(XP,R1,R2,R3,N4)
C CALCULATE EIGENVALUES FOR TOPphLGION Y-DIRECTION
      R1=SO $ R3=B
      CALL EIGEN(ETAP,R1,R2,R3,N4)
C CALCULATE EIGENVALUES FOR BOTTOM REGIION
```

```
      R1=S1  $  R2=DN  $  R3=A
      CALL  EIGEN(XIN,R1,R2,R3,N4)
C      CALCULATE EIGENVALUES BOTTOM REGION Z-DIRECTION
      R1=SN  $  R2=DN  $  R3=H-ZJ-W
      CALL  EIG(XN,R1,R2,R3,N4)
C CALCULATE EIGENVALUES FOR BOTTOM REGION
      R1=S1   $   R3=B
      CALL  EIGEN(ETAN,R1,R2,R3,N4)
      WRITE(6,99)(XIP(J),J=1,N4)
      WRITE(6,98)
      WRITE(6,99)(ETAP(J),J=1,N4)
      WRITE(6,98)
      WRITE(6,99)(XIN(J),J=1,N4)
      WRITE(6,98)
      WRITE(6,99)(ETAN(J),J=1,N4)
      WRITE(6,98)
      WRITE(6,99)  (XP(J),J=1,N4)
      WRITE(6,98)
      WRITE(6,99)  (XN(J),J=1,N4)
      WRITE(6,98)
99   FORMAT(1X,(5E15.6))
98   FORMAT(//)
      RETURN
      END

      SUBROUTINE  EIG(XX,S,D,H,N)
      DIMENSION  XX(50)
      DOUBLE  PRECISION  X,X1,X2,Y,Y1,Y2,PI,PI2
      F(Z)=1+C*Z*DCOS(Z)/DSIN(Z)
C  N  MUST  BE  LESS  THAN  50
      C=D/(S*H)
      PI=3.1415926535897932
      PI2=.5*PI
C  XX=ETAJ*ZJUNCTION
      IF(S.LE.0)GO  TO  1001
C  GUESS  AT  FIRST  ROOT
      X1=PI2
      M=1   $   IC=1
200   Y1=F(X1)
      IF(Y1.GT.0)GO  TO  10
C  Y1  IS  NEGATIVE,  DECREASE  X
      X2=X1  $  Y2=Y1
5    X1=.5*(X2+(2*M-1)*PI2)
      Y1=F(X1)
      IF(Y1.GT.0)  GO  TO  20
C  Y1  IS  NEGATIVE
      X2=X1   $   Y2=Y1
      GO TO 5
10   CONTINUE
C  Y1  IS  POSITIVE,  INCREASE  X
      X2=.5*(X1+M*PI)
      Y2=F(X2)
      IF(Y2.LT.0)  GO  TO  20
      X1=X2  $   Y1=Y2
      GO TO 10
```

```
20    X=(X1+X2)/2.
      Y=F(X)
      IF(DABS(Y) .LT. 1.0E-6) GO TO 100
      IF(Y.LT.0) GO TO 30
      X1=X   $   Y1=Y
      GO TO 20
30    X2=X
      Y2=Y
      GO TO 20
100   CONTINUE
      ZZ=X
      XX(IC)=ZZ
      M=M+1  $  IC=IC+1
      X1=X+PI
      IF(IC.GT. N) GO TO 308
      GO TO 200
308   RETURN
1001  WRITE(6,234)
234  FORMAT(1X,45HRECOMBINATION VELOCITY OF ZERO NOT ALLOWED )
      END

      SUBROUTINE EIGEN(XX, S,D,H,N)
C
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
C
       REAL NIA1,NIA2
C
      DIMENSION XX(50)
      F(Z)=TAN(Z)-C/Z
C SOLVES EQUATION X*TANX=C
C N MUST BE .LE. 200
      C=S*H/D
      IF(C.EQ.0) GO TO 1001
C GUESS AT FIRST ROOT
      X1=PI/4.
      M=1   $   IC=1
200   Y1=F(X1)
      IF(Y1.GT.0)GO TO 10
C  Y1 IS NEGATIVE
      X2=X1
      Y2=Y1
5     X1=.5*(X2+(2*M-1)*PI2)
      Y1=F(X1)
      IF(Y1.GT.0)GO TO 20
C  Y1 IS NEGATIVE
      X2=X1
      Y2=Y1
      GO TO 5
10    X2=(M-1)*PI+.8*(X1-(M-1)*PI)
      Y2=F(X2)
      IF(Y2.LT.0)GO TO 20
      X1=X2
      Y1=Y2
      GO TO 10
20    X=(X1+X2)/2.
```

```
      Y=F(X)
      IF(ABS(Y) .LT. 1.0E-6)GO TO 100
      IF(Y .LT. 0) GO TO 30
      X1=X
      Y1=Y
      GO TO 20
30    X2=X
      Y2=Y
      GO TO 20
100   XX(IC)=X
      M=M+1  $  IC=IC+1
      X1=X+PI
      IF(IC.GT.N) GO TO 308
      GO TO 200
308   CONTINUE
      RETURN
1001   WRITE(6,234)
234 FORMAT(45HRECOMBINATION VELOCITY OF ZERO NOT ALLOWED         )
      END

      SUBROUTINE MOBIL(XMUN,XMUP)
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
C
C
      REAL LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2
C
C MOBILITY OF ELECTRONS
      RQ=2./3.
      BB1=A1*T*T/(NA**RQ)
      D=NA*BB1*(1.-.5*BB1)
      X1=AO*(T**1.5)/D
      ZZ=-A3*ALOG(T)
      CALL EXPON(ZZ,ANS)
      X2=A2*ANS
      R=1./X2 + 1./X1
      XMUN=1./R
C MOBILITY OF HOLES
      ZZZ=-B3*ALOG(T)
      CALL EXPON(ZZZ,ANS)
      X1=B2*ANS
      BB1=B1*T*T/(ND**RQ)
      D=ND*BB1*(1.-.5*BB1)
      X2=BO*(T**1.5)/D
      R=1./X2  +1./X1
      XMUP=1./R
      RETURN
      END
```

```
      SUBROUTINE WIDTH(VOLTS)
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  KB,KBTG,LAMBDA,LN,LP,MUN,MUP,NA,ND,NI,NIA1,NIA2
C
      ABC=(1./ND  +  1./NA)
      W2=(2.*EPSO*(8.85E-14)/Q)*(VBI-VOLTS)*ABC
      W=SQRT(W2)
      RETURN
      END

      SUBROUTINE SPEC
C
C  CALCULATE  SPECTRAL  RESPONSE
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK3/EPSO,AO,A1,A2,A3,BO,B1,B2,B3,EGGO,ALPHAO,BETAO
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK9/SPTOP,SNBOT
C
      REAL  LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2
C
      DIMENSION  WAV(200),SSP(200),SSN(200),SR(200)
C
      SPTOP=-1.
      SNBOT=-1.
      I=0
90    I=I+1
      E=EGGO-.15+.025*(I-1)
      IF((E.GT.5.0).OR.(I.GT.200))GO  TO  100
      WAV(I)=1.2402/E
      FFF=WAV(I)*Q*POW*(5.03306E21)*(1-RE)
      PIN=2*B*H*POW*1000.
      CALL  SHORT(S1P,S1N,E)
      SSN(I)=S1N*FFF/PIN
      SSP(I)=S1P*FFF/PIN
       SR(I)=SSN(I)+SSP(I)
      GO TO 90
100  CONTINUE
      MAX=I-1
       I=I-1
C      NORMALIZE SPECTRAL  RESPONSE
      XMAX=0.
      DO  110  K=1,MAX
      IF(SR(K).GT.XMAX)XMAX=SR(K)
110  CONTINUE
      DO  120  K=1,MAX
```

```
      SSN(K)=SSN(K)/XMAX
      SSP(K)=SSP(K)/XMAX
      SR(K)=SR(K)/XMAX
      IF(SSN(K) .GT. SNBOT) SNBOT=SSN(K)
      IF(SSP(K) .GT. SPTOP) SPTOP=SSP(K)
120   CONTINUE
C  PLOT  GRAPH
      CALL  GRAPH(WAV,SSN,SSP,SR,I)
      RETURN
      END

      SUBROUTINE  GRAPH(WAV,SN,SP,SR,I)
      DIMENSION  WAV(200),SN(200),SP(200),SR(200)
      CALL  CALPLT(1.5,.75,-3)
      XPG=5.0
      XDV=10.0
      XTIC=.5
      YPG=5.0
      YDV=10.0
      YTIC=.5
      CALL  ASCALE(WAV,XPG,I,1,XDV)
      CALL  ASCALE(SR,YPG,I,1,YDV)
      CALL  AXES(0.,0.,0.,XPG,0.0,WAV(I+2),-XTIC,XDV,
     120HWAVELENGTH  (MICRONS)  ,.14,-20)
      CALL  AXES(0.,0.,90.,YPG,0.0,.2,-YTIC,YDV,
     1  28HNORMALIZED  SPECTRAL  RESPONSE  ,.14,28)
      SFX=1./WAV(I+2)
      SFY=5.0
      CALL  CALPLT(WAV(1)*SFX,SN(1)*SFY,3)
      DO  100  J=1,I
      CALL  CALPLT(WAV(J)*SFX,SN(J)*SFY,2)
100   CONTINUE
      CALL  CALPLT(WAV(1)*SFX,SP(1)*SFY,3)
      DO  101  J=1,I
      CALL  CALPLT(WAV(J)*SFX,SP(J)*SFY,2)
101   CONTINUE
      CALL  CALPLT(WAV(1)*SFX,SR(1)*SFY,3)
      DO  103  J=1,I
      CALL  CALPLT(WAV(J)*SFX,SR(J)*SFY,2)
103   CONTINUE
      CALL  CALPLT(0.,6.,-3)
       RETURN
       END

      SUBROUTINE  SHORT(S1P,S1N,E)
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,S0,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKK0,MUN,MUP,TAUN,TAUP,DN,DP,PHI0,NI,LN,LP,VBI
      COMMON/BLK6/PI,PI2,Q,ZJ,T,T0,NIA1,NIA2,TN0,TP0,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,KB,KBTG,NIA1,NIA2
C
```

```
C CALCULATES THE SPECTRAL RESPONSE COMPONENTS
C  CALCULATES  DOUBLE  SUMMATION  OVER  I,J
      CALL  ABSORP(E,ALP1)
      ALPHA=ALP1
      S1P=0   $   S1N=0
      DO  10  I=1,NEIGV
      DO  20  J=1,NEIGV
      CALL  NUMBS(I,J,SNIJ,SPIJ)
      S1P=S1P+SPIJ
      S1N=S1N+SNIJ
20   CONTINUE
10   CONTINUE
      RETURN
      END

      SUBROUTINE DCURENT(IO)
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(50),XIN(50),XIP(50),ETAP(50),XN(50),XP(50)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  NNO,NPO,LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2
      REAL  KB,KBTG,IO,NN,NP
C
      Y1(X,Z)=Z*COSH(X)+SINH(X)
      Y2(X,Z)=Z*SINH(X)+COSH(X)
      Y3(X,Z)=(Z+TANH(X))/(1+Z*TANH(X))
C  DOPING  DENSITIES
      PPO=NA
      NNO=ND
      NPO=NI*NI/PPO
      PNO=NI*NI/NNO
      SUM1=0   $   SUM2=0
      DO  10  I=1,NEIGV
      DO  20  J=1,NEIGV
       DEN2=(ETAP(J)/B)**2  +(XIP(I)/A)**2
       GIJ2=LP*LP/(1.+LP*LP*DEN2)
       GIJ=SQRT(GIJ2)
      DEN3=(XIN(I)/A)**2  +(ETAN(J)/B)**2
      SIJ2=LN*LN/(1.+LN*LN*DEN3)
      SIJ=SQRT(SIJ2)
      NP=SP*GIJ/DP   $   NN=SN*SIJ/DN
      UJNNORM=A+(SO*A*A/DN)*(COS(XIN(J))/XIN(J))**2
      VINNORM=B+(S1*B*B/DN)*(COS(ETAN(I))/ETAN(I))**2
      F1=SIN(XIN(J))    $    F2=SIN(ETAN(I))
      HP=H-ZJ-W
      F3=16*A*A*B*B*Q*DN*NI*NI/(NA*SIJ)
      F4=(F1/XIN(J))**2   $   F5=(F2/ETAN(I))**2
      F6=1./(UJNNORM*VINNORM)
      TERMN=F3*F4*F5*F6*Y3((HP/SIJ),NN)
      UJPNORM=A+(SO*A*A/DP)*(COS(XIP(J))/XIP(J))**2
```

```
      VIPNORM=B+(S1*B*B/DP)*(COS(ETAP(I))/ETAP(I))**2
      F1=SIN(XIP(J))   $  F2=  SIN(ETAP(I))
      G3=16*A*A*B*B*Q*DP*NI*NI/(ND*GIJ)
      G4=(F1/XIP(J))**2   $   G5=(F2/ETAP(I))**2
      G6=1./(UJPNORM*VIPNORM)
      TERMP=G3*G4*G5*G6*Y3((ZJ/GIJ),NP)
      SUM1=SUM1+TERMN
      SUM2=SUM2+TERMP
20   CONTINUE
10   CONTINUE
      IO=SUM1+SUM2
      RETURN
      END

       SUBROUTINE  NUMBS(I,J,SNIJ,SPIJ)
C
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(50),XIN(50),XIP(50),ETAP(50),XN(50),XP(50)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,FI@2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
C
      REAL  LAMBDA,NA,ND,MUN,MUP,NI,LN,LP,NIA1,NIA2,KB,KBTG
C ***********************************************************
C
C
       WJPNOR=.5*ZJ-.25*ZJ*SIN(2*XP(J))/XP(J)
       DEN2=(ETAP(I)/B)**2  +(XP(J)/ZJ)**2
       GIJ2=LP*LP/(1.+LP*LP*DEN2)
       GIJ=SQRT(GIJ2)
       VIPNOR=B+(SO*B*B/DP)*(COS(ETAP(I))/ETAP(I))**2
        HP=H-ZJ-W
       WJNNOR=.5*HP-.25*HP*SIN(2*XN(J))/XN(J)
      VINNOR=B+(S1*B*B/DN)*(COS(ETAN(I))/ETAN(I))**2
      DEN3=(XN(J)/HP)**2  +(ETAN(I)/B)**2
      SIJ2=LN*LN/(1.+LN*LN*DEN3)
      SIJ=SQRT(SIJ2)
       XLAMJ=XP(J)/ZJ
      SPI1=4*B*B*XLAMJ/WJPNOR
      SPI2=ZJ*(1-COS(XP(J)))/XP(J)
      SPI3=(SIN(ETAP(I))/ETAP(I))**2
      CC=ALPHA*ALPHA*GIJ2-1
      AA=A
      AALP=ALPHA
      DPP=DP
      SSO=SO
      DD=GIJ/CC
      CALL  INTEG(AA,AALP,GIJ,CC,DPP,SSO,SPI4)
      SPIJ=ALPHA*SPI1*SPI2*SPI3*SPI4/(VIPNOR)
C ************************************************************
      SNI1=4*B*B
      XLAMJ=XN(J)/HP
      SNI2=HP*(1-COS(XN(J)))/XN(J)
```

```
      SNI3=(SIN(ETAN(I))/ETAN(I))**2
      EE=ALPHA*ALPHA*SIJ2-1
      SSO=S1
      DPP=DN
      SNI4=XLAMJ/WJNNOR
      CALL  INTEG(AA,AALP,SIJ,EE,DPP,SSO,SNI5)
      SNIJ=ALPHA*SNI1*SNI2*SNI3*SNI4*SNI5/(VINNOR)
      RETURN
      END

       SUBROUTINE  INTEG(AA.AALP,GIJ,CC,DP,SO,SPI4)
       ARG1=2*AA/GIJ
       ARG2=2*AA*AALP
       CALL  EXPON(-ARG2,ARG3)
       ARG4=1-ARG3   $   ARG5=1+ARG3
       ARG6=GIJ**4
      DP2=DP*DP
      GIJ2=GIJ*GIJ
      SO2=SO*SO
      IF(AALP.LE.0)GO  TO  200
       A11=-2*SO*GIJ2/(AALP*DP)
       A12=AALP*SO*ARG6/DP
       A13=SO2*ARG6/(DP2)
       A1=((A11+A12)*ARG4+A13*ARG5)/CC
C      CC=ALPHA*ALPHA*GIJ2-1
       B11=-GIJ*(1+SO2*GIJ2/(DP2))/AALP
       B12=AALP*(GIJ**3)
       B13=SO*(GIJ**3)/DP
       B1=((B11+B12)*ARG4+B13*ARG5)/CC
       C11=-SO*AALP*ARG6/DP
       C12=-SO2*ARG6/(DP2)
       C1=(C11*ARG4+C12*ARG5)/CC
50    B=(1./GIJ)+(SO2*GIJ/(DP2))
       A=2*SO/DP
       R=TANH(ARG1)
       IF(ARG1.GT.700)  GO  TO  100
       SPI4=(A1+B1*R+C1/COSH(ARG1))/(A+B*R)
       RETURN
100   SPI4=(A1+B1*R)/(A+B*R)
       RETURN
200    CONTINUE
      A11=-4*SO*GIJ2*AA/DP
      A12=2*SO2*ARG6/DP2
      A1=(A11+A12)/CC
      B11=-GIJ2*(1+SO2*GIJ2/DP2)*2*AA
      B12=SO*GIJ*GIJ2*2/DP
      B1=(B11+B12)/CC
      C1=-SO2*ARG6*2/(DP2*CC)
      GO TO 50
       END
```

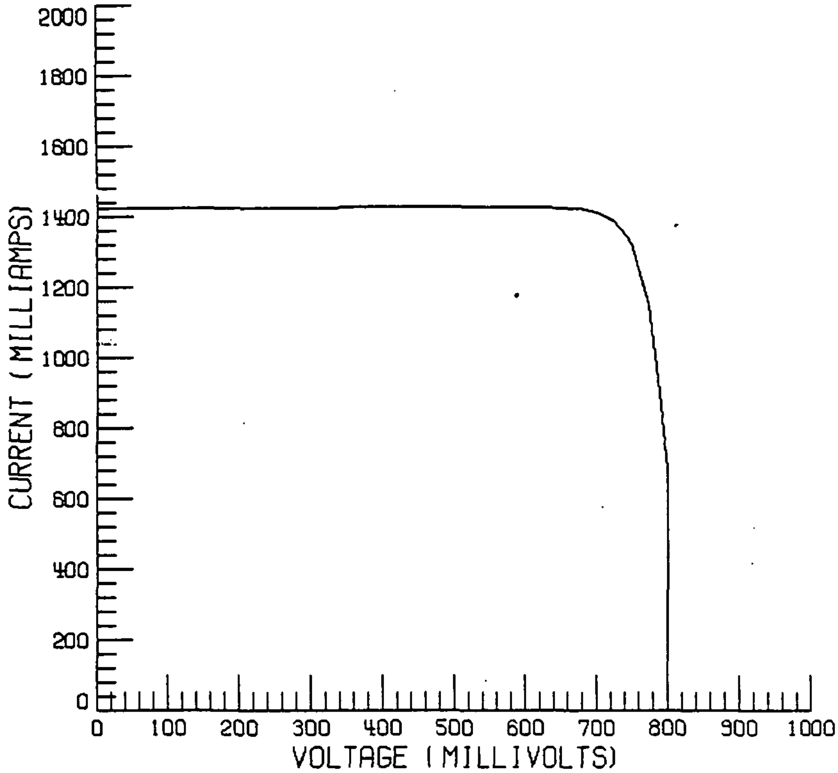
```
      FUNCTION FUN(X)
      IF(X.LT.-230)GO TO 10
      FUN=EXP(X)
      RETURN
10    FUN=0
      RETURN
      END

      SUBROUTINE IV(WAVE)
C
C  CALCULATE CURRENT-VOLTAGE CURVE
C
C
      COMMON/BLK2/POW,LAMBDA,NA,ND,B4,SN,SP,SO,S1,RE,RS,RSH,A,B,H
      COMMON/BLK4/XKKO,MUN,MUP,TAUN,TAUP,DN,DP,PHIO,NI,LN,LP,VBI
      COMMON/BLK5/ETAN(50),XIN(50),XIP(50),ETAP(50),XN(50),XP(50)
      COMMON/BLK6/PI,PI2,Q,ZJ,T,TO,NIA1,NIA2,TNO,TPO,W,ALPHA
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      COMMON/BLK8/VOC,PMAX,EFF,ISC
C
C
      DIMENSION AMPS(100),VOLTS(100)
      REAL IREC,IB,IO,ISC,I
      REAL LAMBDA,NA,ND,LN,LP,MUP,MUN,NIA1,NIA2,KB,KBTG,NI
C CALCULATE IV CURVE
      FFF=Q*PHIO*(1-RE)
      E=1.2402/WAVE
      ICOUNT=0       $ PMAX=-.5
      DELVO=.0125
      DELV=.025
      V=-DELV
100   CONTINUE
      ICOUNT=ICOUNT+1
      V=V+DELV
      CALL WIDTH(V)
C CALCULATE ISC (LIGHT CURRENT)
      CALL SHORT(S1P,S1N,E)
       YA1=FFF*S1P
       YA2=FFF*S1N
       ISC=YA1+YA2
C CALCULATE DARK CURRENT
       CALL DCURENT(IO)
       IREC=4*A*B*Q*NI*W*PI2*2*SINH(V/(2*KBTG))
       IREC=IREC/((VBI-V)/KBTG)
       IREC=IREC/SQRT(TAUN*TAUP)
C SOLVE FOR I
       U1=1+RS/RSH
       U=.999
       IB=ISC-IREC-V/RSH+IO
        VOLTS(ICOUNT)=V*1000
110   CONTINUE
       Z=(V+U*IB*RS)/KBTG
       F=IB*U*U1-IB+IO*EXP(Z)
       FP=IB*U1+IO*(RS*IB/KBTG)*EXP(Z)
       U2=U-F/FP
```

```
      ERROR=ABS(U2-U)
      IF(ERROR.LT.1.0E-6) GO TO 120
      U=U2
      GO TO 110
120   I=U2*IB
      AMPS(ICOUNT)=I*1000
      WRITE(6,99)ISC,IO,IREC,V,YA1,YA2
99    FORMAT(1X,6E15.7)
      P=I*V
      IF(P.GT.PMAX)PMAX=P
      IF((I.LT.0).OR.(VBI.LT.(V+DELV)))GO TO 130
      IF(V.GT..85) DELV=DELVO
      GO TO 100
130   AMPS(ICOUNT)=0.
      PIN=POW*1000*2*B*H
      VOC=KBTG*ALOG(1.+(ISC-IREC)/IO)
      EFF=PMAX*100/PIN
      IF(ICOUNT .GT. 1) VOLTS(ICOUNT)=VOLTS(ICOUNT-1)+DELV/100.
      IF(ICOUNT .EQ. 1) VOLTS(ICOUNT)=VOC
      CALL GRAPHIV(VOLTS,AMPS,ICOUNT)
      CALL NFRAME
      RETURN
      END

      SUBROUTINE GRAPHIV(X,Y,I)
      DIMENSION X(100),Y(100)
      COMMON/BLK7/NEIGV,KB,KBTG,XGRAPH
      XPG=5.0
      XDV=10.
      XTIC=.5
      YPG=5.0
      YDV=10.0
      YTIC=.5
      CALL ASCALE(X,XPG,I,1,XDV)
      CALL ASCALE(Y,YPG,I,1,YDV)
      CALL AXES(0.,0.,0.,XPG,0.0,X(I+2),-XTIC,XDV,
     1 20HVOLTAGE (MILLIVOLTS) ,.14,-20)
      CALL AXES(0.,0.,90.,YPG,0.0,Y(I+2),-YTIC,YDV,
     1 19HCURRENT (MILLIAMPS) ,.14,19)
      SFX=1./X(I+2)
      SFY=1./Y(I+2)
      CALL CALPLT(X(1)*SFX,Y(1)*SFY,3)
      DO 100 J=1,I
      CALL CALPLT(X(J)*SFX,Y(J)*SFY,2)
100   CONTINUE
      CALL CALPLT(0.,6.,-3)
      CALL CHARACT(0.0,0.0,.1,5HGRAPH,0.0,5)
      CALL WHERE(XX,YY,IXX)
      CALL NUMBER(XX+.07,0.,.1,XGRAPH,0.0,-1)
      CALL NFRAME
      RETURN
      END
```

a)



b)

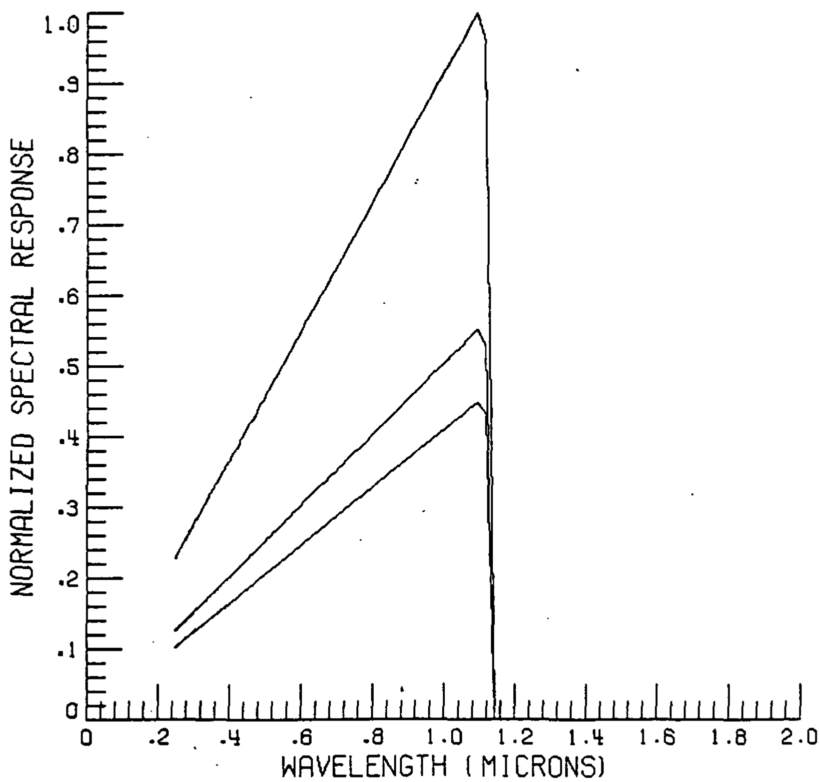


FIGURE D1. Representative output from the program "VSC3D" illustrating the spectral response, the current-voltage relation and contour plots of the current density in the planes $Z=Z_j$ and $Z=Z_j+W$.

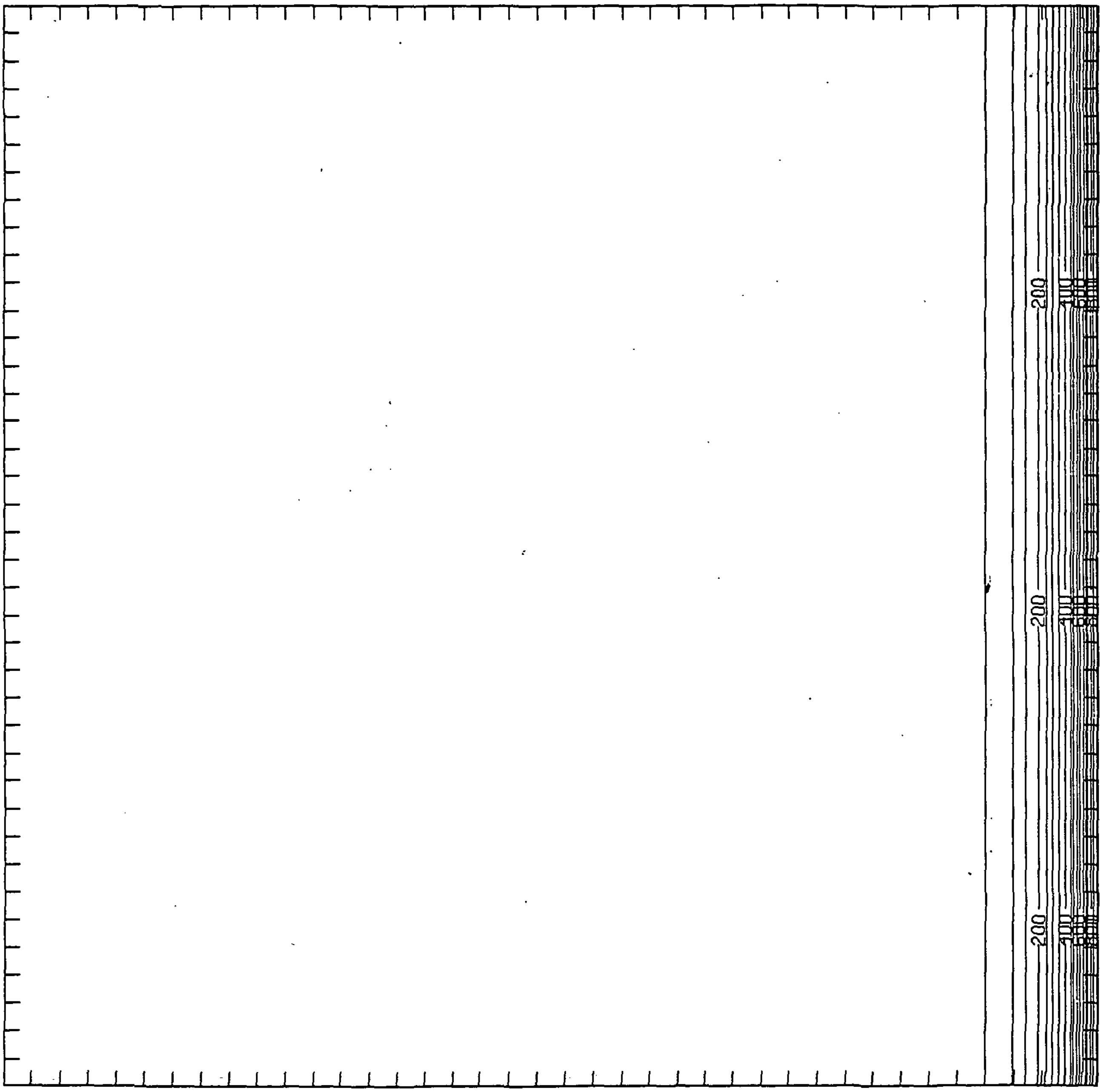


FIGURE D1. (c) Contour plot of current density in plane Z_j. $J_p(x,y)$ = constant.

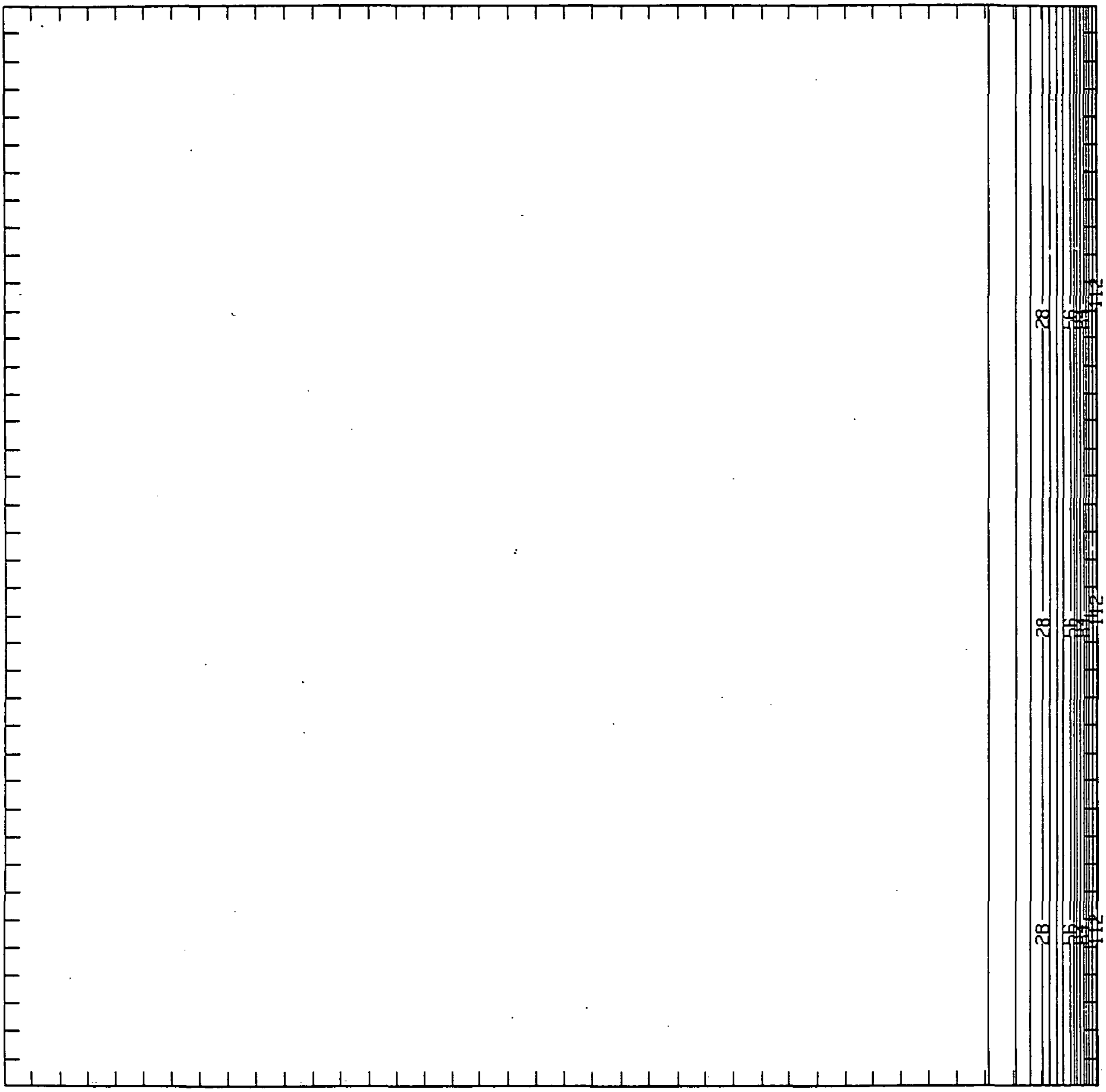


FIGURE D1. (d) Contour plot of current density in plane Z_j+W. $J_n(x,y)$ = constant.