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Mattis, Richard L/A BASIC program for ca  
QC100 .U57 NO.400-. 11. 1975 C.2 NBS-PUB

**NBS SPECIAL PUBLICATION**

**400-11**

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

*Semiconductor Measurement Technology:*

# A BASIC Program for Calculating Dopant Density Profiles from Capacitance-Voltage Data

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*Semiconductor Measurement Technology:*  
**A BASIC Program for Calculating Dopant Density Profiles  
from Capacitance-Voltage Data**

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2. Special publication no. 400-11

This activity was supported by  
The Defense Advanced Research Projects Agency  
under ARPA Order 2397, Program Code 4D10



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U.S. DEPARTMENT OF COMMERCE, Rogers C. B. Morton, *Secretary*  
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

Issued June 1975

**Library of Congress Cataloging in Publication Data**

Mattis, Richard L.

A BASIC Program for Calculating Dopant Density Profiles from Capacitance-Voltage Data.

(Semiconductor Measurement Technology) (National Bureau of Standards Special Publication; 400-11)

Supt. of Docs. No.: C 13.10:400-11

1. Electronic Data Processing—Ion Implantation. 2. Electronic Data Processing—Diodes, Semiconductor. 3. Electronic Data Processing—Electric Measurements. 4. BASIC (Computer Program Language) I. Buehler, Martin G., joint author. II. United States. National Bureau of Standards. III. Title. IV. Series. V. Series: United States. National Bureau of Standards. Special Publication; 400-11. QC100.U57 No. 400-11 [TK7871.85] 389'.08s

[621.3815'.2'028] 75-619089

**National Bureau of Standards Special Publication 400-11**

Nat. Bur. Stand. (U.S.), Spec. Publ. 400-11, 39 pages (June 1975)

CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE  
WASHINGTON: 1975

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For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402  
(Order by SD Catalog No. C13.10:400-11). Price \$1.00 (Add 25 percent additional for other than U.S. mailing.)

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## PREFACE

This work was carried out as a part of the Semiconductor Technology Program in the Electronic Technology Division at the National Bureau of Standards. The Semiconductor Technology Program serves to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. The Program receives direct financial support principally from three major sponsors: The Defense Advanced Research Projects Agency (ARPA), The Defense Nuclear Agency (DNA) and the National Bureau of Standards. The specific work reported herein was supported by ARPA.\*

The computer program CV1, the subject of this report, is derived from a program reported by D. B. DeVries, G. Lee, and S. Watelski in Integrated-Circuit Process Control and Development, Technical Report AFAL-TR-73-268, August 1973. The present program contains improvements in the peripheral capacitance correction, the error function calculations, the numerical integration, the plot routine, and data input/output. The present report is intended as a guide for persons using the program described herein. It is not intended to provide a detailed comparison of the present and the original programs.

The authors are indebted to several persons who assisted in the editing and preparation of this report. Gerard N. Stenbakken performed a critical and constructive reading of the text. The several figures were prepared by Edgar C. Watts and Leo R. Williams. The typing of the final draft was done by Frances C. Butler.

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\* Through ARPA Order 2397, Program Code 4D10.





A BASIC Program for Calculating Dopant Density  
Profiles from Capacitance-Voltage Data

by

Richard L. Mattis and Martin G. Buehler

*Abstract:* A computer program is presented which is suitable for calculating dopant density vs. depth profiles from capacitance-voltage data for the case of a Gaussian-diffused  $p$ - $n$  junction diode. The program includes corrections for peripheral capacitance of round or rectangular diodes and back depletion of the space-charge region into the diffused layer. Inputs to the program consist of the surface dopant density, the junction depth, the background dopant density in the diffused layer, the junction diameter, three scaling parameters, and the capacitance-voltage data pairs. Output from the program is in the form of a plot and an optional listing of dopant density as a function of depth. The equations underlying the program are given and are related to the program whose operation is described in detail. A second program, for generating idealized capacitance-voltage data for a Gaussian-diffused diode on material with a constant dopant density is also included.

*Key Words:* BASIC; capacitance-voltage measurements; computer programs; dopant profiles; error function; Gaussian diffusion; plotting, computer; semiconductors; silicon.

## 1. INTRODUCTION

The capacitance-voltage (C-V) method is widely used to measure dopant density versus depth profiles of semiconductor specimens [1-4]. The basic equations for calculating dopant density  $N(W)$  as a function of depletion width  $W$  were derived by Schottky [5] and are suitable for the case of a large area one-sided abrupt junction diode under reverse bias conditions. However, in many cases the dimensions of the diode are not large compared with the depletion width, so the peripheral capacitance can cause a significant error in the calculated dopant density profile. Similarly, when the diffused layer dopant density is not large compared to the dopant density of the region to be profiled, back depletion into the diffused layer can cause significant error in the calculated dopant density profile [6].

A computer program, henceforth denoted CV1 for convenience and listed in Appendix A, is presented. It is suitable for calculating dopant density versus depth profiles from C-V data for the case of a Gaussian-diffused  $p$ - $n$  junction diode. The case of a Gaussian diffusion is treated because of its common usage in the semiconductor industry. Program CV1 is not intended for profiling junctions which are part of transistors or other multi-junction structures. The program has not yet been satisfactorily tested on diodes diffused in epitaxial material in which the layer and substrate are of opposite conductivity type; the program has been proven, however, on diodes diffused in epitaxial material in which the layer and substrate are of the same conductivity type and on diodes diffused in bulk material. Program CV1 is not intended to take into account the effects of diffusion capacitance which occur under heavy forward bias conditions; it is recommended that caution be exercised in interpreting any data taken in forward bias conditions. The program includes corrections for peripheral capacitance of round and rectangular diodes and back depletion of the space-charge region into the diffused layer. Inputs to the program consist of the surface dopant density, the junction depth, the background dopant density in the diffused layer, the junction diameter, three scaling parameters, and the C-V data pairs. Output from the program is in the form of a plot and an optional listing of dopant density as a function of depth.

The equations underlying program CV1 are given in section 2 along with a somewhat expanded discussion relating to the calculation of the complementary error function and its inverse. The program is described in detail in section 3. In section 4, program modifications and check-out are presented, including the discussion of a second computer program which generates idealized C-V data for the case of a Gaussian-diffused junction diode fabricated in material of constant background dopant density. For convenience, this second program is henceforth denoted CV2.

The programs described in this report are written in the BASIC language. A description of the BASIC language can be found in several books [7-9]. However, when using the programs described below the reader must be alert to the particular characteristics of the BASIC he may be using. The particular type of BASIC employed in the programs described in this report is applicable to a time-sharing system, has a six decimal place precision, can handle positive and negative numbers in the range  $10^{38}$  to  $10^{-38}$ , and can accommodate programs as long as 256 lines plus comment statements. This particular BASIC is compatible with most of the BASIC in use. However, some of its characteristics are worthy of comment to avoid possible confusion. These are described in Appendix B.

## 2. EQUATIONS

In this section, the equations which are employed to calculate the dopant density profile from the experimental C-V data are given. These equations relate to the peripheral correction, the back depletion correction and the calculation of the complementary error function and its inverse.

### 2.1. The Peripheral Correction

The Schottky equations for calculating dopant density  $N(W)$  and depletion width  $W$  have been referred to above and are given below as eqs (1) and (2),

$$N(W) = \frac{2}{q\kappa\epsilon_0 A_j^2} \left[ \frac{d}{dV} \left( \frac{1}{C_m^2} \right) \right]^{-1} \quad (1)$$

$$W = \frac{\kappa\epsilon_0 A_j}{C_m} \quad (2)$$

where  $q$  is the electronic charge,  $\kappa$  is the relative dielectric constant of the test specimen,  $\epsilon_0$  is the permittivity of free space,  $A_j$  is the area of the diode,  $C_m$  is the measured capacitance and  $V$  is the applied voltage. In program CV1, the peripheral capacitance is first subtracted from the measured capacitance [10-13]. The peripheral capacitance calculation for a circular diode can be written as

$$C_{pt} = \frac{\kappa\epsilon_0 \pi^2 D/2}{\ln \left[ \left( 1 + \frac{W}{x_j} \right) / \left( 1 + \frac{4W}{\pi D + 4x_j} \right) \right]} \quad (3)$$

where  $D$  is the diode diameter and  $x_j$  is the junction depth. The corrected or plane capacitance,  $C$ , is then given by

$$C = C_m - C_{pt} \quad (4)$$

Equation (3) was derived by assuming that the peripheral region is a one sided junction. After the plane capacitances have been determined, an apparent profile  $N(W)$  vs.  $W$  is calculated using eqs (1) and (2).

### 2.2. The Back Depletion Correction

The back depletion correction [10] is based on eqs (5) through (10) below:

$$N(A) = N_0 \exp \left[ - \left( \frac{x_j - A}{L} \right)^2 \right] - N_b \quad (5)$$

$$L = \frac{x_j}{\sqrt{\ln \frac{N_0}{N_b}}} \quad (6)$$

$$\operatorname{erfc} \left( \frac{x_j - A}{L} \right) = \operatorname{erfc} \left( \frac{x_j - A + W}{L} \right) + \frac{2}{\sqrt{\pi}} \frac{N_b W}{N_0 L} \quad (7)$$

$$\frac{1}{N(W)} = \frac{1}{N(A)} + \frac{1}{N(B)} \quad (8)$$

$$I = \int_0^W N(w) dw = \int_0^A N(a) da \quad (9)$$

$$\int_0^A N(a) da = \frac{\sqrt{\pi} L N_0}{2} \left[ \operatorname{erfc} \left( \frac{x_j - A}{L} \right) - \operatorname{erfc} \left( \frac{x_j}{L} \right) \right] - N_b A \quad (10)$$

As shown in figure 1, A is the depletion width on the heavily-doped side of the junction, B is the depletion width on the lightly-doped side of the junction, N(A) and N(B) are the respective net dopant densities at distances A and B from the junction, N<sub>0</sub> is the dopant density at the surface of the diffused layer, and N<sub>b</sub> is the estimated background dopant density in the diffused layer. The characteristic length of the Gaussian diffusion is represented by L, and I is the area of either of the two shaded regions in figure 1. The lower case w and a are used as variables of integration; whereas, upper case W and A represent specific values of w and a. The quantities W, A and B are related by eq (11).

$$W = A + B \quad (11)$$

In computer program CV1, the integral on the left in eq (9) is calculated by numerical integration of the N(W) vs. W data. Equation (7) is used in calculating the first step in the numerical integration and the trapezoidal approximation is used in subsequent steps. The value of this integral, I, is used to solve eq (10) for A. Knowing A, N(A) is calculated from eq (5), N(B) is calculated from eq (8) and B is calculated from eq (11). The desired profile is a plot or listing of N(B) vs. B.

Equation (12) below is used to calculate a true Gaussian profile for comparison with the experimentally determined profile.

$$N(B) = N_b - N_0 \exp \left[ - \left( \frac{x_j + B}{L} \right)^2 \right] \quad (12)$$

Experimental profiles sometimes show a decrease in N(B) for small B. A plot of the true Gaussian profile can be helpful in determining whether such an experimental observation is caused by the diffusion tail or by some other phenomenon. The true Gaussian plot is also helpful in evaluating the adequacy of the assumed N<sub>b</sub> value. If the experimental plot and the true Gaussian plot do not asymptotically approach the same background density, the calculation should perhaps be repeated using a different assumed N<sub>b</sub> value.

### 2.3. The Complementary Error Function

The solution of eqs (7) and (10) calls for calculating the complementary error function and its inverse. The calculation of the complementary error function employs equations given by Stegun and Zucker [14] as

$$\operatorname{erf}(x) = \frac{2x}{\sqrt{\pi}} e^{-x^2} \sum_{N=0}^{\infty} \frac{(2x^2)^N}{1 \cdot 3 \cdots (2N+1)} \quad (13)$$

$$\operatorname{erfc}(x) = 1 - \operatorname{erf}(x) \quad (14)$$

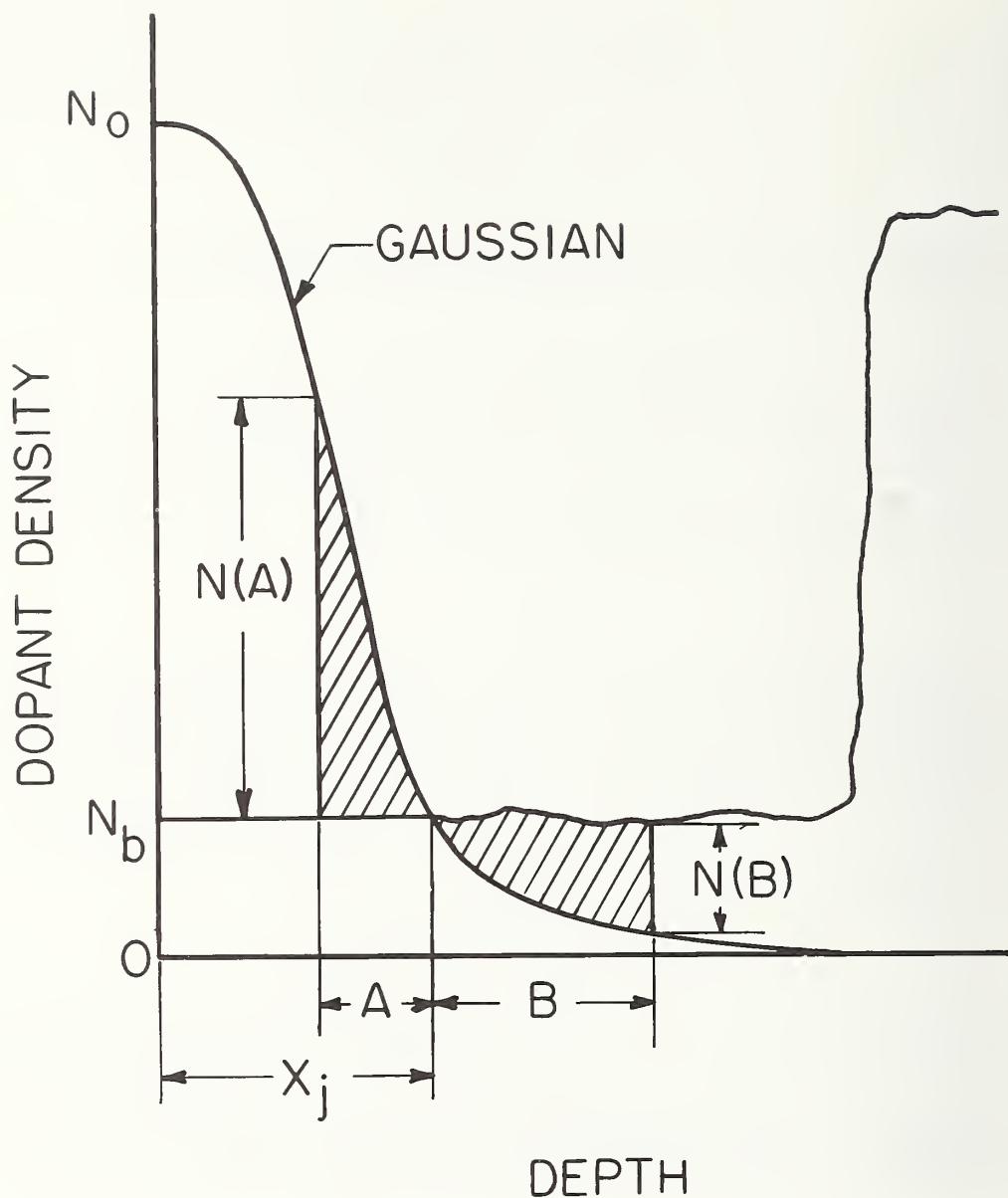


Figure 1. Schematic representation of the depletion region of a  $p$ - $n$  junction diode diffused in an epitaxial semiconductor. (The distances  $A$  and  $B$  have their origins at the junction. Note that the actual background dopant density, represented by the irregular line to the right of the junction, is assumed to be constant within the diffused layer to the left of the junction.)



$$\operatorname{erfc}(x) = \frac{e^{-x^2}}{\sqrt{\pi}} \left[ \frac{2x}{2x^2 + 1 - \frac{1 \cdot 2}{2x^2 + 5 - \frac{3 \cdot 4}{2x^2 + 9 - \dots}}} \right] \quad (15)$$

The reader is advised that eqs (13) to (15) and the software that implements them (see sec. 3.3.) have been thoroughly proven within the range of applicability. Other approximations to the error function and its complement should be used only with extreme caution. In program CV1, the power series representation of eq (13) is used when  $x \leq 1$ , and the continued fraction of eq (15) is used when  $x > 1$ .

#### 2.4. The Inverse Complementary Error Function

The inverse complementary error function is calculated by interpolation in a table of values. The equation to be solved is

$$\begin{aligned} y &= \operatorname{erfc}^{-1}(x) \\ \text{or} \quad x &= \operatorname{erfc}(y) \end{aligned} \quad (16)$$

where  $x$  is given and  $y$  is to be determined. The given variable  $x$  is first transformed using

$$z = -100 \frac{\ln(x)}{\ln(10^{-7})} + 100 \quad (17)$$

to yield a value of  $z$  from 0 to 100 corresponding to a value of  $x$  from  $10^{-7}$  to 1. The transformation is illustrated in figure 2. The  $10^{-7}$  lower limit was chosen so that eq (10) could be solved for all practical ratios of  $N_0$  to  $N_b$ . The table of values (see listing in lines 150 to 188 of Appendix A) lists those values of  $y$  corresponding to integer values of  $z$  from 1 to 100. For example, the first value in the table  $y = 3.74580$ , corresponds to  $z = 1$  or  $x = 1.17490 \times 10^{-7}$ . To calculate  $y$  from a given  $x$ ,  $z$  is first calculated and three data pairs  $(z_1, y_1)$ ,  $(z_2, y_2)$ , and  $(z_3, y_3)$  are chosen from the table such that

$$\begin{aligned} \text{and} \quad z_3 &> z \geq z_2 > z_1 \\ y_3 &< y \leq y_2 < y_1 \end{aligned} \quad (18)$$

This is illustrated in figure 3. A parabolic fit to these three data pairs is made by simultaneously solving the equations

$$\begin{aligned} y_1 &= az_1^2 + bz_1 + c \\ y_2 &= az_2^2 + bz_2 + c \\ y_3 &= az_3^2 + bz_3 + c \end{aligned} \quad (19)$$

to yield the coefficients

$$a = \frac{(y_3 - y_1)(z_2 - z_1) - (y_2 - y_1)(z_3 - z_1)}{(z_3 - z_1)(z_2 - z_1)(z_3 - z_2)} \quad (20)$$

$$b = \frac{y_2 - y_1}{z_2 - z_1} - a(z_2 + z_1) \quad (21)$$

$$c = y_1 - az_1^2 - bz_1 \quad (22)$$

Equations (20) and (21) can be simplified since  $z_2 - z_1 = 1$ ,  $z_3 - z_1 = 2$ , and  $z_3 - z_2 = 1$ . The simplified equations are

$$a = \frac{y_1 + y_3 - 2y_2}{2} \quad (23)$$

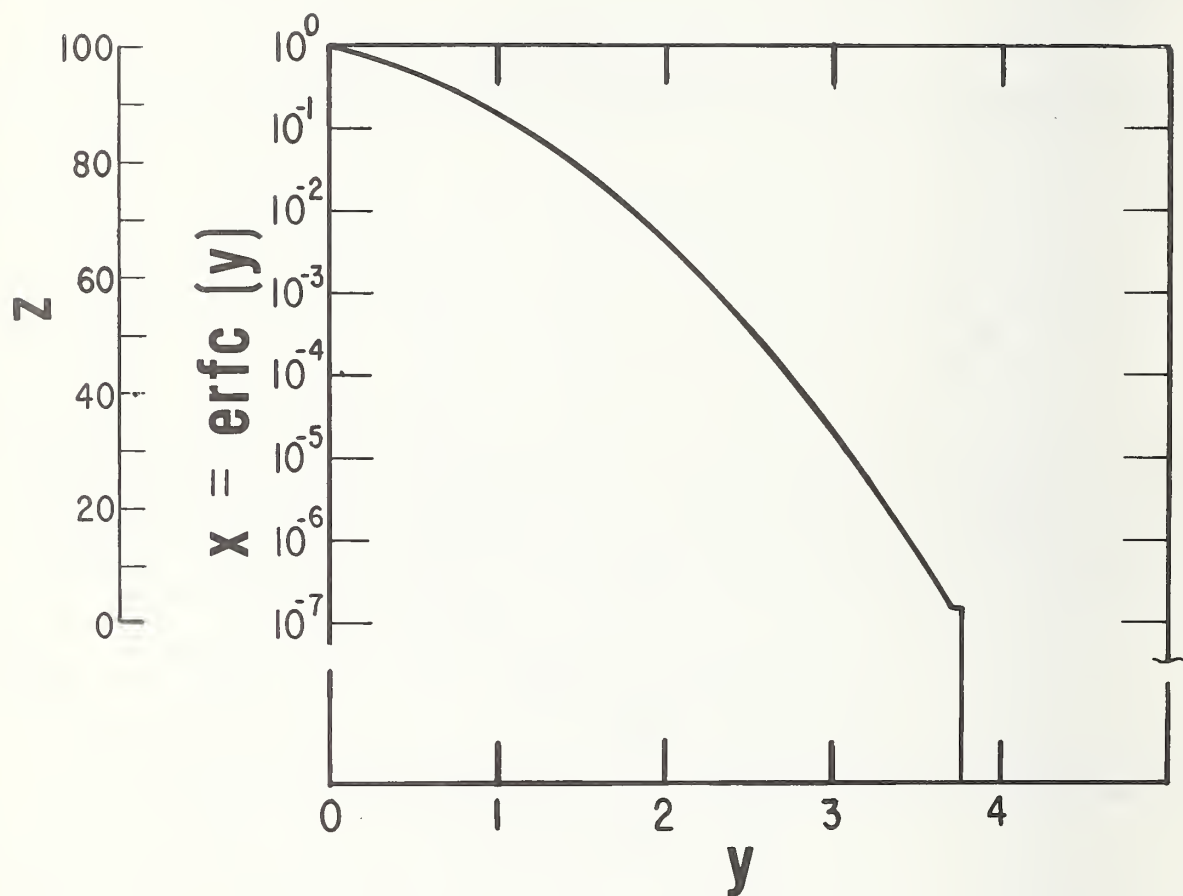


Figure 2. Semilog plot of the function  $x = \text{erfc}(y)$  showing the transformed variable  $z$ . (The discontinuity which occurs at  $z = 2$ , and the fact that  $y = 3.76656$  for  $0 \leq z < 2$  reflect the value of  $y$  calculated by the INERF subroutine rather than the true value of  $y$  as explained in sec. 3.4.)



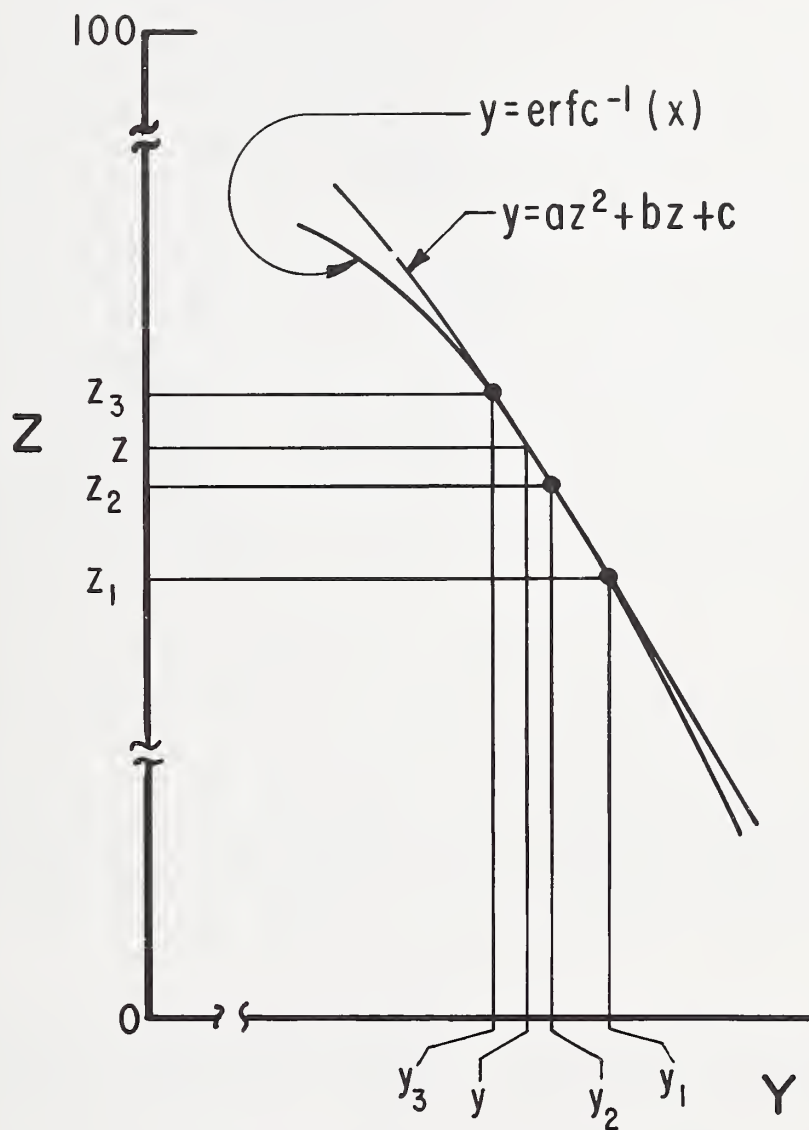


Figure 3. Calculation of  $y = \text{erfc}^{-1}(x)$  by means of a parabolic fit. (The fit is made in terms of the variable  $z$  which is calculated from the given  $x$  by eq (17).)

$$b = (y_2 - y_1) - a(z_2 + z_1) \quad (24)$$

Thus knowing a, b, and c, y can be calculated from z, the transformed value of x, by

$$y = az^2 + bz + c \quad (25)$$

### 3. PROGRAM DESCRIPTION

#### 3.1. Data Input

Two forms of data input are employed. The C-V data are read from a file which is titled CVIN. The file CVIN is entered into the computer before CV1 is executed. Each line of CVIN consists of a line number, the capacitance in picofarads, and the applied voltage in volts, where reverse bias is considered positive. Data are listed in order of decreasing capacitance. A sample CVIN file, based on data reported in [10], is given in Appendix C.

The second form of data input involves entry of scaling and diffused layer parameters as called for by INPUT statements. The program statements which request these data are lines 2514 to 2585 (see listing in Appendix A). The relevant parameters are (1) G1 or 1ST LOG, the minimum value of dopant density which is within the range of the plot (that is, the dopant density at the origin of the plot), (2) G2 or CHAR/DEC, the number of teletypewriter carriage spaces between decades of dopant density (the plot is semi-log), (3) G3 or LINES/UM, the number of teletypewriter line feeds to represent 1  $\mu$ m on the plot (all positive values are permitted), (4) D or DIAMETER, the diameter of the diode in mils, (5) X5 or JCT DEPTH, the junction depth of the diffused layer in micrometres, (6) NO or SURFACE DENS, the density of diffusant atoms at the surface of the diffused layer (as measured for instance by junction depth and sheet resistivity on a pilot slice [15]) in (centimetres)<sup>-3</sup>, and (7) N3 or ESTIMATED NB, the background dopant density within the diffused layer in (centimetres)<sup>-3</sup>. An example of such data input is given in the sample calculation of Appendix C.

#### 3.2. Data Output

Data output is in the form of a plot of dopant density versus distance from the junction, N(B) vs. B. Following this plot, final values of A and N(A) representing the maximum penetration of the depletion region into the diffused layer and the net dopant density at that point, are printed out (lines 3990 to 3992) along with the percent peripheral capacitance correction at the last data point (i.e., the maximum peripheral capacitance correction), and an indication of whether the range of the INERF subroutine has been exceeded (see sec. 3.4.). Finally a true Gaussian profile is calculated and plotted for comparison with the experimental plot. The experimental N(B) vs. B values are written into a file named NBVSB, and the numerical values of the true Gaussian plot are written into a file named IDEAL. These can be listed if desired after the program has run as is done in Appendix C.

#### 3.3. The ERF Subroutine

The ERF subroutine consists of lines 1400 to 1565 in the listing of Appendix A. When this subroutine is called it operates on the variable E, calculating  $E1 = \text{erf}(E)$  and  $J1 = \text{erfc}(E)$  where E corresponds to x in eqs (13) through (15). If  $E < 10^{-32}$ , E1 and J1 are set equal to 0 and 1 respectively (lines 1400 to 1406). If  $E > 9$ , E1 and J1 are set to equal 1 and 0 respectively (lines 1410 to 1416). If  $10^{-32} \leq E \leq 1$ , E1 and J1 are calculated from eqs (13) and (14). In lines 1430 to 1434 the first 10 terms (to N = 9) of the power series are summed. Additional terms would contribute to the seventh and higher significant figures which is beyond the range of BASIC. In line 1440 the series is multiplied by the pre-factor indicated in eq (13) to get  $E1 = \text{erf}(E)$ .

If  $9 \geq E > 1$ ,  $J1 = \text{erfc}(E)$  is calculated from eq (15). The first approximation to the continued fraction is of the form  $2x/(2x^2 + 1)$ , as calculated in lines 1500 to 1508 and represented by F5. A second approximation to the continued fraction includes the term  $2x^2 + 5$  in eq (15) and is calculated in lines 1510, 1512, and 1520 to 1526 and represented by F9. The first and second approximations are compared in lines 1528 and 1530. If the first and second approximations differ by 1 part in  $10^6$  or more, a third approximation is calculated in lines 1538 to 1546 and 1520 to 1526 to include the term  $2x^2 + 9$  in eq (15). The second and third approximations are then compared to determine whether the continued fraction has converged.

Continued iterations are made, each time comparing the present with the previous approximation, until a relative difference of less than 1 part in  $10^6$  is obtained. In line 1550 the continued fraction is multiplied by the pre-factor indicated in eq (15) to get  $J1 = \text{erfc}(E)$ .

Each approximation of the continued fraction is expressed as a quotient of two expressions (line 1526). As the order of the approximation increases, the number of terms which are multiplied together to construct the two expressions increases. The two expressions could become excessively large and cause overflow. This is prevented by dividing several terms by  $E3 = 10^{25}$  whenever the denominator of this quotient exceeds  $10^{25}$ . This is done in lines 1532 to 1537. The division by this scale factor does not affect the result since it is applied to both numerator and denominator of the quotient.

#### 3.4. The INERF Subroutine

The INERF subroutine consists of lines 1000 to 1080 in the listing of Appendix A. When this subroutine is called, it operates on the variable H9 and calculates  $E = \text{erfc}^{-1}(H9)$  by a table look-up approach. Note that H9 in the program corresponds to  $x$  in eq (16) and  $E$  corresponds to  $y$ . If  $H9 > 1$  ( $x > 1$  in figure 2) the inverse complementary error function is not defined;  $E$  is set equal to zero and the flag Z5 (which is printed when the main program is run) is set equal to 2 (lines 1000 to 1003). If  $H9 = 1$ ,  $E$  is set equal to zero (lines 1004 to 1007). The transformed variable H0 which corresponds to  $z$  is calculated in line 1010 by eq (17). If H0 is less than 2 (corresponding to H9 less than  $1.39 \times 10^{-7}$ )  $E$  is set equal to 3.76656 and flag Z5 is set equal to 1 in lines 1012 to 1018. This lower limit arises because (1) the transformation of eq (17) was defined to be applicable for  $x$  in the range  $10^{-7}$  to 1, (2) the value of  $x$  corresponding to  $z = 0$  does not appear in the data table which runs from  $z = 1$  to 100, and (3) the parabolic fit requires that  $z$  not be less than  $z_2$  (eq (18)) so that interpolation cannot be performed for values of  $x$  (H9) for which  $z$  (H0) is less than 2. Factors (2) and (3) therefore serve to make the lower limit of H9 be  $1.39 \times 10^{-7}$  rather than  $10^{-7}$ .

In lines 1020 to 1045,  $z_1, z_2, z_3, y_1, y_2$ , and  $y_3$  are defined as H1, H2, H3, H5, H6, and H7, respectively (see figure 3). The coefficients of the parabolic fit  $a, b$ , and  $c$  or I1, I3, and I4 are calculated by means of eqs (23), (24), and (22), respectively in lines 1050 to 1065. The unknown  $E$  ( $y$ ) is then calculated in line 1070 as in eq (25).

#### 3.5. The TABLE Data File

The TABLE data file consists of lines 150 to 188 in the listing of Appendix A. As discussed in sections 2.4. and 3.4. and referring to eqs (16) and (17), TABLE is a list of  $y$  ( $E$ ) values which correspond to integer values of  $z$  (H0) from 1 to 100 inclusive and which facilitate the computation of the function  $E = \text{erfc}^{-1}(H9)$  for H9 values from  $1.39 \times 10^{-7}$  to 1.

#### 3.6. The PLOT Subroutine

The PLOT subroutine consists of lines 2150 to 2460 in the listing of Appendix A. The purpose of the PLOT subroutine is to produce a semilog plot of dopant density  $N(B)$  across the paper of the teletypewriter printout versus distance from the junction B down the paper. The subroutine is also used to plot the true Gaussian profile for comparison with the experimental profile.

The PLOT subroutine can be understood with the help of the flow chart of figure 4 and the partial table of symbols in table 1. Some of the line numbers in the main program are also found in table 1. The flags Z3, Z6, and Z7 are all initially zero. The PLOT subroutine operates on the quantities X1 and Y1 which are calculated from B and N2 (where N2 corresponds to  $N(B)$ ) in lines 3240 and 3270. These in turn are derived from the C-V data (lines 3000 to 3230) in the first plot and calculated values (lines 4010 to 4050) in the second plot. The first X1, Y1 pair ( $Z6 = 0$ ) is stored as X2, Y2. The Y1 values of succeeding X1, Y1 pairs are accumulated in Y2 until an X1, Y1 pair is input for which  $X2 > X1$ , that is, which should be plotted at a farther position along the depth axis. When this occurs Y2 is averaged and integerized. If no data points have yet been plotted ( $X0 = 0$ ), + signs are printed at decade intervals along the dopant density axis and X0 is set equal to 1 before proceeding further. The depth X2 is compared with the line space on the plot X0. If  $X2 > X0$ , a series of tick marks in the form of + signs are printed along the depth axis until X0 is advanced to X2 (where the data point is to be plotted). The origin of the depth axis is the first of these

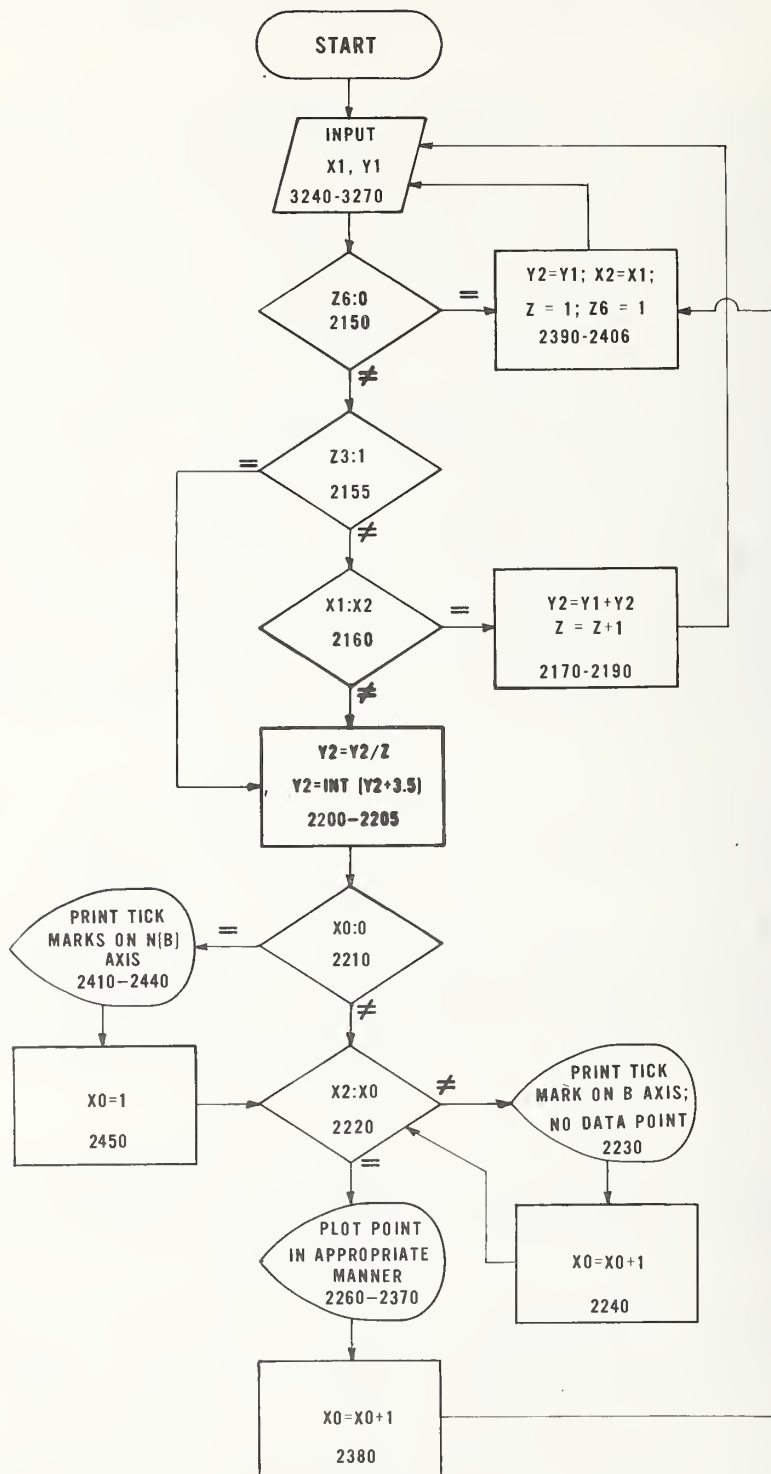


Figure 4. Flow chart of the PLOT subroutine.



Table 1 — Symbols Used in PLOT Subroutine

---

B	distance from junction into the specimen, $\mu\text{m}$
G1	minimum value of dopant density to be plotted, $\text{cm}^{-3}$
G2	scale factor for N(B); number of carriage spaces to represent one decade of dopant density
G3	scale factor for B; number of lines (line feeds) to represent 1 $\mu\text{m}$
X0	line number along the depth axis; initial value 0
X1	scaled value of B integerized for plotting purposes (line 3270)
X2	temporary storage of X1 value as further X1 values are being calculated,
Y1	scaled value of N2 (N(B))
Y2	accumulated, averaged and integerized value of Y1; accumulated as further X1 values are being calculated, averaged and integerized for plotting purposes (lines 2180, 2200 and 2205)
Z	number of data points plotted at same depth position
Z3	flag for last data point; Z3 = 1 after last data point (lines 3001, 3290, 2385), otherwise 0
Z6	flag for first data pair; Z6 = 0 for the first (X1, Y1) pair, otherwise 1
Z7	flag for experimental or true Gaussian plot; Z7 = 0 if experimental data is being plotted, 1 if true Gaussian is being plotted

---

tick marks and not the set of tick marks denoting the scale on the dopant density axis as shown in figure 5. There are six possible ways in which the data point may appear in the plot. (1) If  $Y2 < 3$ , the data point is off scale at the low end (dopant density too small); this is represented by the symbol < to the left of the tick mark preceded by the value of Z to indicate how many data points are off scale at that depth value (lines 2260 and 2310). (2) If  $Y2 > 71$ , the data point is off scale at the high end (dopant density too large); this is represented by the symbol > to the left of the tick mark preceded again by the value of Z (lines 2300 and 2370). (3) If a single X1, Y1 pair (for which  $Z = 1$ ) falls on the depth axis, an asterisk \* is printed on the axis at that depth value in place of the usual + sign (lines 2270 and 2330). (4) If an average of several X1, Y1 pairs ( $Z > 1$ ) falls on the depth axis, a 0 is printed on the depth axis at that depth value in place of the usual + sign and the value of Z is printed to the left of the 0 (lines 2270, 2329, and 2342). (5) If a single X1, Y1 pair ( $Z = 1$ ) falls within the range of the plot but not on the depth axis, a \* is printed at the proper number of carriage spaces at the proper depth position (lines 2290 and 2350). (6) If more than one X1, Y1 pair ( $Z > 1$ ) falls at the same position along the depth axis and Y2 is such that it is within the range of the plot but not on the depth axis, a 0 is printed at the proper number of carriage spaces at the proper depth position, and the value of Z is printed to the left of the tick mark (lines 2290, 2349, and 2362). After the point is plotted X0 is incremented (that is, the depth axis is advanced one line), Z is reset to 1, X1 and Y1 are changed to X2 and Y2, and a new X1, Y1 pair is sought (lines 2380 to 2406). The process continues until either all the C-V data have been processed (lines 3001, 3290, 2155, 2385) or the true Gaussian plot has been completed. Note that the quantities Z3, Z6, and X0 are reset to zero before the start of the second plot (lines 4000 to 4002). The flag Z7 at line 3282 determines whether experimental or calculated values of X1 and Y1 are sent to the PLOT subroutine.

An example plot, showing the six possible print-outs discussed above, is shown in figure 5. In practice it is desirable to choose G1 and G2 so that as few points as possible are off scale. It is also desirable to choose G3 so that no more X1, Y1 pairs than necessary are

averaged and represented by a single data point on the plot. Averaged points mean reduced resolution.

It should be noted that the PLOT subroutine breaks down when 10 or more X1, Y1 pairs are averaged to produce one printed data point. Because Z is printed in I2 format (line 2312), and because one of those two spaces is reserved for the sign (even though the sign is positive and not printed), a two-digit number cannot be represented, and the print-out reverts to exponential format. The data point may or may not be plotted properly depending on whether it lies outside or inside the field of the exponential number and tick mark. This problem could be resolved by printing Z in I3 format and adjusting the TAB(x) arguments accordingly. A carriage space otherwise available for plotting would be sacrificed, however.

As one further comment, it is possible to nearly disable the PLOT subroutine by a proper choice of scale factor G3 when plots are not desired. If G3 is made sufficiently small, for example, 0.01, all dopant density values corresponding to distances of less than 50  $\mu\text{m}$  are averaged and plotted as a single point. In addition the true Gaussian plot will probably not appear at all since, for such small values of G3, X1 is always 1 (line 3270). The FOR-NEXT loop (lines 4010 to 4050) is therefore completed for all necessary B values before any points are plotted, and the program advances to line 4060 and exists.

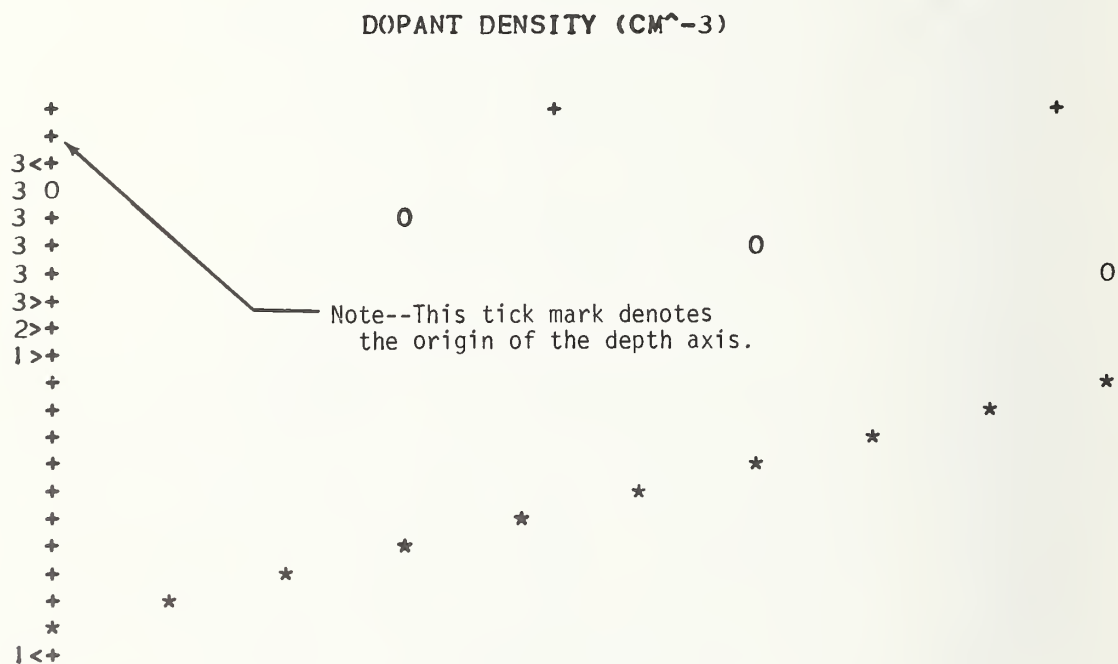


Figure 5. A plot artificially constructed to show the six types of printed output of the PLOT subroutine. (The points which are off-scale to the left appear as the first and last plotted symbols in the direction of the depth axis. The points which lie on the depth axis appear as the second and next to last plotted symbols. The points which are off-scale to the right appear near the center of the plot between the increasing and decreasing sections. The remaining majority of the points appear within the bounds of the plot. The tick marks on the dopant density axis are one decade apart; the dopant density at the origin is entered as G1 in line 2515 of Appendix A, and the number of carriage spaces representing one decade is entered as G2 in line 2525. The number of tick marks on the depth axis representing one micrometre is entered as G3 in line 2540.)



### 3.7. The Main Program

The main portion of the program consists of lines 098 to 100, 210 to 570, and 2500 to 4060 as listed in Appendix A. A summary flow chart is given in figure 6.

In lines 210 to 220, the values stored in TABLE are read for later use by the INERF subroutine. Flags and other quantities are assigned initial values in lines 2500 to 2508. Input of scaling and diffused layer parameters occurs in lines 2514 to 2585 as discussed in section 3.1.

In lines 2589 to 2682, several constants are entered or calculated for later use. The constants are (1) K, the dielectric constant of silicon, (2) P, the circumference of the diode in mils, (3) L, the characteristic length of the diffused layer, as defined in eq (6) and used in several equations, (4) K3, equal to  $\text{erfc}(x_j/L)$ , and used to solve eq (10), (5) K1, the coefficient of W in the second term on the right-hand side of eq (7), (6) K5, which has the value  $\kappa\epsilon_0 A_j$  where  $A_j = \pi D^2/4$ , used in solving eq (2), where the factor  $4.48649\text{E-}03$  includes the conversion of D from mils to micrometres and assumes  $\epsilon_0 = 8.8542 \times 10^{-14}$  F/cm,

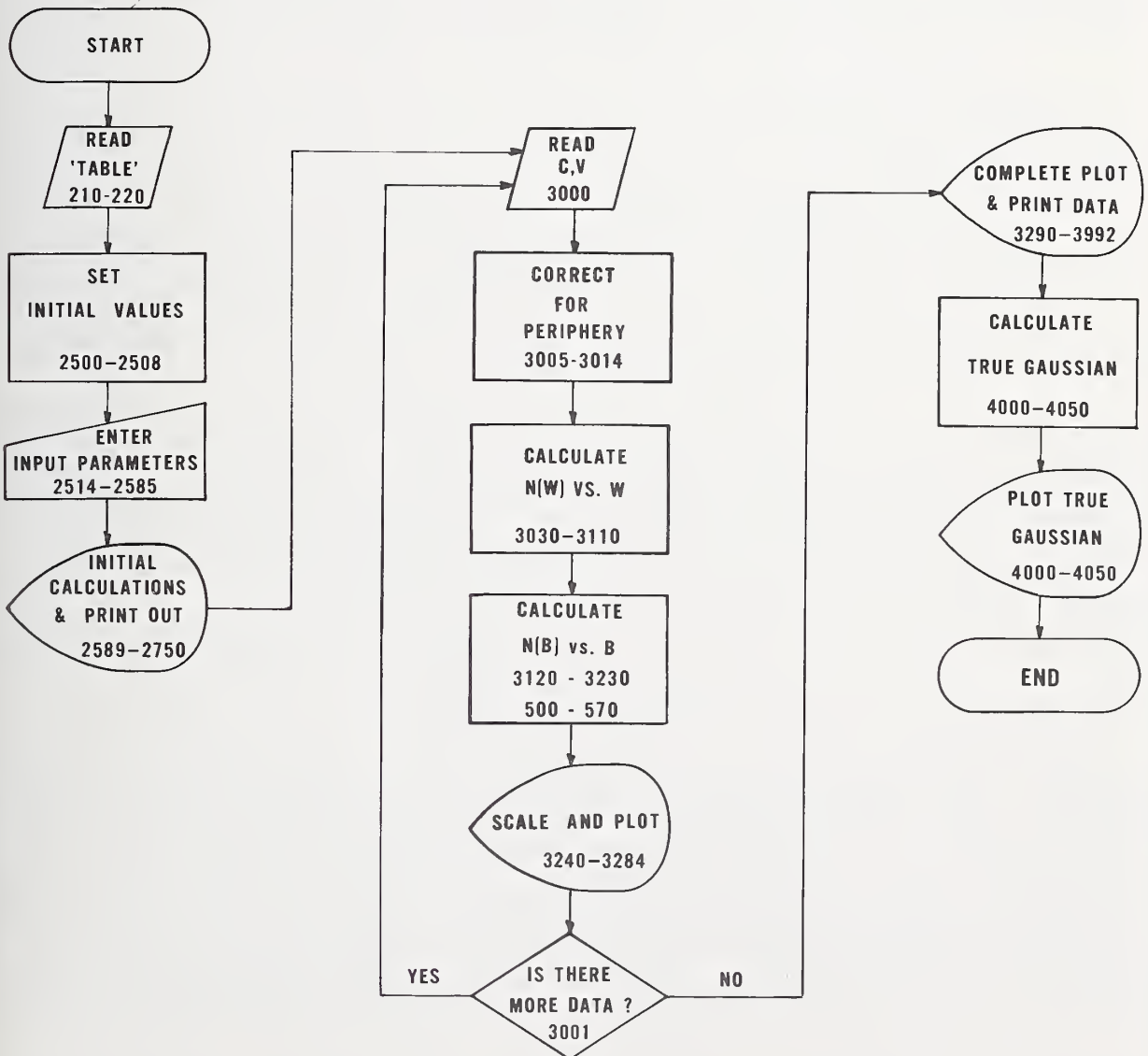


Figure 6. Summary flow chart of program CV1.

(7) K7, which is 2 times K5 and is used to solve eq (2) for a single W value from two successive capacitance values (line 3090), (8) K6, which has the value  $2/q\kappa\epsilon_0 A_j^2$  where  $A_j = \pi D^2/4$ , used in solving eq (1), where the factor  $5.49166E+18$  includes the conversion of D from mils to centimetres, and assumes  $q = 1.602 \times 10^{-19}$  C, (9) K8, which is  $\pi$  times 25.4, the conversion factor for converting mils to micrometres, used in eq (3), and (10) K9, which has the value  $\kappa\epsilon_0 \pi^2 D/2$ , including the appropriate conversion factor from mils to centimetres, and used to solve eq (3). These relationships are summarized in table 2.

Table 2 — Derivation of Constants Found  
in Program Lines 2660 to 2682

$$K5 = \left( \frac{25.4 \text{ } \mu\text{m}}{1 \text{ mil}} \right)^2 \times \frac{\pi}{4} \times 8.8542 \times 10^{-6} \frac{\text{pF}}{\mu\text{m}} \times K \times D^2$$

where D is given in mils

$$K7 = 2 \times K5$$

$$K6 = \left( \frac{1 \text{ mil}}{0.00254 \text{ cm}} \right)^4 \left( \frac{4}{\pi} \right)^2 \times \frac{2}{1.602 \times 10^{-19} \text{ coul} \times 8.8542 \times 10^{-14} \text{ F/cm}} \\ \times \left( \frac{10^{-12} \text{ F}}{\text{pF}} \right)^2 \times \frac{1}{K D^4}$$

where D is given in mils

$$K8 = \frac{25.4 \text{ } \mu\text{m}}{1 \text{ mil}} \times \pi$$

$$K9 = 8.8542 \times 10^{-2} \frac{\text{pF}}{\text{cm}} \times 0.00254 \frac{\text{cm}}{\text{mil}} \times \frac{\pi^2}{2} \times K \times D$$

where D is given in mils

After these constants are calculated, the program number Z9<sup>1</sup>, values of P, K and L, and a heading to the plot are printed in lines 2690 to 2750.

The C-V data are read from file CVIN in line 3000. The peripheral correction is implemented in lines 3005 to 3014. The measured capacitance C3 is separated into its plane and peripheral components by the iterative loop in lines 3006 to 3014. In line 3005, a first estimate W0 of the depletion width W is calculated from eq (2). The peripheral capacitance C5 is calculated from eq (3) in line 3006, and a new value of depletion width W1 is calculated from eqs (4) and (2). The new value W1 is renamed W0 and is inserted into eq (3). Successive iterations are made until the relative difference between W1 and W0 is  $10^{-6}$  or less. The plane capacitance C1 is then used in subsequent calculations.

In lines 3030 to 3070, a second C-V pair is read if the previous C-V pair was the first. Two C-V pairs are required to calculate the derivative in eq (1). The quantities C2 and V2 thenceforth denote the previous C-V pair (see also lines 3100 and 3110). Flag Z2 is zero when the first data pair is read in line 3000; thereafter Z2 = 1.

An apparent profile N(W) versus W is calculated in lines 3080 and 3090 by eqs (1) and (2) where plane capacitances rather than measured capacitances are operated on. The taking of the absolute value in line 3080 permits the voltage V1 to be measured with either polarity, although reverse bias is generally assigned positive values for convenience.

The back depletion correction is performed in lines 3120 to 3230. The heart of the calculation is the iteration which computes A in lines 3140 to 3175. A numerical integration is performed to evaluate the integral of eq (9). Although the trapezoidal approximation is employed after the first step (line 3130), the first step is calculated assuming that the Gaussian form of the diffusion continues past the junction to the depth represented by the first N(W) versus W point.

<sup>1</sup>Any value of Z9 can be entered in line 098. The authors find it helpful to increment Z9 by 0.01 each time the program is altered.

The first step numerical integration is carried out in lines 500 to 570. Referring to eq (7) a first estimate  $A_0 = 0$  is made for A in line 500. The right-hand side of eq (7) is calculated in lines 505 to 515. A second estimate  $A_1$  is found by calculating A on the left-hand side of eq (7) in lines 520 to 525. The second estimate is compared with the first estimate; if the relative difference is greater than  $10^{-5}$  further estimates are calculated by repeatedly placing the value of  $A_1$  calculated in line 525 back into the right-hand side of eq (7) (lines 530 to 545). When a suitable value of  $A_1$  is obtained, it is used in eq (10) to calculate the desired integral (line 550 to 560).

Having thus calculated the integral in eq. (10), the same equation is effectively rearranged in lines 3135 and 3145 so that the expression  $\text{erfc}(x_j - A)/L$  is on the left-hand side of the equation and everything else is on the right-hand side. An initial value of A,  $A_0$ , is placed in the right-hand side and a corrected value  $A_1$  is calculated on the left-hand side in lines 3140 to 3155. The values  $A_1$  and  $A_0$  are compared in line 3160; if their relative difference is greater than  $10^{-5}$ , the value  $A_1$  becomes the initial value  $A_0$  and a new corrected value  $A_1$  is calculated (lines 3165 and 3170). The iteration continues until sufficient agreement between  $A_0$  and  $A_1$  is achieved, and A is set equal to  $A_1$ . Using eqs (5), (8), and (11),  $N(A)$ ,  $N(B)$  and B are calculated in lines 3190 to 3210. The  $N(B)$  versus B pairs are written into file NBVSB in line 3215 for later listing if desired. The values of  $N(W)$  and W are saved as N7 and X7 in lines 3220 and 3230 for subsequent use in the trapezoidal numerical integration. Scaling and plotting is then done in lines 3240 to 3280.

After all the C-V data have been processed and the print-out of line 3990 is completed, a true Gaussian dopant density profile is generated in lines 4010 to 4050. Equation (12) is solved in line 4020 for a set of B values given in line 4010. The  $N(B)$  versus B values are written into IDEAL for later listing if desired in line 4025 and plotted in line 4040. This represents the profile that would be calculated if (1) the diffused layer were a pure Gaussian having parameters  $N_0$ ,  $N_b$  and  $x_j$  which were accurately known, (2) the dopant density of the specimen were uniform at a level  $N_b$ , and (3) various assumptions such as zero diffusion capacitance and abrupt space charge region boundaries were valid.

A sample calculation using program CV1 is given in Appendix C.

#### 4. MODIFICATIONS AND TROUBLE-SHOOTING

##### 4.1. Limitation on Program Length

Program CV1 contains 249 statements (exclusive of comment statements). As stated in section 1, the maximum number of statements permitted by BASIC is 256. The user must therefore exercise caution in attempting to expand the program to meet his individual needs. Additional space could be created by compressing the TABLE data file to more than five entries per line. Even more space could be made available by removing statements relating to the true Gaussian plot if that is not needed. This could be done by deleting lines 2504, 3282 and 4000 through 4050 and deleting IDEAL from line 099.

##### 4.2. Formation of Subprograms

The problem of program length discussed above can be solved and other advantages can be gained by separating one or all of the ERF, INERF and PLOT subroutines and the TABLE data file from the main program and creating each as an independent program or file. These subprograms can then be executed by the main program using CALL statements in place of the present GOSUB statements. When this is done, substantial additions can be made to the main program before the limit on program length is reached. This procedure has the advantage of making the subprograms available to be called by other programs. The authors have employed the ERF subroutine in this manner. If the INERF subroutine is to be set up as an independent subprogram, a means for reading in the TABLE values, presently done in lines 100 and 210 to 220, must be included in the program which calls INERF. In all such subprograms, an END statement must be included as the last statement.

##### 4.3. Rectangular Diodes

In some applications it may be desirable or necessary to measure dopant density profiles using rectangular rather than circular diodes. The equation for the peripheral correction



in such a diode is given in [12]. This equation can be coded to solve for the plane capacitance in place of the existing lines 3005 to 3014 using a similar approach (only line 3006 need actually be changed). It is then necessary to enter the dimensions of the rectangle in place of the circular diameter in the present lines 2550 and 2555. Other lines which need to be altered are 2590 and 2660 to 2682. The changes which are necessary are given in table 3. The statements in table 3 should be inserted into the listing of Appendix A in place of the existing statements. No statement appears after line number 2681 in table 3 indicating that for rectangular diodes that line should be deleted from the listing of Appendix A.

Table 3 — Statements to be Modified in CV1  
for the Case of Rectangular Junctions

---

```

2550 PRINT "WIDTH (MILS) = ";
2552 INPUT S1
2555 PRINT "LENGTH (MILS) = ";
2557 INPUT S2
2590 P=2*(S1+S2)
2660 K5=5.71238E-03*K*S1*S2
2670 K6=3.38753E+18/(K*S1*S1*S2*S2)
2680 K7=1.14248E-02*K*S1*S2
2681
2682 K9=5.56326E-05*K
3006 C5=K9*12.7*(S1+S2)/LOG(1+W0/X5)+K9*X5*(X5+W0)/W0

```

---

#### 4.4. LOG ER Errors

On occasion program CV1 produced a LOG ER statement indicating that it was attempting to compute the logarithm of a negative number. The log computation is performed in line 3240. The negative number originates in line 3200 and may be produced if the input parameters  $D$ ,  $x_j$ ,  $N_0$  and  $N_b$  (lines 2550 to 2585) are not sufficiently accurate.

#### 4.5. Program CV2

A second BASIC computer program, titled CV2, has been written which generates idealized C-V data for a Gaussian diffused  $p$ - $n$  junction diode. Such data can be used for checking program CV1. For example, when ideal data are generated for the case  $N_0 = 10^{18} \text{ cm}^{-3}$ ,  $N_b = 3 \times 10^{16} \text{ cm}^{-3}$ ,  $x_j = 1.0 \text{ } \mu\text{m}$  and  $D = 6 \text{ mils}$  and are entered as CVIN into program CV1, a profile corresponding to a true Gaussian which asymptotically approaches  $N(B) = 3 \times 10^{16} \text{ cm}^{-3}$  should be calculated. If it is not, there is an error in either program CV1 or CV2.

Program CV2 is listed in Appendix D. Input parameters are entered from the teletypewriter in lines 100 to 127. The built-in voltage is entered as the constant  $V_0$ ; it does not take account of the dependence of built-in voltage on the applied bias [10]; the agreement of a profile calculated via CV2-CV1 with the originally assumed profile is independent of the choice of built-in voltage. The C-V data, however, are more in agreement with experimental data if an appropriate choice of built-in voltage is entered. The calculation begins with a set of  $A$  (represented in CV2 as  $A1$ ) values given in line 150. The initial and final capacitance values and the capacitance interval are determined by the coefficients of  $X5$  in line 150 which can be altered as needed. Given the set of  $A$  values, the corresponding  $B$  (represented as  $B1$ ) values are calculated from eq (7), modified by letting  $W = B - A$  so that  $B$  is given as an implicit function of  $A$ . This modified eq (7) is solved in lines 160 to 260. The voltage  $V1$  is calculated using eq (12) of [10] in lines 320 to 350, and the plane capacitance is calculated in line 360 by eq (2) of this report. The peripheral capacitance is added in lines 370 to 380 using eqs (3) and (4). The C-V pairs are printed out in line 390 and written into file GAUSCV in line 395. By renaming GAUSCV as CVIN, the C-V data file can be made compatible with the input required for program CV1. The subroutine for calculating the complementary error function in lines 1400 to 1565 is identical with that subroutine in CV1. The constants in lines 142 to 144 are analogous to the constants in lines 2640, 2681 and 2682 of CV1 and are derived from the same values of  $\epsilon_0$  and  $q$ . A sample calculation using program CV2 is performed in Appendix E.

As was the case with CV1 (sec. 4.3.), program CV2 can be modified if necessary to make it applicable to rectangular diodes. The alterations which need to be made are given in table 4. The statements in table 4 replace the statements having the same line number in the listing given in Appendix D. The statement with line number 143 should be deleted from the listing given above for the case of rectangular diodes.

Table 4 — Statements to be Modified in CV2  
for the Case of Rectangular Junctions

---

```
105 PRINT "WIDTH (MILS) = ";
106 INPUT S1
107 PRINT "LENGTH (MILS) = ";
108 INPUT S2
143
144 K9=5.56326E-05*K
360 C1=5.71238E-03*K*S1*S2/(A1+B1)
375 C2=K9*(12.7*(S1+S2)/LOG(1+W/X5)+(X5+W)*X5/W)
```

---

# APPENDIX A: LISTING OF PROGRAM CVI

```

050 * PROGRAM CVI -- CALCULATES A DOPANT
051 * DENSITY PROFILE FROM C-V DATA PAIRS
052 * FOR A GAUSSIAN DIFFUSED P-N JUNCTION
053 *
098 Z9=10.52
099 FILES CVIN,NBVSBI,IDEAL
100 DIM H(105)
120 *
121 * "TABLE" DATA FILE
122 *
150 DATA 3.74580 , 3.72492 , 3.70394 , 3.68285 , 3.66164
152 DATA 3.64031 , 3.61887 , 3.59731 , 3.57562 , 3.55382
154 DATA 3.53189 , 3.50982 , 3.48763 , 3.46531 , 3.44286
156 DATA 3.42026 , 3.39753 , 3.37465 , 3.35163 , 3.32847
158 DATA 3.30515 , 3.28168 , 3.25805 , 3.23427 , 3.21032
160 DATA 3.18620 , 3.16192 , 3.13747 , 3.11283 , 3.08802
162 DATA 3.06303 , 3.03785 , 3.01247 , 2.98690 , 2.96113
164 DATA 2.93515 , 2.90896 , 2.88256 , 2.85593 , 2.82908
166 DATA 2.80200 , 2.77467 , 2.74711 , 2.71929 , 2.69122
168 DATA 2.66288 , 2.63427 , 2.60539 , 2.57621 , 2.54674
170 DATA 2.51696 , 2.48687 , 2.45645 , 2.42570 , 2.39460
172 DATA 2.36315 , 2.33133 , 2.29913 , 2.26653 , 2.23352
174 DATA 2.20009 , 2.16621 , 2.13188 , 2.09707 , 2.06176
176 DATA 2.02594 , 1.98957 , 1.95265 , 1.91513 , 1.87699
178 DATA 1.83821 , 1.79875 , 1.75857 , 1.71764 , 1.67592
180 DATA 1.63335 , 1.58990 , 1.54550 , 1.50009 , 1.45360
182 DATA 1.40597 , 1.35710 , 1.30691 , 1.25528 , 1.20210
184 DATA 1.14722 , 1.09049 , 1.03172 , .97069 , .90715
186 DATA .84078 , .77121 , .697981 , .62052 , .53808
188 DATA .449681 , .35403 , .24928 , .1327 , 0
200 *
201 * READ VALUES FROM "TABLE"
202 * FOR "INERF" SUBROUTINE
203 *
210 FOR H0=1 TO 100
215 READ H(H0)
217 IF H0=100 THEN 2500
220 NEXT H0
495 *
496 * CALCULATE FIRST VALUE OF INTEGRAL I
497 *
500 A0=0
505 E=(X5-A0+X)/L
510 GOSUB 1400
515 H9=J1+(1.12838*N3*X)/(N0*L)
520 GOSUB 1000
525 A1=X5-E*L
530 IF ABS((A1-A0)/A1)<=1.0E-05 THEN 550
540 A0=A1
545 GO TO 505
550 E=(X5-A1)/L
555 GOSUB 1400
560 I=(L*N0/1.12838)*(J1-K3)-N3*A1
570 GO TO 3135

```



```

990 *
991 * "INERF" SUBROUTINE
993 *
1000 IF H9<=1 THEN 1004
1001 E=0
1002 Z5=2
1003 GO TO 1080
1004 IF H9<1 THEN 1010
1005 E=0
1007 GO TO 1080
1010 H0=(-100*LOG(H9)/LOG(1.00000E-07))+100
1012 IF H0>=2 THEN 1020
1014 E=3.76656
1016 Z5=1
1018 GO TO 1080
1020 H2=INT(H0)
1025 H3=H2+1
1030 H1=H2-1
1035 H5=H(H1)
1040 H6=H(H2)
1045 H7=H(H3)
1050 I1=(H7+H5-2*H6)/2
1060 I3=H6-H5-I1*(H2+H1)
1065 I4=H5-I1*H1*H1-I3*H1
1070 E=I1*H0*H0+I3*H0+I4
1080 RETURN
1390 *
1391 * "ERF" SUBROUTINE
1393 *
1400 IF E>=1.00000E-32 THEN 1410
1402 E1=0
1404 J1=1
1406 GO TO 1565
1410 IF E<=9 THEN 1420
1412 E1=1
1414 J1=0
1416 GO TO 1565
1420 IF E>1 THEN 1500
1430 E1=1+.666667*E^2+.266667*E^4+7.61905E-02*E^6
1432 E1=E1+1.69312E-02*E^8+3.07840E-03*E^10+4.73600E-04*E^12
1434 E1=E1+6.31467E-05*E^14+7.42903E-06*E^16+7.82903E-07*E^18
1440 E1=1.12838*E*E1*EXP(-(E^2))
1445 J1=1-E1
1450 GO TO 1565
1500 F2=0
1502 F4=1
1504 F1=2*E
1506 F3=2*E*E+1
1508 F5=F1/F3
1510 F6=1
1512 F8=F3+4
1514 E2=1.0E-06
1516 E3=1.0E+25
1520 F7=-F6*(F6+1)

```

```

1522 E4=F8*F1+F7*F2
1524 E5=F8*F3+F7*F4
1526 F9=E4/E5
1528 E6=ARS(1-(F9/F5))-E2
1530 IF F6<=0 THEN 1550
1531 IF F5>F9 THEN 1548
1532 IF E5<E3 THEN 1538
1534 E4=E4/E3
1535 E5=E5/E3
1536 F1=F1/E3
1537 F3=F3/E3
1538 F2=F1
1539 F4=F3
1540 F1=E4
1541 F3=E5
1543 F6=F6+2
1544 F8=F8+4
1545 F5=F9
1546 GO TO 1520
1548 F9=F5
1550 J1=.56419*F9*EXP(-(E^2))
1555 E1=1-J1
1565 RETURN
2140 *
2141 * "PLOT" SUBROUTINE
2142 *
2150 IF Z6=0 THEN 2390
2155 IF Z3=1 THEN 2200
2160 IF X1>X2 THEN 2200
2170 Z=Z+1
2180 Y2=Y1+Y2
2190 GO TO 2406
2200 Y2=Y2/Z
2205 Y2=IN1(Y2+3.5)
2210 IF X0=0 THEN 2410
2220 IF X2=X0 THEN 2260
2230 PRINT TAB(3)"+"
2240 X0=X0+1
2250 GO TO 2220
2260 IF Y2<3 THEN 2310
2270 IF Y2=3 THEN 2329
2290 IF Y2<=71 THEN 2349
2300 IF Y2>71 THEN 2370
2310 PRINT,2312,Z,"<+"
2312 FMT I2
2320 GO TO 2380
2329 IF Z>1 THEN 2342
2330 PRINT TAB(3)"*"
2340 GO TO 2380
2342 PRINT,2312,Z," 0"
2344 GO TO 2380
2349 IF Z>1 THEN 2362
2350 PRINT TAB(3)"+";TAB(Y2)"*"
2360 GO TO 2380
2362 PRINT,2312,Z,TAB(3)"+";TAB(Y2)"0"

```

```

2364 GO TO 2380
2370 PRINT,2312,Z,">+"
2380 X0=X0+1
2385 IF Z3=1 THEN 2406
2390 Y2=Y1
2394 X2=X1
2398 Z=1
2402 Z6=1
2406 RETURN
2410 FOR YO=3 TO 71 STEP G2
2420 PRINT TAB(YO)"+";
2430 NEXT YO
2440 PRINT
2450 X0=1
2460 GO TO 2220
2490 *
2491 * SET INITIAL VALUES
2492 *
2500 Z2=0
2501 Z3=0
2502 Z5=0
2503 Z6=0
2504 Z7=0
2505 X0=0
2506 X7=0
2507 N7=0
2508 I=0
2510 *
2511 * ENTER SCALING AND
2512 * DIFFUSED LAYER PARAMETERS
2513 *
2514 PRINT "1ST LOG = ";
2515 INPUT G1
2520 PRINT "CHAR/DEC = ";
2525 INPUT G2
2530 PRINT "LINES/UM = ";
2540 INPUT G3
2550 PRINT "DIAMETER (MILS) = ";
2555 INPUT D
2560 PRINT "JCT DEPTH (UM) = ";
2565 INPUT X5
2570 PRINT "SURFACE DENS (CM-3) = ";
2575 INPUT NO
2580 PRINT "ESTIMATED NB (CM-3) = ";
2585 INPUT N3
2586 *
2587 * CALCULATE SEVERAL CONSTANTS
2588 *
2589 K=11.7
2590 P=3.14159*D
2600 L=X5/SQR(LOG(NO/N3))
2610 E=X5/L
2620 GOSUR 1400
2630 K3=J1
2640 K1=1.12838*N3/NO/L

```

```

2660 K5=4.48649E-03*K*D*D
2670 K6=5.49166E+18/(K*D^4)
2680 K7=8.97298E-03*K*D*D
2681 K8=79.7965
2682 K9=1.10982E-03*K*D
2685 *
2686 * PRINT OUT SEVERAL CONSTANTS
2687 * AND PLOT HEADING
2688 *
2690 PRINT "CV N(B) VS. R PROFILE, PROGRAM # ";Z9
2730 PRINT,2735,P,L,K
2735 FMT "P(MILS) =",F7.3," L(UM) =",F6.3," DIEL. CONST. =",F7.3
2740 PRINT,2750
2750 FMT /X22,"DOPANT DENSITY (CM^-3)"/
2990 *
2991 * READ IN C-V DATA AND
2992 * CORRECT FOR PERIPHERY
2993 *
3000 READ #1,C3,V1
3001 IF END #1 THEN 3290
3005 W0=K5/C3
3006 C5=K9/LOG((1+W0/X5)/(1+4*W0/(K8*D+4*X5)))
3008 C1=C3-C5
3009 W1=K5/C1
3010 IF ABS((W1-W0)/W1)<1.0E-06 THEN 3030
3012 W0=W1
3014 GO TO 3006
3030 IF Z2=1 THEN 3080
3040 C2=C1
3050 V2=V1
3060 Z2=1
3070 GO TO 3000
3074 *
3075 * CALCULATE APPARENT
3076 * PROFILE N(4) VS. W
3077 *
3080 N=ABS(K6*(V2-V1)/((1/(C2*C2))-(1/(C1*C1))))
3090 X=K7/(C1+C2)
3094 *
3095 * PERFORM DIFFUSED LAYER CORRECTION
3096 * AND GENERATE CORRECTED PROFILE
3097 *
3100 C2=C1
3110 V2=V1
3120 IF I=0 THEN 500
3130 I=I+(N7+N)*(X-X7)/2
3135 K2=1.12938*I/N0/L
3140 A0=0
3145 H9=K1*A0+K3+K2
3150 GOSUB 1000
3155 A1=X5-E*L
3160 IF ABS((A1-A0)/A1)<1.00000E-05 THEN 3175
3165 A0=A1
3170 GO TO 3145
3175 A=A1

```

```

3190 N1=N0*EXP(-((X5-A)/L)^2)-N3
3200 N2=1/((1/N)-(1/N1))
3210 B=X-A
3215 WRITE #2,N2,B
3220 N7=N
3230 X7=X
3235 *
3236 * CALCULATE SCALING PARAMETERS
3237 *
3240 Y1=G2*LOG(N2/G1)/LOG(10)
3270 X1=INT(G3*B+1.5)
3280 GOSUB 2150
3282 IF Z7=1 THEN 4050
3284 GO TO 3000
3290 Z3=1
3300 GOSUB 2150
3980 *
3981 * PRINT OUT PARAMETERS
3982 * RELATING TO CORRECTIONS
3983 *
3990 PRINT,3992,A,N1,100*C5/(C1+C5),Z5
3992 FMT /"A(UM) =",F9.6," N(A) =",E12.6," %CORR =",F8.4," Z5=",I2//
3995 *
3996 * PLOT TRUE GAUSSIAN PROFILE
3997 *
4000 Z3=0
4001 Z6=0
4002 X0=0
4010 FOR B=.1*L TO 2*L STEP .1*L
4020 N2=N3-N0*EXP(-((X5+B)/L)^2)
4025 WRITE #3,N2,B
4030 Z7=1
4040 GO TO 3240
4050 NEXT B
4060 END

```

As discussed in section 1, the particular type of BASIC employed in this program is compatible with most of the BASIC language family. In the interest of clarification, however, some of the program statements and system commands are now discussed.

The use of external files is employed by use of READ # and WRITE # statements in conjunction with a FILES statement. For instance if a file titled ABC consists of a set of ten numbers to be used as input data, and if these numbers are to be multiplied by 2 and written into a new file titled DEF which is created at the time of program execution, the statements for doing this would be

```
10 FILES ABC, DEF
20 FOR I = 1 TO 10
30 READ # 1, A
40 B = 2 * A
50 WRITE # 2, B
60 NEXT I
70 END
```

The number following the # sign in lines 30 and 50 indicates which file named in the FILES statement of line 10 is to be read from or written into. If program CV1 is to be run on a system which cannot access external files, the C-V data can be entered in DATA statements anywhere in the program after line 188 and read by a READ statement (no # symbol). In place of the WRITE # statement, N(B) and B values can be stored in an array to be called out later in the program by a PRINT statement.

The LET statement has been abbreviated to omit the word LET. For example, in line 505 of Appendix A the statements

```
505 E = (X5 - A0 + X)/L and
505 LET E = (X5 - A0 + X)/L
```

are equivalent. If program CV1 is to be run on a system which requires that LET be present, it should be inserted in all the necessary lines.

The IF END #n statement in line 3001 of Appendix A provides a means for branching in the program if no more data are found in file number n. The end of the C-V data could alternately be signaled by inserting a dummy C-V pair with a negative capacitance after the final actual C-V data pair. Line 3001 could then be

```
3001 IF C3 < 0 THEN 3290.
```

The formatted PRINT statement permits printed outputs to be formatted according to the FMT statement in the line number given following the first comma in the PRINT statement. For example, the formatted PRINT statement in line 3990 of Appendix A refers to the FMT statement in line 3992. The FMT statement dictates that after a line feed (denoted by /) the characters A(UM) = are printed, then the current value of A in F9.6 format, and so on. The use of FMT statements is not necessary, and on systems not having this capability they can be deleted and unformatted PRINT statements used for data output.

Comment statements are introduced by an asterisk (\*) as the first printed character following the line number. In some types of BASIC, REM rather than \* is used for comment statements. These statements may be deleted without affecting the operation of the program.

System commands are more dependent on the system being used. For the system on which program CV1 was run, the program is entered by the command CREATE CV1, listed by the command LIST CV1, and executed by the command BASIC CV1. These system commands are given to the computer as indicated in the sample calculations of Appendices C and E. Other systems may have different but analogous sets of system commands.



## APPENDIX C: SAMPLE CALCULATION USING PROGRAM CV1

A sample calculation using the C-V data given in [10] is shown below. The calculation, which occupies three pages in this report, consists of four parts, each part being introduced by a system command entered from the teletypewriter keyboard following the printing of a question mark (?) by the computer. In the first part, following CREATE CVIN, the C-V data are entered from the teletypewriter or from punched paper tape in the format described in section 3.1. In the second part, following BASIC CV1, the actual calculations are performed and the plots are printed. Note that the numbers following exclamation points (!) are entered by the operator from the keyboard. The scaling is such that the dopant density along the depth axis is  $5 \times 10^{14} \text{ cm}^{-3}$ ; the tick marks on the dopant density axis are one decade apart. The depth axis scale of 5 lines/ $\mu\text{m}$  means that there is  $0.2 \mu\text{m}$  between tick marks. The origin of the depth axis is the second tick mark on that axis as shown in figure 5. In the third part, following LIST NBVSB, the values of N(B) in (centimetres) $^{-3}$  and B in micrometres calculated from the experimental data are listed in two columns (three columns including the line number). In the fourth part, following LIST IDEAL, the values of N(B) in (centimetres) $^{-3}$  and B in micrometres calculated for a true Gaussian profile are listed in two columns.

?CREATE CVIN  
BEGIN

0010	36.12	,	-.3502
0020	27.07	,	-.1649
0030	22.09	,	.0903
0040	20.14	,	.2561
0050	18.07	,	.5034
0060	16.13	,	.8387
0070	15.13	,	1.073
0080	13.16	,	1.703
0090	12.08	,	2.2
0100	11.12	,	2.782
0110	10.14	,	3.558
0120	9.102	,	4.686
0130	8.2	,	6.059
0140	7.507	,	7.489
0150	6.806	,	9.424
0160	6.213	,	11.64
0170	5.918	,	12.99
0180	5.609	,	14.66
0190	5.356	,	16.25
0200	5.113	,	18
0210	4.919	,	19.59
0220	4.714	,	21.48
0230	4.522	,	23.49
0240	4.32	,	25.87
0250	4.11	,	28.79
0260	3.911	,	32.7
0270	3.764	,	39.25
0280	3.614	,	58.2
0290	3.524	,	84.99

?BASIC CV1

RUN

1ST LOG = ! 5.0E+14

CHAR/DEC = ! 40

LINES/UM = ! 5

DIAMETER (MILS) = ! 20

JCT DEPTH (UM) = ! 2.460

SURFACE DENS (CM $^{-3}$ ) = ! 3.2E+18

ESTIMATED NR (CM $^{-3}$ ) = ! 1.4E+15

CV N(B) VS. B PROFILE, PROGRAM # 10.52

P(MILS) = 62.832 L(UM) = .885 DIEL. CONST. = 11.700

# DOPANT DENSITY (CM<sup>-3</sup>)



A(UM) = .702596 N(A) = .603808E 17 %CORR = 5.8594 Z5= 0

```

+
+
2 +
2 +
2 +
3 +
2 +
2 +
2 +

```

4060 EXIT

?LIST NBVSB

0010	.104092E 16,	.447257
0020	.122829E 16,	.608752
0030	.128460E 16,	.730555
0040	.131533E 16,	.823065
0050	.134157E 16,	.938722
0060	.137968E 16,	1.04371
0070	.136185E 16,	1.17367
0080	.138005E 16,	1.34141
0090	.139834E 16,	1.47976
0100	.138794E 16,	1.63754
0110	.139385E 16,	1.83752
0120	.140371E 16,	2.07621
0130	.141149E 16,	2.31893
0140	.141358E 16,	2.57758
0150	.142793E 16,	2.86961
0160	.140783E 16,	3.10777
0170	.141941E 16,	3.29169
0180	.141391E 16,	3.48179
0190	.140322E 16,	3.66729
0200	.139964E 16,	3.8466
0210	.138769E 16,	4.02515
0220	.138298E 16,	4.21878
0230	.135869E 16,	4.42891
0240	.138375E 16,	4.67049
0250	.168842E 16,	4.93474
0260	.347350E 16,	5.17544
0270	.967007E 16,	5.38478
0280	.239498E 17,	5.54458

?LIST IDEAL

0010	.605266E 15,	.884547E-01
0020	.957787E 15,	.176009
0030	.115881E 16,	.265364
0040	.127106E 16,	.353819
0050	.133243E 16,	.442273
0060	.136529E 16,	.530728
0070	.138253E 16,	.619183
0080	.139138E 16,	.707638
0090	.139583E 16,	.796092
0100	.139802E 16,	.884547
0110	.139908E 16,	.973002
0120	.139958E 16,	1.06146
0130	.139981E 16,	1.14991
0140	.139992E 16,	1.23837
0150	.139996E 16,	1.32682
0160	.139999E 16,	1.41528
0170	.139999E 16,	1.50373
0180	.140000E 16,	1.59218
0190	.140000E 16,	1.68064

# APPENDIX D: LISTING OF PROGRAM CV2

```

080 FILES GAUSCV
090 PRINT "VER 16, 3/11/75"
100 PRINT "JCT DEPTH (UM) = ";
102 INPUT X5
105 PRINT "DIAMETER (MILS) = ";
108 INPUT D
110 PRINT "SURFACE DENS (CM^-3) = ";
112 INPUT N0
120 PRINT "BACKGROUND DENS (CM^-3) = ";
125 INPUT N3
126 PRINT "BUILT-IN VOLTAGE = ";
127 INPUT V0
130 K=11.7
140 L=X5/SQR(LOG(N0/N3))
142 K2=N3*1.12838/N0/L
143 K8=79.7965
144 K9=1.10982E-03*K*D
146 PRINT,147
147 FMT /X6,"C3",X12,"V1"/
150 FOR A1=0.10*X5 TO 0.36*X5 STEP 0.02*X5
160 E=(X5-A1)/L
165 J3=E
170 GOSUB 1400
175 J2=J1
190 B0=0
200 E=(X5+B0)/L
210 GOSUB 1400
220 B2=((J2-J1)/K2)-A1
230 IF ABS((B2-B0)/B2)<1.0E-07 THEN 260
240 B0=B2
250 GO TO 200
260 B1=B2
320 V5=(A1*A1)-(B1*B1)-(2*X5*(A1+B1))
330 V6=(N0*L*L/N3)*EXP(-((X5-A1)/L)^2)
340 V7=-((N0*L*L/N3)*EXP(-((X5+B1)/L)^2)
350 V1=9.04768E-15*N3*(V5+V6+V7)/K
360 C1=4.48649E-03*K*D*D/(A1+B1)
370 W=A1+B1
375 C2=K9/LOG((1+1/X5)/(1+4*W/(K8*D+4*X5)))
380 C1=C1+C2
390 PRINT C1,-V0-V1
395 WRITE #1,C1,-V0-V1
400 NEXT A1
490 STOP
1400 IF E>=1.00000E-32 THEN 1410
1402 E1=0
1404 J1=1
1406 GO TO 1565
1410 IF E<=0 THEN 1420
1412 E1=1
1414 J1=0
1416 GO TO 1565
1420 IF E>1 THEN 1500

```

```

1430 E1=1+.666667*E^2+.266667*E^4+7.61905E-02*E^6
1432 E1=E1+1.69312E-02*E^8+3.07840E-03*E^10+4.73600E-04*E^12
1434 E1=E1+6.31467E-05*E^14+7.42903E-06*E^16+7.82003E-07*E^18
1440 E1=1.12838*E*E1*EXP(-(E^2))
1445 J1=1-E1
1450 GO TO 1565
1500 F2=0
1502 F4=1
1504 F1=2*E
1506 F3=2*E*E+1
1508 F5=F1/F3
1510 F6=1
1512 F8=F3+4
1514 E2=1.0E-06
1516 E3=1.0E+25
1520 F7=-F6*(F6+1)
1522 E4=F8*F1+F7*F2
1524 E5=F8*F3+F7*F4
1526 F9=E4/E5
1528 E6=ABS(1-(F9/F5))-E2
1530 IF E6<=0 THEN 1550
1531 IF F5>F9 THEN 1548
1532 IF E5<E3 THEN 1538
1534 E4=E4/E3
1535 E5=E5/E3
1536 F1=F1/E3
1537 F3=F3/E3
1538 F2=F1
1539 F4=F3
1540 F1=E4
1541 F3=E5
1543 F6=F6+2
1544 F8=F8+4
1545 F5=F9
1546 GO TO 1520
1548 F9=F5
1550 J1=.56419*F9*EXP(-(E^2))
1555 E1=1-J1
1565 RETURN
1570 END

```



# APPENDIX E: SAMPLE CALCULATION USING PROGRAM CV2

A sample calculation using the diode parameters given in the first paragraph of section 4.5. is performed below. The idealized C-V data thus generated by program CV2 are then entered into program CV1 to see if in fact the originally assumed profile is produced.

As in Appendix C, characters following a question mark (?) or exclamation point (!) are entered by the operator from the teletypewriter. The command BASIC CV2 initiates execution of program CV2 and produces a tabulation of C-V pairs which are also written into file GAUSCV. The command RENAME GAUSCV CVIN gives a new name to this file so that it is compatible with program CV1. The command BASIC CV1 and subsequent commands have already been dealt with in Appendix C. The fact that files NBVSB and IDEAL give plots which can be superimposed means that CV1 and CV2 are probably free of errors.

```
?BASIC CV2
RUN
VER 16, 3/11/75
JCT DEPTH (UM) = ! 1.0
DIAMETER (MILS) = ! 6
SURFACE DENS (CM^-3) = ! 1.0E+18
BACKGROUND DENS (CM^-3) = ! 3.0E+16
BUILT-IN VOLTAGE = ! 0.7
```

C3	V1
8.78502	-.402974
7.12055	-.151537
5.92403	.231969
5.02001	.79025
4.31095	1.5765
3.73864	2.6554
3.2663	4.10603
2.86967	6.02497
2.53223	8.53001
2.24239	11.7635
1.99179	15.8967
1.77412	21.1343
1.58445	27.7186
1.41877	35.9334

```
490 EXIT
```

```
?RENAME GAUSCV CVIN
```

```
?BASIC CV1
RUN
1ST LOG = ! 1.0E+15
CHAR/DEC = ! 30
LINES/UM = ! 20
DIAMETER (MILS) = ! 6
JCT DEPTH (UM) = ! 1.0
SURFACE DENS (CM^-3) = ! 1.0E+18
ESTIMATED NB (CM^-3) = ! 3.0E+16
CV N(B) VS. B PROFILE, PROGRAM # 10.52
P(MILS) = 18.850 L(UM) = .534 DIEL. CONST. = 11.700
```

# DOPANT DENSITY (CM<sup>-3</sup>)



A(UM) = .349797 N(A) = .197082E 18 %CORR = 6.2929 Z5= 0



4060 EXIT

?LIST NBVSB

0010	.198504E 17,	.139579
0020	.223280E 17,	.174132
0030	.244271E 17,	.212609
0040	.261692E 17,	.255602
0050	.275252E 17,	.303834
0060	.285190E 17,	.358139
0070	.291942E 17,	.419452
0080	.296157E 17,	.48879
0090	.298453E 17,	.567187
0100	.299551E 17,	.65569
0110	.299981E 17,	.755298
0120	.300119E 17,	.866951
0130	.300139E 17,	.991534

?LIST IDEAL

0010	.957664E 16,	.534022E-01
0020	.163715E 17,	.106804
0030	.210858E 17,	.160207
0040	.242848E 17,	.213609
0050	.264083E 17,	.267011
0060	.277876E 17,	.320413
0070	.286641E 17,	.373816
0080	.292094E 17,	.427218
0090	.295413E 17,	.48062
0100	.297392E 17,	.534022
0110	.298546E 17,	.587425
0120	.299206E 17,	.640827
0130	.299575E 17,	.694229
0140	.299777E 17,	.747631
0150	.299885E 17,	.801033
0160	.299942E 17,	.854436
0170	.299971E 17,	.907837
0180	.299986E 17,	.96124
0190	.299993E 17,	1.01464
0200	.299997E 17,	1.06804

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U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. Special Publication 400-11	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE <i>Semiconductor Measurement Technology: A BASIC Program for Calculating Dopant Density Profiles from Capacitance-Voltage Data</i>		5. Publication Date June 1975	
		6. Performing Organization Code	
7. AUTHOR(S) Richard L. Mattis and Martin G. Buehler		8. Performing Organ. Report No.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS  NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234		10. Project/Task/Work Unit No. See item 15	
		11. Contract/Grant No. ARPA Order 2397, Program Code 4D10; DNA IACRO 74-811	
12. Sponsoring Organization Name and Complete Address (Street, City, State, ZIP) Jointly Sponsored by NBS, Washington, D. C. 20234, Defense Nuclear Agency, Washington, D. C. 20305, and Advanced Research Projects Agency, Arlington, Virginia 22209		13. Type of Report & Period Covered Final 9/72 to 9/74	
		14. Sponsoring Agency Code	
15. SUPPLEMENTARY NOTES  4251126, 4251555, 4251522			
16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)  A computer program is presented which is suitable for calculating dopant density vs. depth profiles from capacitance-voltage data for the case of a Gaussian-diffused $p-n$ junction diode. The program includes corrections for peripheral capacitance of round or rectangular diodes and back depletion of the space charge region into the diffused layer. Inputs to the program consist of the surface dopant density, the junction depth, the background dopant density in the diffused layer, the junction diameter, three scaling parameters, and the capacitance-voltage data pairs. Output from the program is in the form of a plot and an optional listing of dopant density as a function of depth. The equations underlying the program are given and are related to the program whose operation is described in detail. A second program, for generating idealized capacitance-voltage data for a Gaussian-diffused diode on material with a constant dopant density is also included.			
17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) BASIC; capacitance-voltage measurements; computer programs; dopant profiles; error function; Gaussian diffusion; plotting, computer; semiconductors; silicon.			
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