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DAMAGE PROFILES IN SILICON AND THEIR IMPACT ON DEVICE RELIABILITY

G. H. Schwuttke

International Business Machines Corporation

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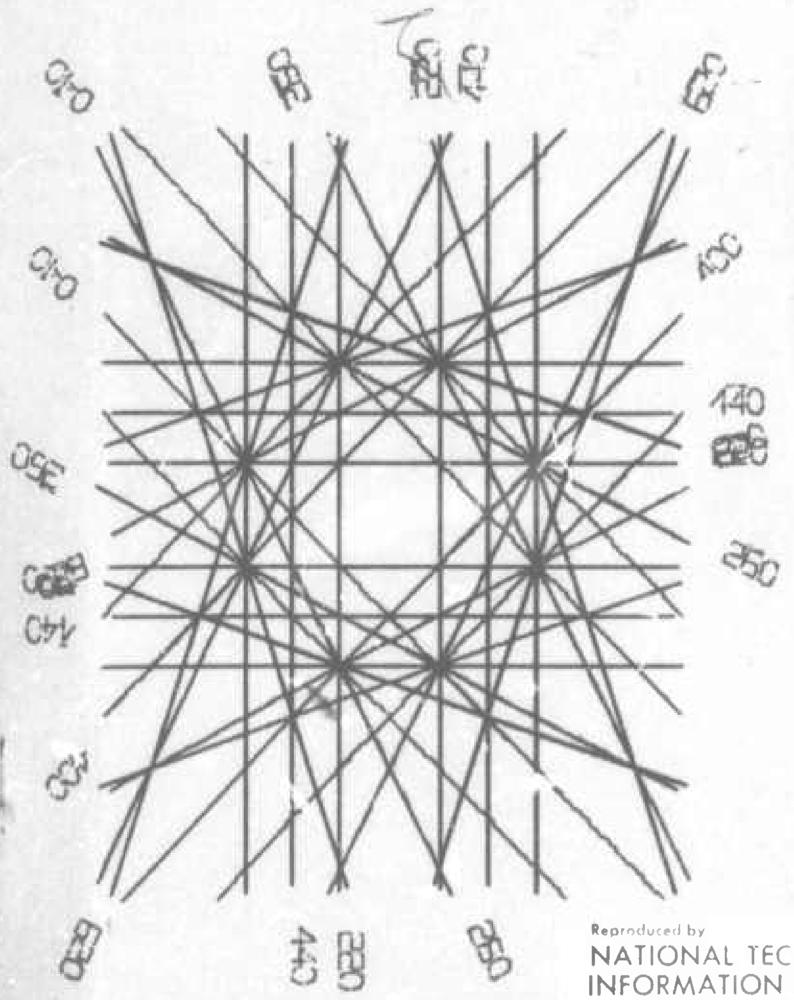

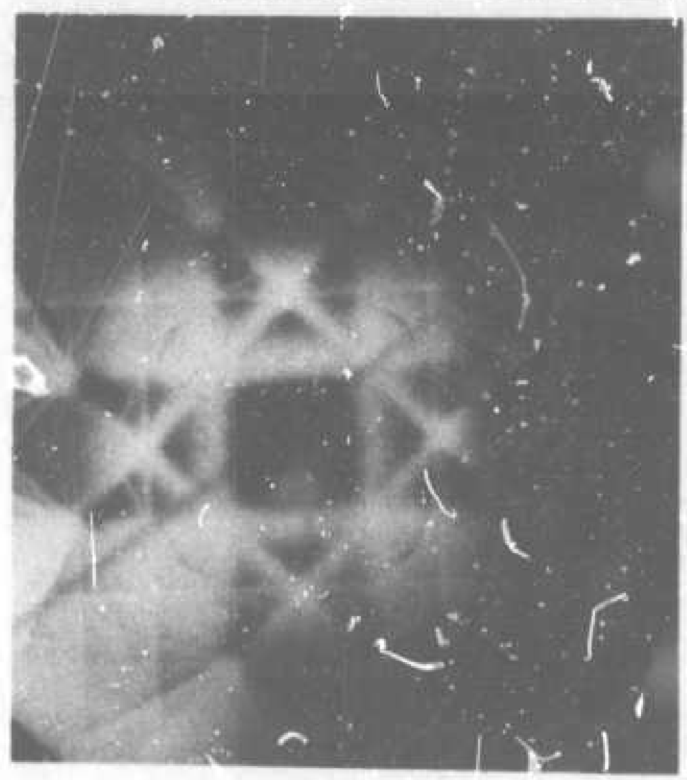

Kikuchi Map of (001) Silicon.
(Left) Computer generated.
(Right) Micrograph taken with
200 keV electrons.

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13. ABSTRACT

This report summarizes investigations done during the contract period of January 1, 1975, to June 30, 1975. It describes work dealing with improvements of advanced measurement techniques. Chapter 1 deals with the computer generation of Kikuchi patterns needed for complex structural analysis of crystal defects in silicon. The program is applicable to a large variety of problems and can be used to generate Kikuchi maps for different crystal structures, each desired crystal orientation, and electron energy. The program can also be used to generate channeling patterns for scanning electron microscopy application. The report provides a complete set of computer-generated Kikuchi maps for silicon and 200 keV electrons. A complete program in Fortran IV using an IBM 1800 computer is also given. The second part describes the application of MOS C-V and MOS G-V measurements for the evaluation of epitaxial films on silicon or insulator substrates. It is shown that the presence of an underlying junction requires important precautions with use of the MOS C-V measurement technique. The junction requires an increased number of components in the equivalent network, which impedes the analysis. This chapter shows how to solve the problem. Values for MOS dot diameter, layer and substrate resistivity, oxide thickness, etc. are given and refer to ranges where meaningful lifetime measurements can be carried out.

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Security Classification

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Defect analysis						
Kikuchi patterns						
Transmission electron microscopy						
Epitaxial layers						
Lifetime measurements						

CONTENTS

Chapter 2

Electrical Characterization of Quasi MOS Structures on Silicon

by W. R. Fahrner, E. F. Gorey, and C. P. Schneider

LIST OF INVESTIGATORS

The project is supervised by Dr. G. H. Schwuttke, principal investigator. The following people contributed to the work in this report:

Dr. W. Fahrner	-	Investigator (Visiting Scientist)
Dr. H. Kappert	-	Investigator (Visiting Scientist)
Dr. G. H. Schwuttke	-	Principal Investigator
Mr. E. F. Gorey	-	Technical Support
Mr. C. P. Schneider	-	Technical Support
Mr. H. Ilker	-	Technical Support

SUMMARY

This report summarizes work done during the contract period of January 1, 1975 to June 30, 1975. It describes research programs dealing with improvements of advanced measurement techniques. Such improvements became imperative during the course of the contract work and are needed for subsequent structural and electrical characterization of impact sound stressed (ISS'ed) silicon wafers before and after oxidation and epitaxy.

The first chapter advances the analytical capabilities of transmission electron microscopy through the application of computer-generated Kikuchi patterns. Kikuchi lines in electron diffraction patterns are used for complex crystal defect analysis based on two-beam orientation of the specimen. Since our Hitachi microscope permits seeing only about 4° of a diffraction pattern it is impossible to index Kikuchi lines without a detailed Kikuchi map. Therefore it was necessary to computer-generate Kikuchi plots. A program for the generation of such plots was written. The program was used to generate Kikuchi maps for the three main orientations (001), (011) and (111) for Si and 200 keV electrons.

An additional benefit of this computer program is that it is applicable to a large variety of problems. By changing proper parameters the same program can be used to generate maps for all kinds of crystal structures, each desired crystal orientation, electron energy, crystallographic order and maximum index-number of lines. The program considers also parameters such as map-scales and camera length of the microscope.

In addition the program can be used to compute and print out channeling patterns used for crystal orientation analysis in the scanning electron microscope. The report provides a complete set of Kikuchi maps for silicon and 200 keV electrons as well as the complete program to generate other patterns.

The second part of the report describes the application of MOS C-V measurements to the evaluation of epitaxial silicon films on silicon or insulator substrates. It is shown that the presence of a semiconductor junction under the MOS structure requires certain considerations to be made if meaningful measurements are to be obtained. The junction requires an increased number of components in the equivalent network, which impedes the analysis.

A solution to this problem is given. If one side of the junction is oxidized, a quasi MOS structure is obtained. The equivalent network of such a structure is discussed and the conditions for MOS C-V and G-V measurements are given. When the MOS admittance can be measured the following information can be obtained:

1. Surface-state density, the corresponding capture cross sections, the charge density in the oxide, and deep energy levels.

2. The doping concentration.

3. The minority carrier lifetime.

The discussion concentrates on the measurement of minority carrier lifetime in epitaxial silicon films. Values for layer and substrate resistivity, dot diameter, oxide thickness, etc., are given to establish the range for this "Quasi MOS Capacitance Technique."

Chapter 1

COMPUTER GENERATION OF KIKUCHI MAPS FOR TRANSMISSION ELECTRON MICROSCOPY (TEM) AND SCANNING ELECTRON MICROSCOPY (SEM) INVESTIGATIONS

by
H. Kappert

INTRODUCTION

Electron diffraction patterns of samples of very good crystalline perfection and of a thickness such that inelastic scattering of electrons is fairly high, show a distinct line structure superimposed on the background intensity. This line pattern is known as the Kikuchi pattern. A similar pattern (known as Coates or channeling pattern) appears in the SEM when the intensity of the backscattered electrons is recorded as an angular dependence of the incoming beam in reference to the sample orientation.

Several applications of the TEM technique such as Burgers vector determination, crystal orientation determination, and indexing of unknown spot pattern make use of such Kikuchi patterns (1-8). For such applications it is convenient to have Kikuchi maps which show the geometrical configuration of the pattern and give the indices of all lines in it.

One way to obtain such maps is to take many images in the TEM of overlapping parts of the diffraction pattern for different tilt angles of the specimen and assemble these images in a composite map. Another way is to generate plots of indexed

Kikuchi maps through a computer. The advantage of the second way is that once a program is available it is very easy to select any desired crystalline structure, sample orientation, different wavelength of electrons or even x-rays, scale of map, or order of Kikuchi lines, just by changing some parameters in the program.

To generate Kikuchi maps very good instructions can be found in the literature (4,7,9). We followed mainly the recipe given by C. T. Young and J. L. Lytton (9).

GEOMETRY

Kikuchi lines are originated by inelastically scattered electrons in the specimen. The energy losses of these electrons are small enough that they still can be considered coherent, but they have changed direction in reference to the primary electron beam. Therefore, in spite of the primary beam being off Bragg angle θ for a certain set of net planes, a particular fraction of the inelastically scattered electrons makes a Bragg reflection at these planes, e.g., (h, k, l) in Fig. 1. This can be regarded as a virtual incoming electron beam for each set of net planes, which is split below the specimen into a transmitted and a diffracted part. We find this situation not only in the plane that corresponds to the plane of the drawing in Fig. 1 but in all directions whenever the Bragg

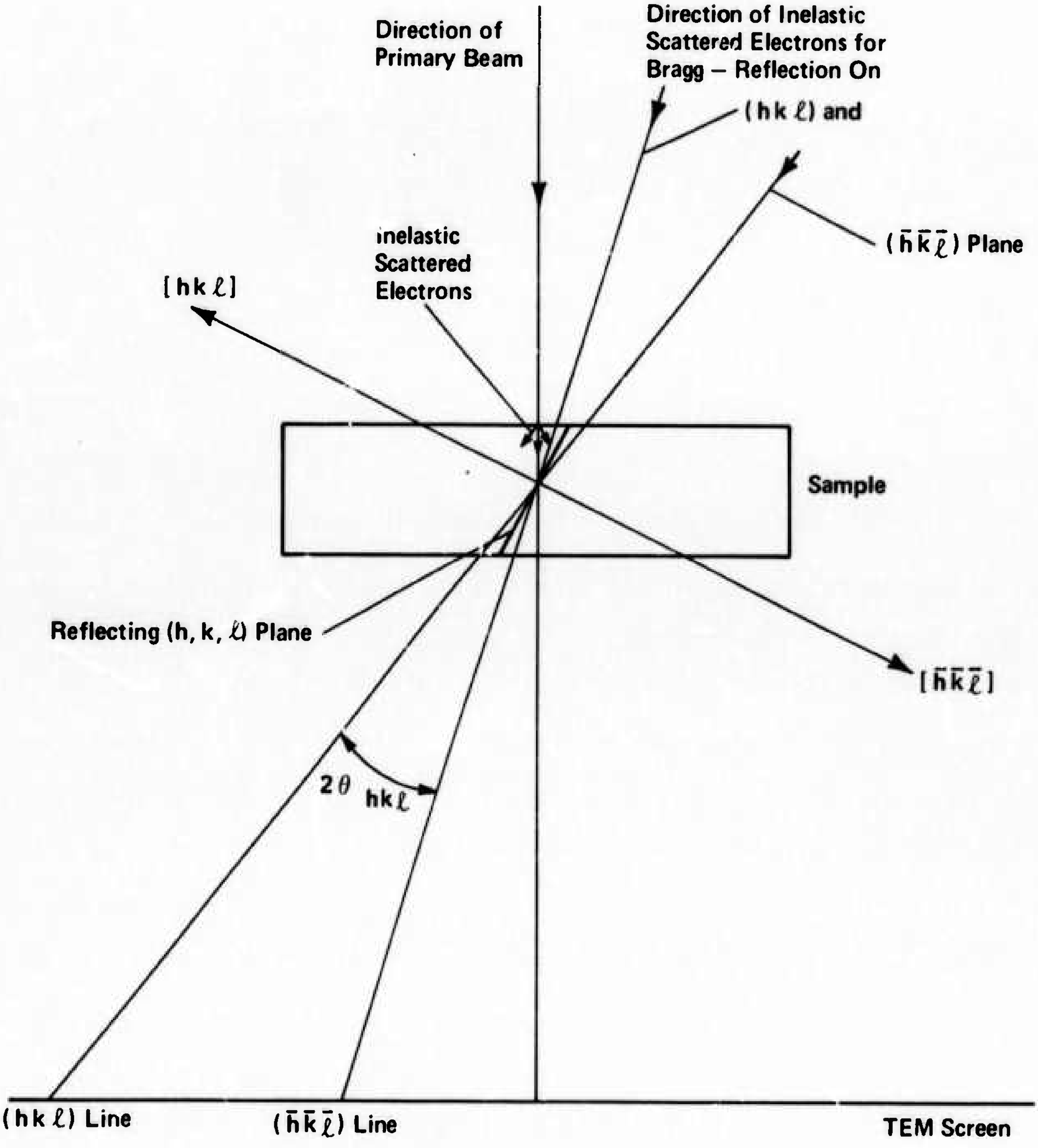


Fig. 1. Geometry for formation of Kikuchi lines.

condition is satisfied for the (h, k, l) plane. Therefore all the directions of the particular fraction of elastically scattered electrons in Bragg conditions for a certain set of net planes (h, k, l) are represented by a cone (Fig. 2), where the cone axis is in the direction of the plane normal (h, k, l) and the half opening angle is 90°-θ (Kossel cone). The same geometry can be used for channeling patterns in the SEM. In the SEM the primary beam itself has to be tilted along a cone surface to get a signal of the backscattered electrons with less or more intensity than for the background intensity that appears as dark or bright lines on the TV display.

The real Kikuchi line pattern is the intersection of all the cones produced by the different sets of net planes, with the image plane in the TEM below the specimen. The real channeling pattern is the intensity modulation of the backscattered electrons above the sample, as seen by the collector and displayed on the TV screen, dependent on the tilt angle of the primary beam in reference to the sample orientation.

The usual way to generate Kikuchi and channeling maps is to make a stereographic projection of all the cones, which are thus represented as circles on the projection sphere (Fig. 2). This may be done because the projection keeps the angles between intersecting lines or circles on the sphere constant, results in only small distortions of the distances especially

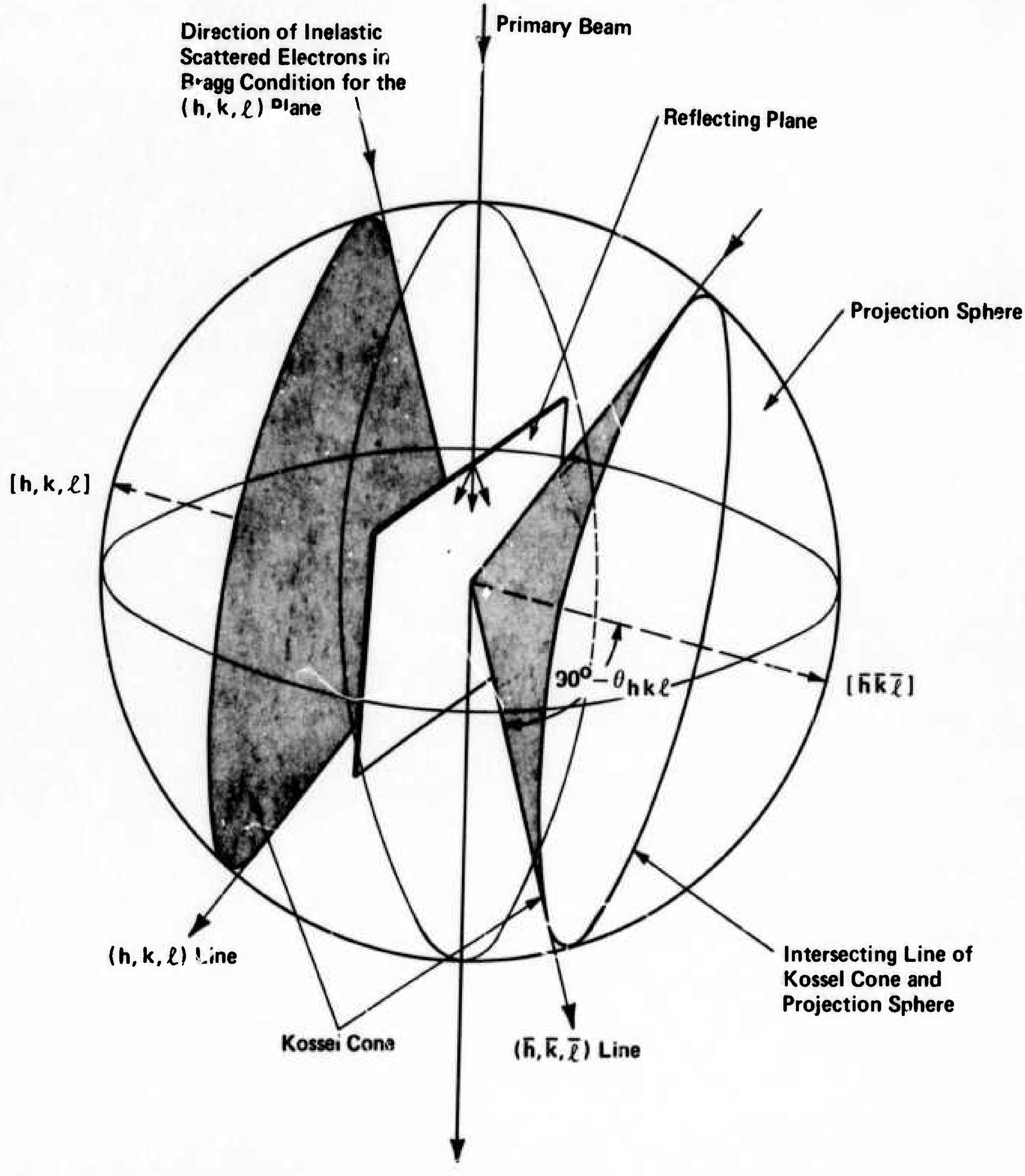


Fig. 2. Geometry of Kossel cones and their intersection with the projection sphere.

close to the center pole , and has the advantage that standard stereographic pole maps can be used for indexing purposes. The stereographic projection of the intersecting lines of the diffraction cones with the projection sphere appears as circles in the projection plane, which are called Kikuchi circles. The radius and center of each Kikuchi circle has to be calculated. Subsequently the part of the circle that is within the plotting area has to be determined and to be drawn.

ORIENTATION

Standard stereographic projections are made from G to O and are observed from the top, as shown in Fig. 3. The channeling patterns in the SEM are observed in the same way. To find the correct orientation between standard stereographic pole maps, channeling map and channeling pattern on the screen, we have only to consider which lenses are used to focus the primary beam onto the sample surface and how the tilt angle is related to the TV display.

The G to O direction of the standard stereographic projection, as shown in Fig. 3, is just the opposite to the direction in which the electrons go in the TEM to form the Kikuchi pattern on the screen. One gets around this orientation problem

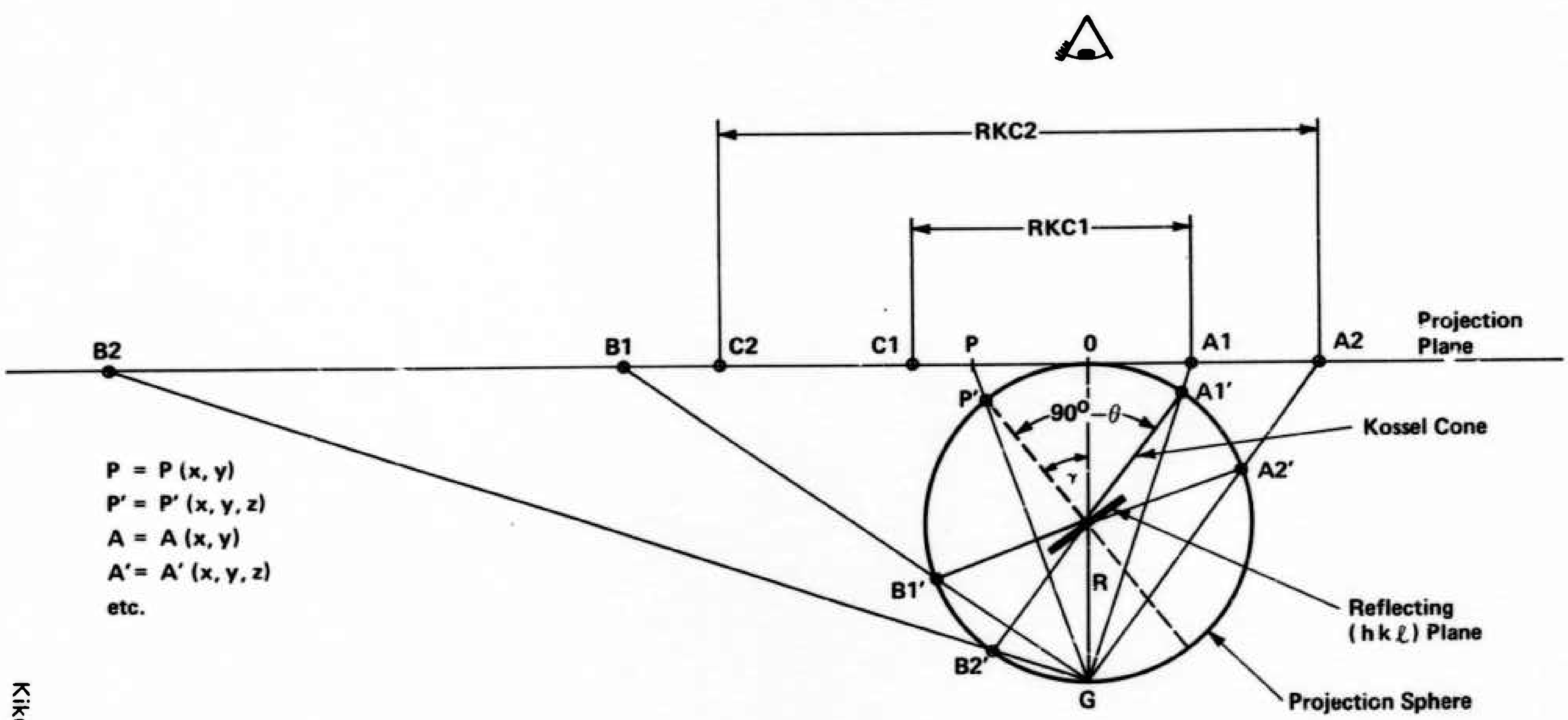


Fig. 3. Used projection and geometry to calculate radius and center of the Kikuchi circles.

by turning the projection upside down (1). Therefore standard stereographic projections have to be inverted for indexing purposes. Another possibility is to use the standard stereographic projection without inversion. This requires an adjustment of the Kikuchi maps such that the indexed reflections in the diffraction pattern correspond to the planes in the crystal. From the geometry shown in Fig. 2, one can see that the cone representing the directions of diffracted electrons intersects the projection sphere at the lower hemisphere as well as at the upper hemisphere. A downward projection--that is, the unconventional projection from O to G (Fig. 3)--would result in the real Kikuchi map as seen on the TEM screen.

An upward projection--that is, the conventional stereographic projection from G to O (Fig. 3)--results in the same map, except that this one is rotated by 180° in reference to the real Kikuchi pattern on the TEM screen. To do it this way was recently proposed by Head et al. (10). We decided to use this method because a rotation of 180° is more convenient than a mirror inversion, and we can use standard stereographic projections as in x-ray studies.

The correct orientation between the sample, the TEM micrograph, the diffraction pattern, standard pole map and Kikuchi map is found as follows:

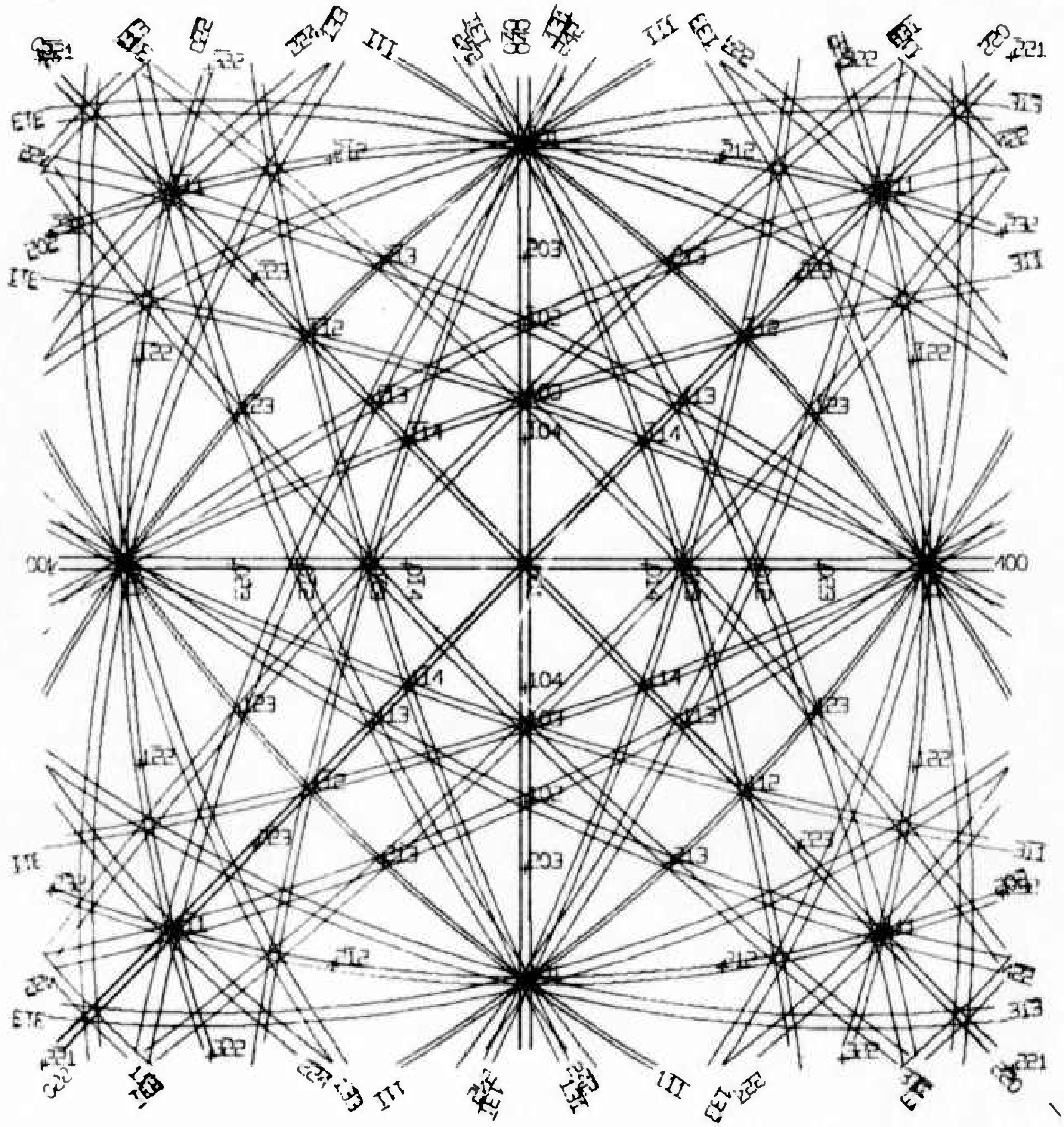


Fig. 4. (001) map for Si 200 keV, xo = yo = 11cm, R = 11cm, RMN = 2, SMSQ = 5.

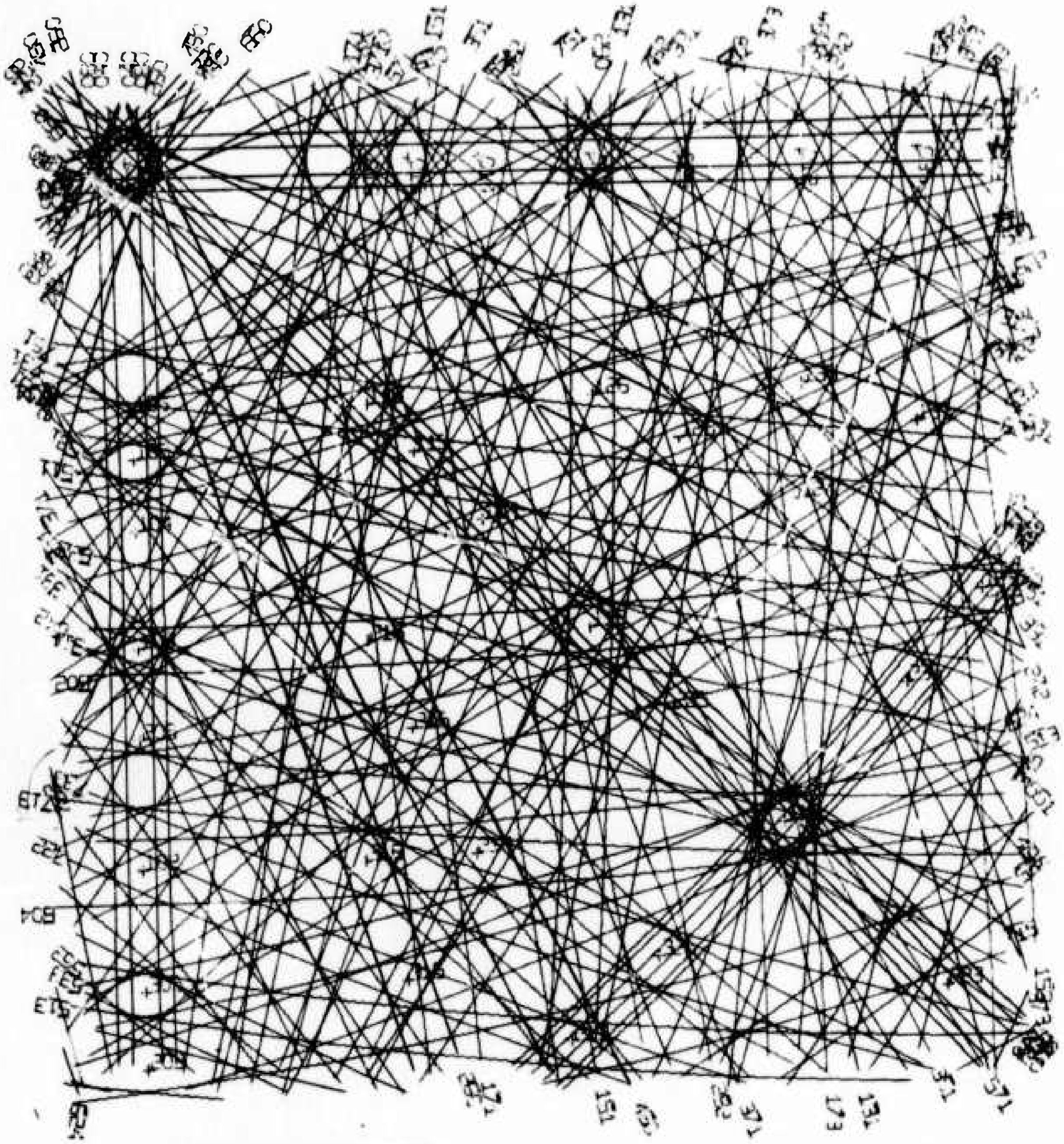


Fig. 5. (001) map for Si 200 keV, $x_0 = y_0 = 20$cm, R = 32cm, RMN = 4, SMSQ = 9.

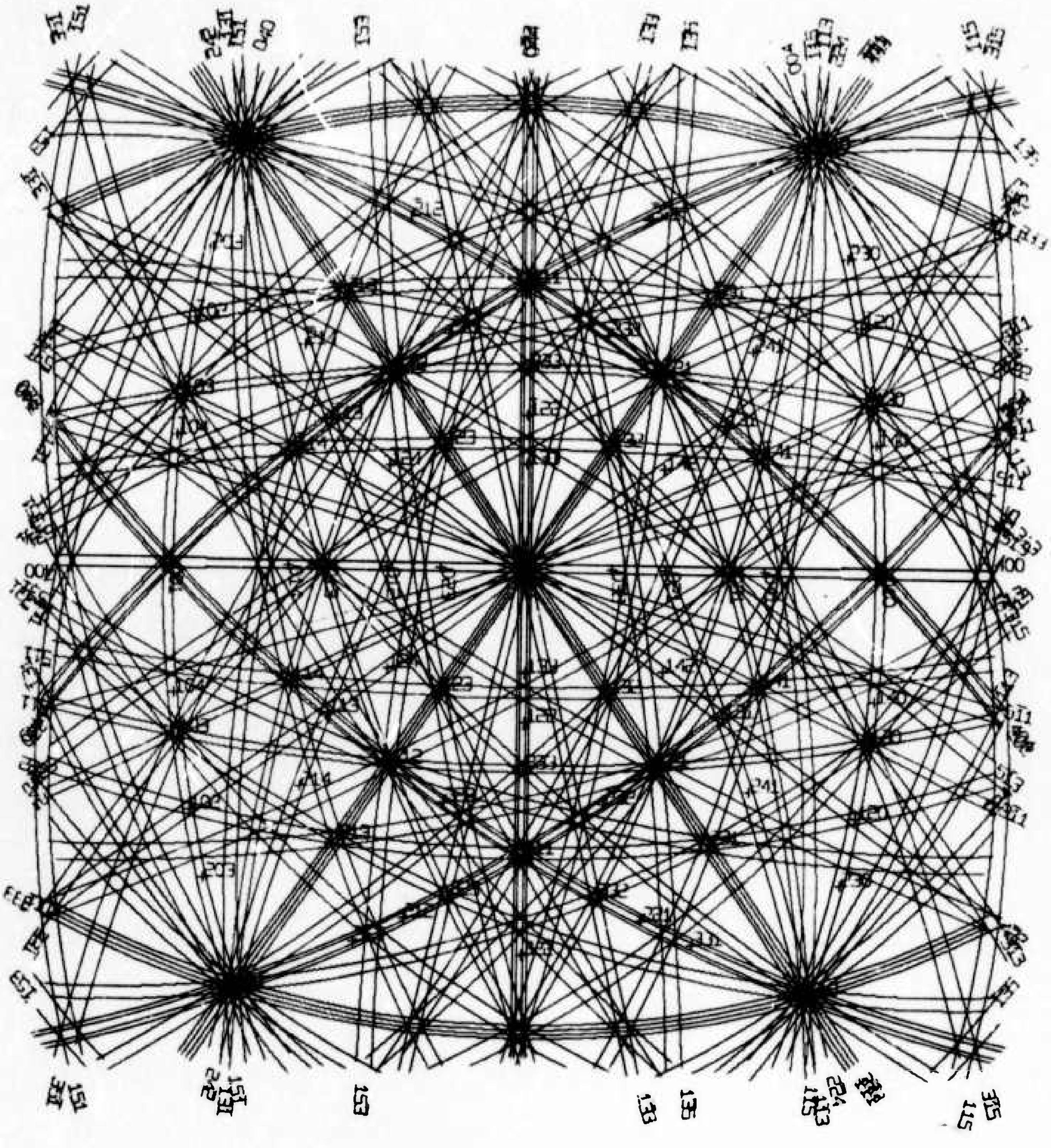


Fig. 6. (011) map for Si 200 keV, xo = yo = 12cm, R = 11cm, RMN = 4, SMSQ = 5.

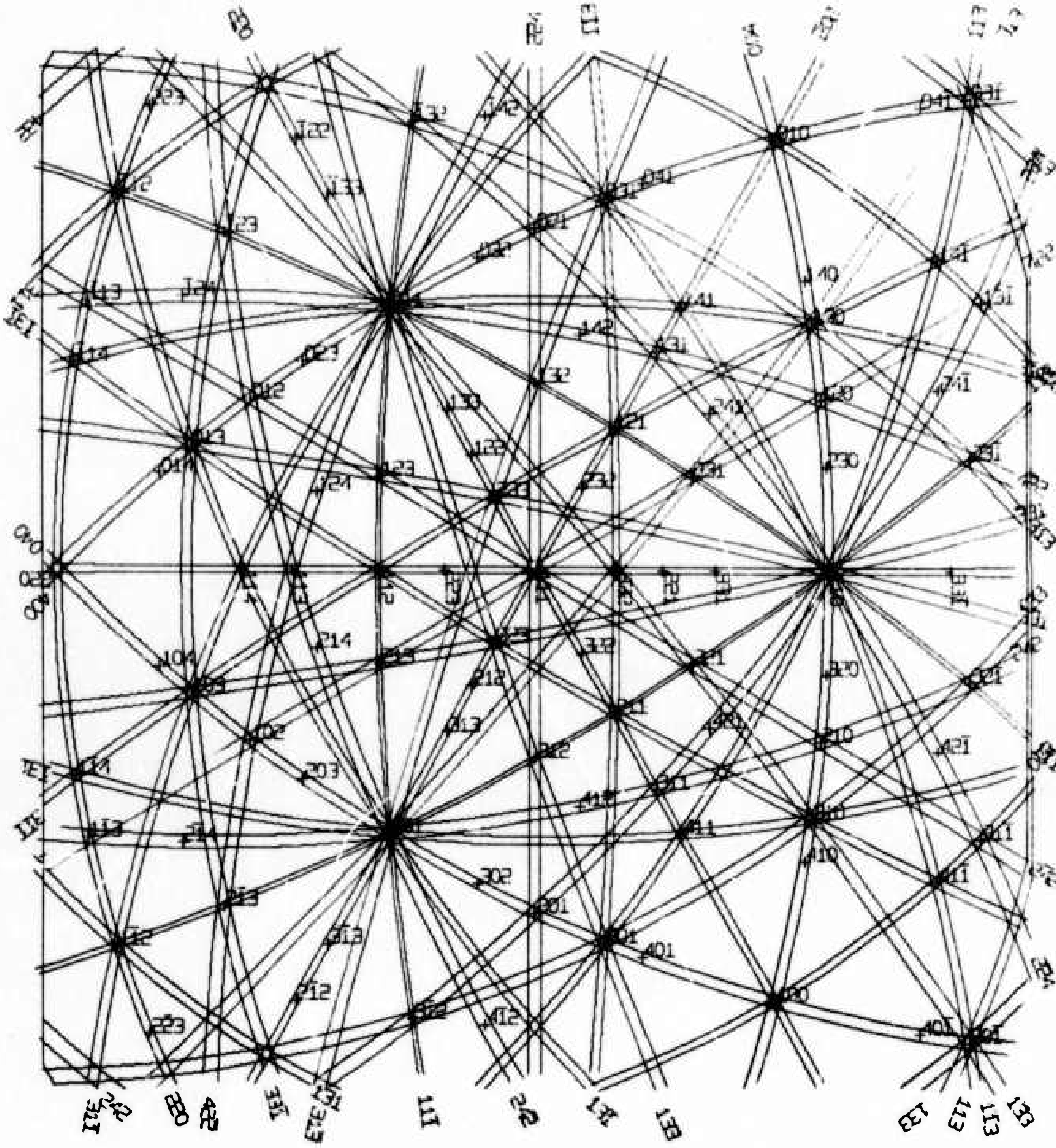


Fig. 7. (111) map for Si 200 keV, xo = yo = 12cm, R = 11cm, RMN = 2, SMSQ = 5.

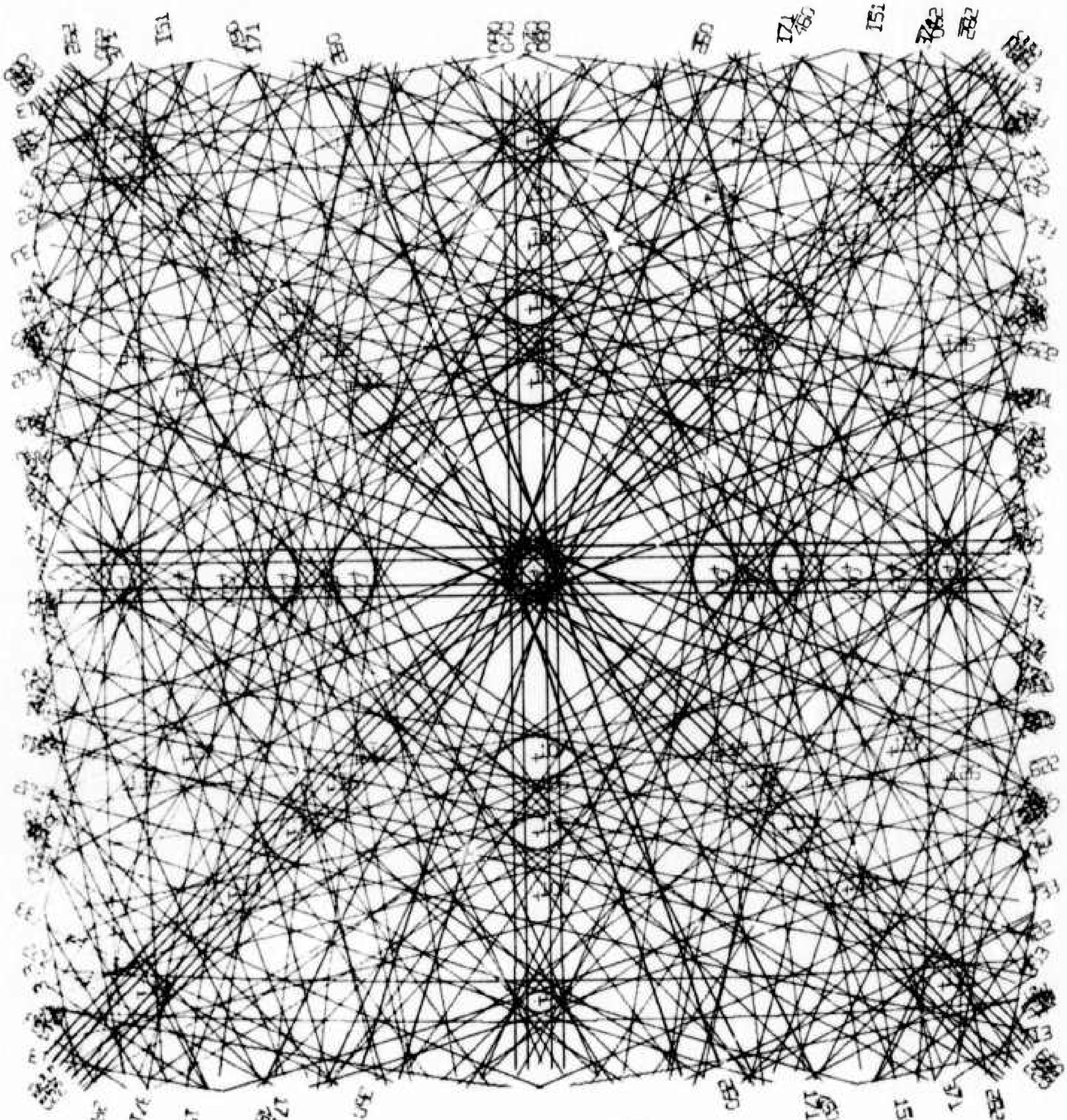


Fig. 8. (001) map for Si 200 keV, xo = yo = 12cm, R = 32cm, RMN = 4, SMSQ = 9.

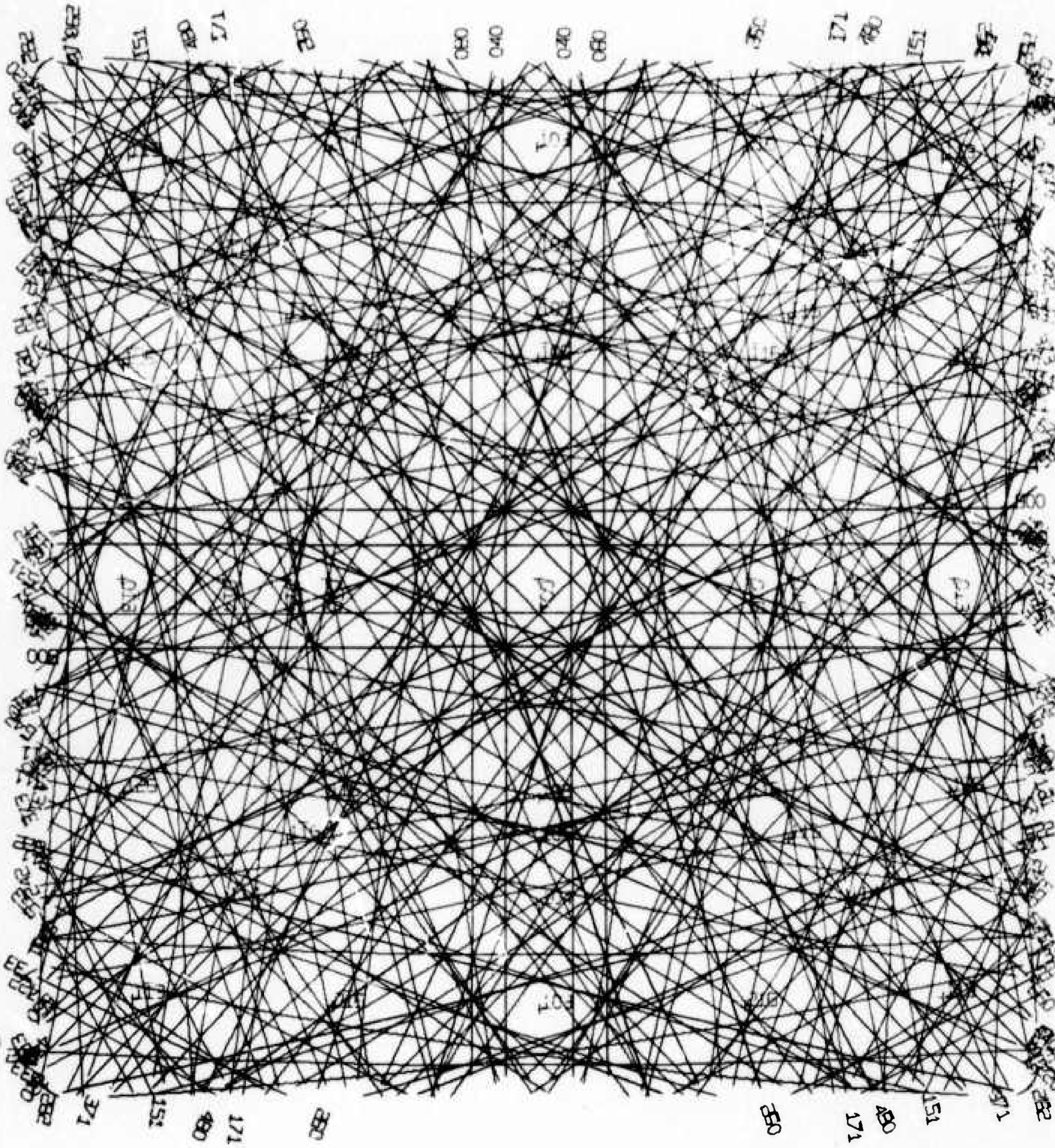


Fig. 9. (001) map for Si 30 keV, xo = yo = 12cm, R = 32cm, RMN = 4, SMSQ = 9.

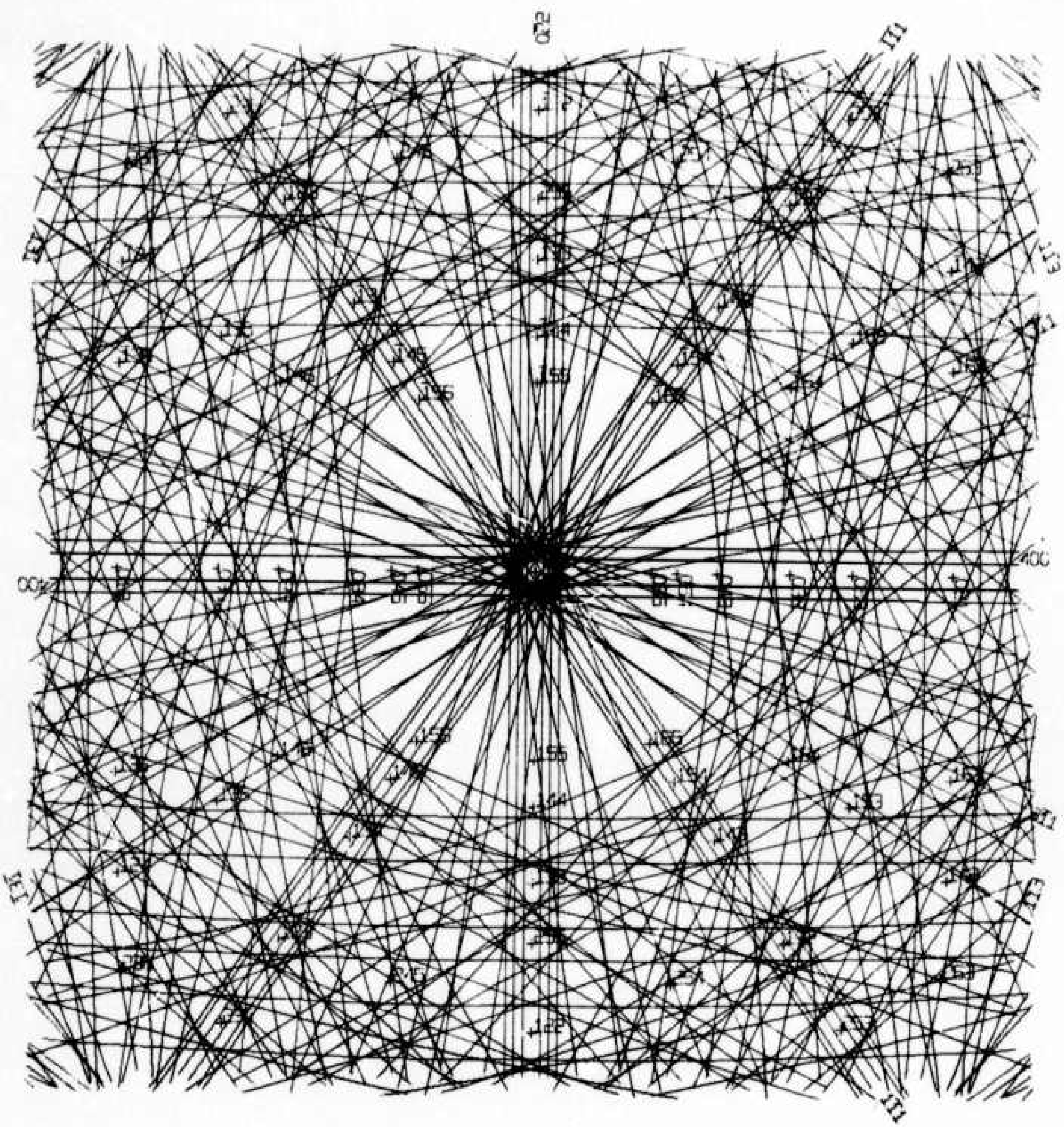


Fig. 10. (011) map for Si 200 keV, xo = yo = 12cm, R = 32cm, RMN = 4, SMSQ = 9.

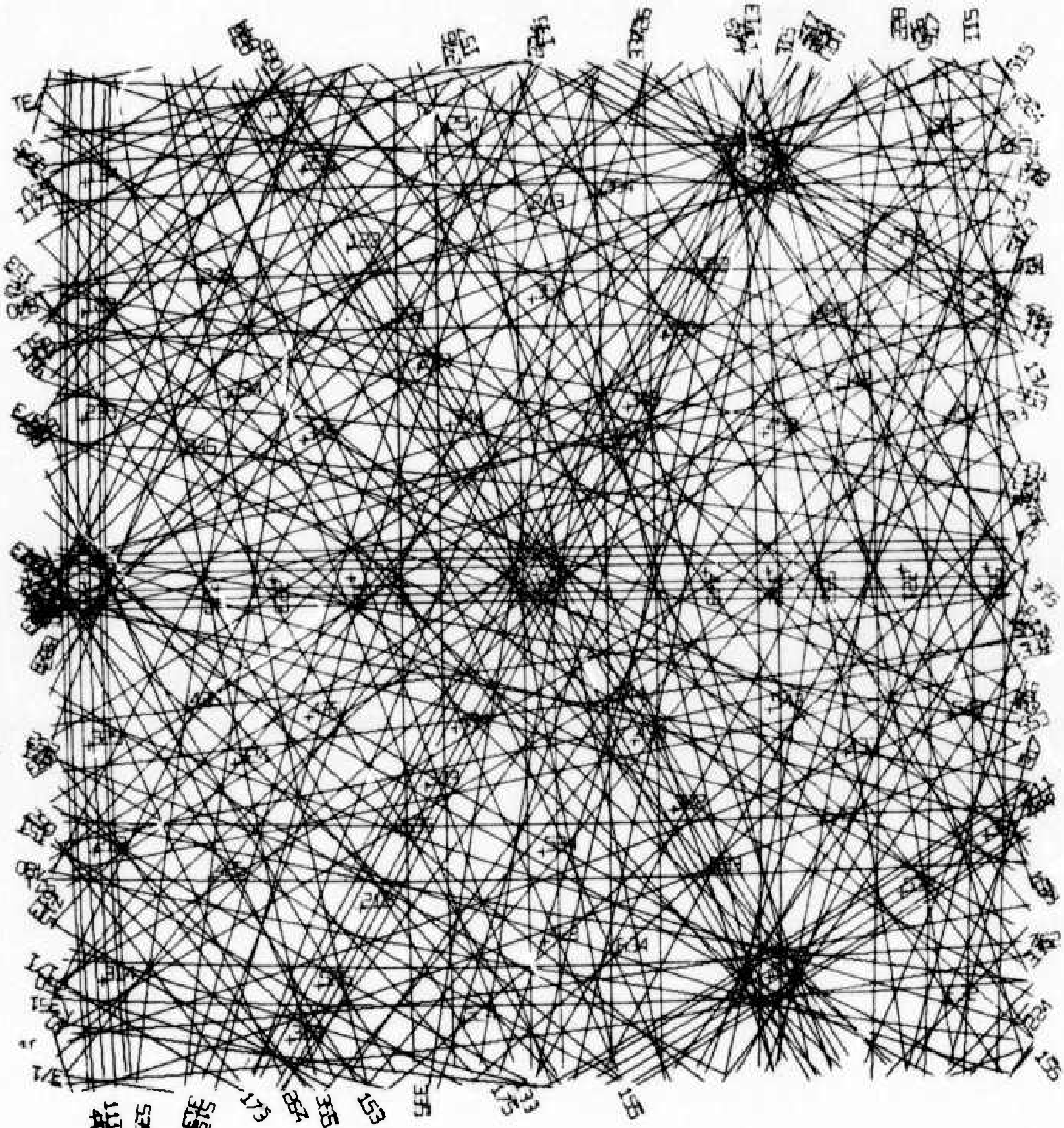


Fig. 11. (111) map for Si 200 keV, xo = yo = 12cm, R = 32cm, RMN = 4, SMSQ = 9.

1. Consider the rotation between micrograph and diffraction pattern that depends on the number of lenses used and their excitation.

2. Orient the Kikuchi plot the same way as the TEM Kikuchi pattern and take negative values of the pole indices as plotted in the map.

3. Rotate a standard stereographic pole map with the same center pole as the Kikuchi plot by 180° in reference to the pole map plotted within the Kikuchi map.

To avoid any other inversion or rotation we have to use both negatives and prints of the micrograph as recorded in the TEM on the screen.

THE PROGRAM

The program is written in Fortran IV for an IBM 1800 computer. The time used to generate one plot depends on the number of lines that have to be plotted. For example, the plot shown in Fig. 4 takes less time than the plot shown in Fig. 6, where higher order and higher index lines appear. The time for the plot in Fig. 6 was about 50 min. The attached program was used for this plot. Figures 6-11 show different plots generated with the same program when parameters used are as described in each figure caption.

Steps of the program:

1. <u>Selection of diffraction planes</u>

The usual structure factor equation:

$$F = \sum_{j=1}^{n} f_j \exp\,[2\pi i\,(u_j\,h + v_j\,k + w_j\,l] \qquad (1)$$

is used to calculate the structure factors for silicon so that the planes can be selected which give the Bragg reflections. For this calculation the coordinates u, v, w of the position of the 8 atoms in the Si unit cell have to be put into (1). The Bragg equation is used in the form

$$\theta_{hkl} = \frac{\lambda}{2a}\sqrt{h^2 + k^2 + l^2} = 0.0023\sqrt{h^2 + k^2 + l^2} \qquad (2)$$

for 200 keV electrons and Si samples to calculate the Bragg angles θ_{khl} for each plane.

2. <u>Transition to desired orientation with coordinates X31, X32, X33</u>

The coordinate transformation

$$\begin{pmatrix} XH \\ XU \\ XL \end{pmatrix} = \begin{pmatrix} h_1/\sqrt{s_1} & k_1/\sqrt{s_1} & l_1/\sqrt{s_1} \\ h_2/\sqrt{s_2} & k_2/\sqrt{s_2} & l_2/\sqrt{s_2} \\ h_3/\sqrt{s_3} & k_3/\sqrt{s_3} & l_3/\sqrt{s_3} \end{pmatrix} \begin{pmatrix} XHS \\ XUS \\ XLS \end{pmatrix} \qquad (3)$$

is used where (h_3, k_3, l_3) = (X31, X32, X33). The other vectors (h_1, k_1, l_1) and (h_2, k_2, l_2) have to be chosen in accordance with a right-handed Cartesian system.

$s_i = h_i^2 + k_i^2 + l_i^2$.

3. <u>Rejection of high-index and high-order planes</u>

Planes of high-index numbers larger than a maximum number SMSQ = $\sqrt{h^2 + k^2 + l^2}$ have to be rejected; the same is true for planes of higher order than maximum order RMN.

4. <u>Calculation of coordinates in the projection plane</u>

The coordinates of one intersection point of the diffraction cone with the projection sphere have to be calculated. For this purpose spherical polar coordinates are introduced. Then the calculation of the coordinates within the projection plane has to be performed by the equation

$$P_x = 2R \quad \tan \gamma/2 \; \frac{P_x'}{(P_x'^2 + P_y'^2)^{1/2}}$$

$$P_y = 2R \quad \tan \gamma/2 \; \frac{P_y'}{(P_y'^2 + P_y'^2)^{1/2}} \qquad (4)$$

where $\gamma = \cos^{-1} (P_z'/R)$, as can be seen from Fig. 3.

5. <u>Determination of the radius and center of the Kikuchi circle</u>

From Fig. 3 it can be deduced that the radius of the Kikuchi circle is

$$\overline{CA} = 1/2\ (\overline{BO} + \overline{OA}) \qquad (5)$$

and the coordinates of the circle center C are

$$CX = P_x\ (\overline{CO}/\overline{PO})$$
$$CY = P_y\ (\overline{CO}/\overline{PO})$$

6. <u>Provision for an (x,y) array for the plot</u>

Only a small part of the Kikuchi circle in an area with radius RI=SQRT (XO x XO + YO x YO) around the center pole has to be plotted. Therefore it has to be checked whether a particular Kikuchi circle has a part of it inside this area. Then the circle equation

$$[X - CX]^2 + [Y - CY]^2 = R^2 = [\overline{CA}]^2 \qquad (6)$$

is used to provide an array of 50 (x,y) pairs for the plotter.

7. <u>Plotting section</u>

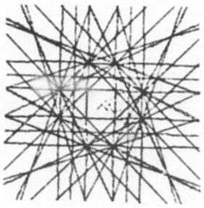
A final check is made to find out which values of the array are inside the plotting square given by XO and YO. The slope of the lines near the border of this square is determined in order to plot the indices of this Kikuchi line pair at the end of the line with the same slope.

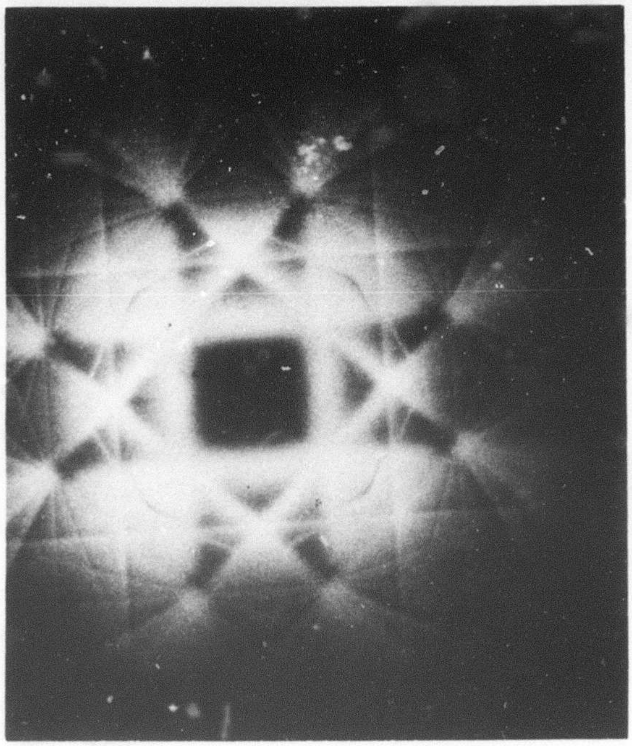
8. Plotting the pole map

An extra program was written to produce pole maps of the same scale as the Kikuchi map. The steps are essentially similar to steps 2, 3, and 4 above.

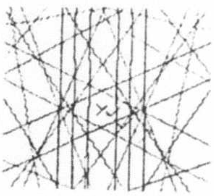
RESULTS

The size of each plot is about 24 x 24 cm^2, which is the maximum usable size of the plotter used. The numbers inside the map represent the indices of the pole where the location is indicated by a +. The numbers outside the map represent the indices of a certain Kikuchi line pair. The indices are plotted at one end of the respective Kikuchi line with the same slope as the lines at this end. Figures 4, 5, 6, and 7 represent (001), (011), and (111) Kikuchi maps with the same scale for Si with 200 keV electrons. Figures 8, 10, and 11 again represent (001), (011), and (111) Kikuchi maps for Si with 200 keV electrons but for about three times larger scale and with higher-order and higher-index lines. Figure 5 is a larger scale plot of the lower-right quadrant of Fig. 4; and Fig. 9 is the same plot as Fig. 8 but with 30 keV electrons and can be used as a map for channeling pattern for the SEM. Figure 12 gives several examples of Kikuchi poles as shown on the maps and in the TEM.





(001) pole



(114) pole

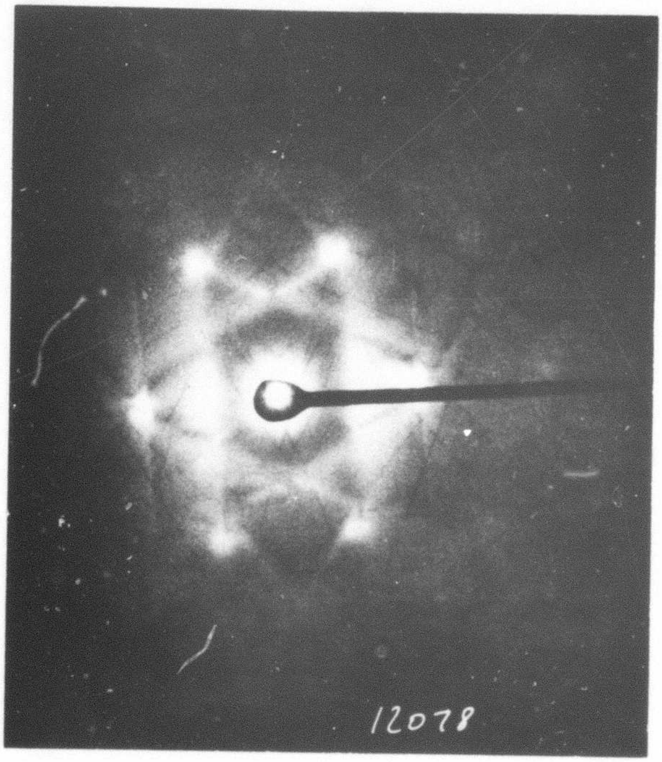
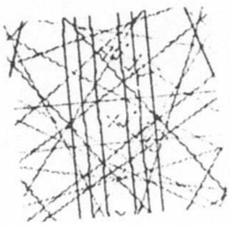
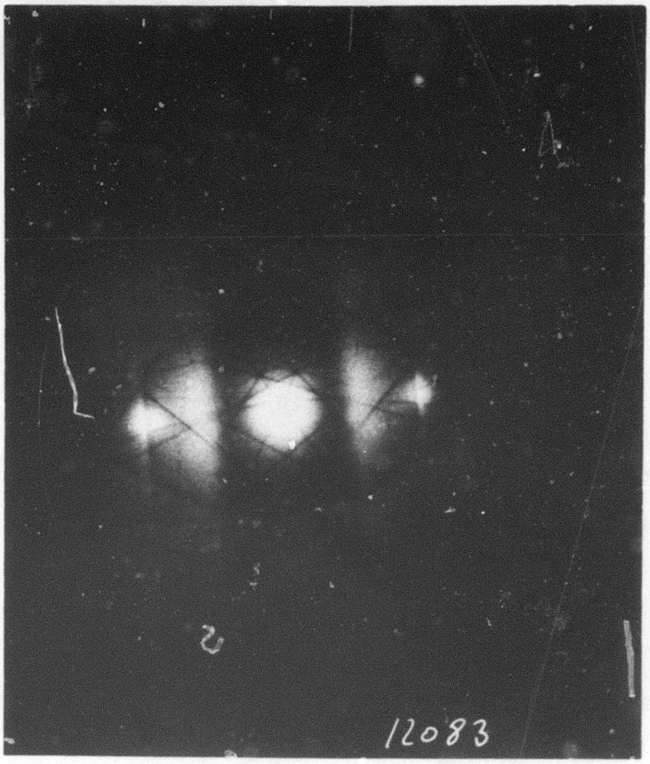


Fig. 12. Kikuchi poles of Si with 200 keV electrons as shown on the map of Fig. 5 and in the Hitachi TEM.



(116) pole



(115) pole

Fig. 12. Kikuchi poles of Si with 200 keV electrons as shown on the map of Fig. 5 and in the Hitachi TEM.

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REFERENCES

1. P. B. Hirsch et al., Electron Microscopy of Thin Crystals, Butterworths, 1965.
2. S. Amelinckx et al., Modern Diffraction and Imaging Techniques in Material Science, North Holland, 1970.
3. L. E. Murr, Electron Optical Applications in Materials Science, McGraw Hill, 1970.
4. E. Levine et al., J. Appl. Phys. 37, 2141 (1966).
5. P. R. Okamoto et al., J. Appl. Phys. 38, 289 (1967).
6. M. V. Heimendahl, Phys. Stat. Sol. (a) 5, 137 (1971).
7. J. C. Bomback and L. E. Thomas, J. Appl. Cryst. 4, 356 (1971).
8. W. K. Wu and J. Washburn, J. Appl. Phys. 45, 1085 (1974).
9. C. T. Young and J. L. Lytton, J. Appl. Phys. 43, 1408 (1972).
10. A. K. Head et al., Computed Electron Micrographs and Defect Identification, North Holland, 1973.

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*IOCS(CARD, 1443 PRINTER)
*IOCS (PLOTTER)
*TRANSFER TRACE
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      INTEGER H,HI,H1A,HA                                             KIKU0000
      DIMENSION U(8),V(8),W(8),CX(2),CY(2),RKC(2),                    KIKU0001
     1X(50),Y(50),XP(50),YP(50),SF(17,17,9)                           KIKU0002
C
C  READ LATTICE PARAMETER
C
      DO 10 I=1,8                                                     KIKU0010
      READ (2,7) U(I),V(I),W(I)                                       KIKU0012
    7 FORMAT (3F6.2)                                                  KIKU0014
   10 CONTINUE                                                        KIKU0016
C
C
C  READ R OF STEREO SPHERE
C
      READ (2,8) R                                                    KIKU0020
    8 FORMAT (1F6.2)                                                  KIKU0022
C
C  R1=RADIUS OF PLOTTING CIRCLE; X0,Y0 PLOTTING SQUARE
C
      X0=12.5                                                         KIKU0023
      Y0=12.5                                                         KIKU0024
      R1=SQRT(X0*X0+Y0*Y0)                                            KIKU0025
C
C   PRODUCE (H,K,L) VALUES
C
      DO 19 H=1,9                                                     KIKU0050
      H1=H-1                                                          KIKU0051
      DO 29 K=1,9                                                     KIKU0060
      K1=K-1                                                          KIKU0061
      DO 39 L=1,9                                                     KIKU0070
      L1=L-1                                                          KIKU0071
C
C  CALCULATE STRUCTURFACTOR
C
      F1=0.0                                                          KIKU0080
      F2=0.0                                                          KIKU0085
      THET=0.0                                                        KIKU0090
      DO 50 M=1,8                                                     KIKU0095
      A=6.28*(U(M)*H1+V(M)*K1+W(M)*L1)                                KIKU0100
      F1=F1+COS(A)                                                    KIKU0105
      F2= F2+SIN(A)                                                   KIKU0106
   50 CONTINUE                                                        KIKU0107
      F=ROUND(F1**2+F2**2)                                            KIKU0110
      SF(H,K,L)=F                                                     KIKU0117
   39 CONTINUE                                                        KIKU0118
   29 CONTINUE                                                        KIKU0119
   19 CONTINUE                                                        KIKU0120
      XSCAL=0.39
      YSCAL=XSCAL                                                     KIKU5207
      CALL SCALF (XSCAL,YSCAL,0.0,0.0)                                KIKU5208
      DO 20 H=1,17                                                    KIKU0122
```

```
      H1=H-9                                                        KIKU0123
      H1A=IABS(H1)+1                                                KIKU0123
      DO 30 K=1,17                                                  KIKU0124
      K1=K-9                                                        KIKU0125
      K1A=IABS(K1)+1                                                KIKU0125
      DO 40 L=1,17                                                  KIKU0126
      L1=L-9                                                        KIKU0127
      L1A=IABS(L1)+I                                                KIKU0127
      F=SF(H1A,K1A,L1A)                                             KIKU0128
      IF(F-1.)  40,40,60                                            KIKU0129
   60 SO=SQRT(FLOAT(H1*H1+K1*K1+L1*L1))                             KIKU0190
C
C  BRAGG ANGLE 200 KV LAMBDA=0.0251 AE,SI A=5.4308 AE
C
      THET=0.0023*SO                                                KIKU0195
C
C
C  SELECT PLANES OF LOW INDEX
C
      SMSQ=5.                                                       KIKU0200
      IF(SMSQ-SQ) 40,40,140                                         KIKU0205
C
C  CALCULATE COORDINATES ON STEREO SPHERE
C
C  FOR POL (H1,K1,L1)
C
  140 IF (SQ-0.5) 40,40,141                                         KIKU0300
  141 XHS=R*H1/SQ                                                   KIKU0305
      XKS=R*K1/SQ                                                   KIKU0310
      XLS=R*L1/SQ                                                   KIKU0320
C
C  TRANSITION TO DESIRED ORIENTATION WITH COORD. X31,X32,X33
C
      X11=1.                                                        KIKU0360
      X12=0.                                                        KIKU0362
      X13=0.                                                        KIKU0364
      X21=0.                                                        KIKU0365
      X22=1.                                                        KIKU0366
      X23=-I.                                                       KIKU0367
      X31=0.                                                        KIKU0368
      X32=1.                                                        KIKU0369
      X33=1.                                                        KIKU0370
      S1=SQRT(X11*X11+X12*X12+X13*X13)                              KIKU0371
      S2=SQRT(X21*X21+X22*X22+X23*X23)                              KIKU0372
      S3=SQRT(X3I*X3I+X32*X32+X33*X33)                              KIKU0372
      A11=X11/S1                                                    KIKU0375
      A12=X12/S1                                                    KIKU0376
      A13=X13/S1                                                    KIKU0377
      A21=X21/S2                                                    KIKU0378
      A22=X22/S2                                                    KIKU0379
      A23=X23/S2                                                    KIKU0380
      A31=X31/S3                                                    KIKU0381
      A32=X32/S3                                                    KIKU0382
      A33=X33/S3                                                    KIKU0383
      XH=A11*XHS+A12*XKS+A13*XLS                                    KIKU0385
```

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                                                                     PAGE 003

      XK=A21*XHS+A22*XKS+A23*XLS                                     KIKU0386
      XL=A31*XHS+A32*XKS+A33*XLS                                     KIKU0387
      IF(XL) 40,130,130
C
C  REJECT PLANES OF HIGHER ORDER
C
  130 XI1=10000.*(H1A-1)+100.*(K1A-1)+(L1A-1)                        KIKU0390
      DO 80 IH=1,5                                                   KIKU0391
      IH1=IH-1                                                       KIKU0392
      DO 90 IK=1,5                                                   KIKU0393
      IK1=IK-1                                                       KIKU0394
      DO 100 IL=1,5                                                  KIKU0395
      IL1=IL-1                                                       KIKU0396
      IF(IH1+IK1+IL1) 100,100,101                                    KIKU0397
  101 DO 110 N=2,8                                                   KIKU0398
      XI2=N*(10000.*IH1+100.*IK1+IL1)                                KIKU0399
      ROXI=XI1-XI2                                                   KIKU0400
      AROX=ABS(ROXI)                                                 KIKU0402
      IF(AROX-0.1) 45,45,46                                          KIKU0403
   46 IF(ROXI) 100,45,110                                            KIKU0404
   45 DO 111 M=1,8                                                   KIKU0406
      IH5=IH1*M+1                                                    KIKU0407
      IK5=IK1*M+1                                                    KIKU0408
      IL5=IL1*M+1                                                    KIKU0409
      IG=IH1+IK1+IL1                                                 KIKU0410
      IF (IG) 111,111,43                                             KIKU0411
   43 FH=SF(IH5,IK5,IL5)                                             KIKU0412
      IF(FH-1.) 111,111,41                                           KIKU0413
  111 CONTINUE                                                       KIKU0415
   41 RN=FLOAT (N)                                                   KIKU0416
      RM=FLOAT(M)                                                    KIKU0417
      RMN=ROUND(RN/RM)                                               KIKU0418
      IF(RMN-4.) 252,252,40                                          KIKU0419
  110 CONTINUE                                                       KIKU0420
  100 CONTINUE                                                       KIKU0421
   90 CONTINUE                                                       KIKU0422
   80 CONTINUE                                                       KIKU0425
C
C  COORDINATES FOR DIFFR.CONE ON SPHERE
C
  252 IF (XH) 253,254,255                                            KIKU0440
  255 A1=XK/XH                                                       KIKU0442
      PHI=ATAN(A1)                                                   KIKU0444
      GO TO 261                                                      KIKU0446
  254 IF (XK) 257,256,256                                            KIKU0448
  256 C=0.                                                           KIKU0450
      S=1.                                                           KIKU0451
      GO TO 259                                                      KIKU0452
  257 C=0.                                                           KIKU0453
      S=-1.                                                          KIKU0454
      GO TO 259                                                      KIKU0455
  253 IF(XK) 258,260,258                                             KIKU0457
  258 A1=XK/XH                                                       KIKU0459
      PHI=ATAN(A1)+3.141593                                          KIKU0460
      GO TO 261                                                      KIKU0461
```

```
  260 C=-1.                                                     KIKU0462
      S=0.                                                      KIKU0463
      GO TO 259                                                 KIKU0464
  261 C=COS(PHI)                                                KIKU0465
      S=SIN(PHI)                                                KIKU0466
  259 IF (XL) 265,262,263                                       KIKU0466
  262 TH=1.570796                                               KIKU0467
      GO TO 264                                                 KIKU0468
  263 A2=SQRT((R/XL)**2-1.)                                     KIKU0469
      TH=ATAN(A2)                                               KIKU0470
      GO TO 264                                                 KIKU0471
  265 A2=-SQRT((R/XL)**2-1.)                                    KIKU0472
      TH=ATAN(A2)                                               KIKU0473
      IF(TH) 266,266,264                                        KIKU0473
  266 TH=TH+3.141593                                            KIKU0473
C
  264 ARG12=TH+1.570796-THET                                    KIKU0474
      S12=SIN(ARG12)                                            KIKU0475
      C12=COS(ARG12)                                            KIKU0480
      XH12=R*C*S12                                              KIKU0485
      XK12=R*S*S12                                              KIKU0490
      XL12=R*C12                                                KIKU0495
C
      ARG21=TH-1.570796+THET                                    KIKU0500
      S21=SIN(ARG21)                                            KIKU0505
      C21=COS(ARG21)                                            KIKU0510
      XH21=R*C*S21                                              KIKU0515
      XK21=R*S*S21                                              KIKU0520
      XL21=R*C21                                                KIKU0525
C
      ARG11=TH+1.570796+THET                                    KIKU0530
      S11=SIN(ARG11)                                            KIKU0535
      C11=COS(ARG11)                                            KIKU0540
      XH11=R*C*S11                                              KIKU0545
      XK11=R*S*S11                                              KIKU0550
      XL11=R*C11                                                KIKU0555
C
      ARG22=TH-1.570796-THET                                    KIKU0560
      S22=SIN(ARG22)                                            KIKU0565
      C22=COS(ARG22)                                            KIKU0570
      XH22=R*C*S22                                              KIKU0575
      XK22=R*S*S22                                              KIKU0580
      XL22=R*C22                                                KIKU0585
C
C  CALCULATE COORDINATES IN PROJECTION PLANE
C  FOR DIFFR. CONE
C
      A12=SQRT((R/XL12)**2-1.)                                  KIKU0605
      IF(XL12) 271,2710,272                                     KIKU0606
  271 GAM12=(3.141593-ATAN(A12))/2.                             KIKU0607
      GO TO 273                                                 KIKU0608
  272 GAM12= ATAN(A12)/2.                                       KIKU0609
      GO TO 273                                                 KIKU0611
 2710 GAM12=0.785398                                            KIKU0613
  273 TAN12=SIN(GAM12)/COS(GAM12)                               KIKU0615
```

```
      F12=2.*R*TAN12/SQRT(XH12*XH12+XK12*XK12)                          KIKU0620
      A1X=XH12*F12                                                      KIKU0625
      A1Y=XK12*F12                                                      KIKU0630
C
      A21=SQRT((R/XL21)**2-1.)                                          KIKU0635
      IF(XL21) 274,2740,275                                             KIKU0636
  274 GAM21=(3.141593-ATAN(A21))/2.                                     KIKU0637
      GO TO 276                                                         KIKU0638
  275 GAM21= ATAN(A21)/2.                                               KIKU0639
      GO TO 276                                                         KIKU0641
 2740 GAM21=0.785398                                                    KIKU0643
  276 TAN21=SIN(GAM21)/COS(GAM21)                                       KIKU0645
      F21=2.*R*TAN21/SQRT(XH21*XH21+XK21*XK21)                          KIKU0648
      B1X=XH21*F21                                                      KIKU0650
      B1Y=XK21*F21                                                      KIKU0655
C
      A11=SQRT((R/XL11)**2-1.)                                          KIKU0660
      IF(XL11) 278,2780,279                                             KIKU0661
  278 GAM11=(3.141593-ATAN(A11))/2.                                     KIKU0662
      GO TO 280                                                         KIKU0663
  279 GAM11= ATAN(A11)/2.                                               KIKU0664
      GO TO 280                                                         KIKU0666
 2780 GAM11=0.785398                                                    KIKU0668
  280 TAN11=SIN(GAM11)/COS(GAM11)                                       KIKU0670
      F11=2.*R*TAN11/SQRT(XH11*XH11+XK11*XK11)                          KIKU0675
      A2X=XH11*F11                                                      KIKU0680
      A2Y=XK11*F11                                                      KIKU0685
C
      A22=SQRT((R/XL22)**2-1.)                                          KIKU0690
      IF (XL22) 281,2810,282                                            KIKU0691
  281 GAM22=(3.141593-ATAN(A22))/2.                                     KIKU0692
      GO TO 283                                                         KIKU0693
  282 GAM22= ATAN(A22)/2.                                               KIKU0694
      GO TO 283                                                         KIKU0695
 2810 GAM22=0.785398                                                    KIKU0698
  283 TAN22=SIN(GAM22)/COS(GAM22)                                       KIKU0700
      F22=2.*R*TAN22/SQRT(XH22*XH22+XK22*XK22)                          KIKU0705
      B2X= XH22*F22                                                     KIKU0710
      B2Y=XK22*F22                                                      KIKU0715
C
C  CALCULATE RADIUS AND COORDINATES OF KKC RKC1 AND RKC2
C
      ABX1=B1X-A1X                                                      KIKU0720
      ABY1=B1Y-A1Y                                                      KIKU0725
      ABX2=B2X-A2X                                                      KIKU0730
      ABY2=B2Y-A2Y                                                      KIKU0735
C
      RKC(1)=0.5*SQRT(ABX1*ABX1+ABY1*ABY1)                              KIKU0755
      CX(1)=(A1X+B1X)/2.                                                KIKU0760
      CY(1)=(A1Y+B1Y)/2.                                                KIKU0765
C
      RKC(2)=0.5*SQRT(ABX2*ABX2+ABY2*ABY2)                              KIKU0770
      CX(2)=(A2X+B2X)/2.                                                KIKU0775
      CY(2)=(A2Y+B2Y)/2.                                                KIKU0780
      WRITE (5,6968) H1,K1,L1,RKC(1),CX(1),CY(1),RKC(2),CX(2),CY(2)
```

```
 6968 FORMAT (2X,3I3,2X,6F12.2)
C
C  CHECK INTERSECTION OF PLOT CIRCLE WITH KC
C
      DO 500 I=1,2                                                      KIKU0810
      SCH=.5*(R1*R1+CX(I)*CX(I)+CY(I)*CY(I)-RKC(I)*RKC(I))              KIKU0820
      R11=CX(I)*CX(I)+CY(I)*CY(I)                                       KIKU0823
      SCH1=(CY(I)*CY(I)*R1*R1-SCH*SCH)/R11+(SCH*CX(I)/R11)**2           KIKU0830
      IF (SCH1) 401,410,410                                             KIKU0840
  401 SCH2=SCH1+5.E-5                                                   KIKU0841
      IF (SCH2) 40,410,402                                              KIKU0842
  402 SCH1=0.0                                                          KIKU0843
C
C  CALCULATE INTERSECTION
C
  410 SQS=SQRT(SCH1)                                                    KIKU0850
      X1=SCH*CX(I)/R11 +SQS                                             KIKU0860
      X2=SCH*CX(I)/R11-SQS                                              KIKU0870
      Y1=SQRT(R1*R1-X1*X1)                                              KIKU0880
      Y2=SQRT(R1*R1-X2*X2)                                              KIKU0890
      T1=RKC(I)-SQRT((X1-CX(I))**2+(Y1-CY(I))**2)                       KIKU0900
      T1A=ABS(T1)                                                       KIKU0901
      IF(T1A-0.01) 430,430,420                                          KIKU0902
  420 Y1=-Y1                                                            KIKU0920
  430 T2=RKC(I)-SQRT((X2-CX(I))**2+(Y2-CY(I))**2)                       KIKU0930
      T2A=ABS(T2)                                                       KIKU0931
      IF (T2A-0.01) 441,441,440                                         KIKU0940
  440 Y2=-Y2                                                            KIKU0950
      GO TO 450                                                         KIKU0952
  441 RY=ABS(Y1-Y2)-0.1                                                 KIKU0954
      IF (RY) 449,449,450                                               KIKU0956
  449 Y2=-Y2                                                            KIKU0958
  450 X1S=X1-CX(I)                                                      KIKU0960
      X2S=X2-CX(I)                                                      KIKU0970
      Y1S=Y1-CY(I)                                                      KIKU0980
      Y2S=Y2-CY(I)                                                      KIKU0990
      IF(X1S) 505,510,515                                               KIKU0982
  515 IF(Y1S) 517,516,516                                               KIKU0983
  516 ALF1=ATAN(Y1S/X1S)                                                KIKU0984
      GO TO 528                                                         KIKU0985
  517 ALF1=ATAN(Y1S/X1S)+6.283186                                       KIKU0986
      GO TO 528                                                         KIKU0987
  510 IF(Y1S) 520,523,526                                               KIKU0988
  526 ALF1=1.570796                                                     KIKU0990
      GO TO 528                                                         KIKU0992
  523 ALF1=0.                                                           KIKU0994
      GO TO 528                                                         KIKU0995
  520 ALF1=4.712389                                                     KIKU0996
      GO TO 528                                                         KIKU0997
  505 ALF1=ATAN(Y1S/X1S)+3.141593                                       KIKU0999
  528 IF(X2S) 525,530,535                                               KIKU1000
  535 IF(Y2S) 537,536,536                                               KIKU1001
  536 ALF2=ATAN(Y2S/X2S)                                                KIKU1002
      GO TO 5450                                                        KIKU1003
  537 ALF2=ATAN(Y2S/X2S)+6.283186                                       KIKU1004
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```
      GO TO 5450                                                        KIKU1005
  530 IF(Y2S) 540,543,546                                               KIKU1006
  546 ALF2=1.57                                                         KIKU1008
      GO TO 5450                                                        KIKU1009
  543 ALF2=0.                                                           KIKU1010
      GO TO 5450                                                        KIKU1011
  540 ALF2=4.712389                                                     KIKU1013
      GO TO 5450                                                        KIKU1015
  525 ALF2=ATAN(Y2S/X2S)+3.141593                                       KIKU1017
 5450 IF(X1S) 5451,5451,5452
 5452 IF(X2S) 5451,5451,5453
 5453 IF(Y1S) 5455,5451,5454
 5454 IF(Y2S) 5456,5451,5451
 5456 ALF2=ALF2-6.283186
      GO TO 5451
 5455 IF(Y2S) 5451,5451,5458
 5458 ALF1=ALF1-6.283186
 5451 DALF=(ALF1-ALF2)/50.
      J=0                                                               KIKU4999
      DO 600 M1=1,50                                                    KIKU5000
      IF(H1)5501,5501,5502                                              KIKU5002
 5501 M=M1                                                              KIKU5004
      GO TO 5503                                                        KIKU5005
 5502 M=51-M1                                                           KIKU5006
 5503 X(M)=RKC(I)*COS(ALF1-DALF*(M-1))+CX(I)                            KIKU5010
      Y(M)=RKC(I)*SIN(ALF1-DALF*(M-1))+CY(I)                            KIKU5020
      AX=ABS(X(M))                                                      KIKU5030
      AY=ABS(Y(M))                                                      KIKU5040
      IF(XO-AX) 600,550,550                                             KIKU5050
  550 IF(YO-AY) 600,580,580                                             KIKU5060
  580 J=J+1                                                             KIKU5075
      XP(J)=X(M)                                                        KIKU5110
      YP(J)=Y(M)                                                        KIKU5120
  600 CONTINUE                                                          KIKU5200
C
C  PLOTTING SECTION
C
      IF(J-2) 500,699,699
  699 CALL FPLOT (-2,XP(1),YP(1))                                       KIKU5210
      WRITE(5,6962) H,K,L
 6962 FORMAT (8X,3I3)
      DO 700 JJ=1,J                                                     KIKU5220
  700 CALL FPLOT (0,XP(JJ),YP(JJ))                                      KIKU5230
      CALL FPLOT (-1,XP(J),YP(J))                                       KIKU5240
      IF(I-1) 500,500,7000
 7000 DY=YP(J)-YP(J-2)                                                  KIKU5310
      DX=XP(J)-XP(J-2)                                                  KIKU5312
      IF(DX) 7012,7011,7010                                             KIKU5314
 7010 DEL=ATAN(DY/DX)                                                   KIKU5316
      GO TO 7020                                                        KIKU5318
 7011 DEL =0.0                                                          KIKU5320
      GO TO 7020                                                        KIKU5328
 7012 DEL=ATAN(DY/DX)+3.141593                                          KIKU5330
 7020 XB=XP(J)+0.5*COS(DEL)                                             KIKU5335
      YB=YP(J)                                                          KIKU5340
```

```
      HA=IABS(H1)                                                       KIKU5341
      KA=IABS(K1)                                                       KIKU5342
      LA=IABS(L1)                                                       KIKU5343
      CALL FCHAR(XB,YB,.1,.12,DEL)                                      KIKU5345
      WRITE(11,7099) HA,KA,LA                                           KIKU5350
 7099 FORMAT (3I1)                                                      KIKU5351
      XB1=XB-0.35*SIN(DEL)                                              KIKU5360
      YB1=YB+0.35*COS(DEL)                                              KIKU5361
      DXB=0.25*COS(DEL)                                                 KIKU5362
      DYB=0.25*SIN(DEL)                                                 KIKU5363
      XB2=XB1+DXB                                                       KIKU5365
      YB2=YB1+DYB                                                       KIKU5366
      XB3=XB1+2.*DXB                                                    KIKU5367
      YB3=YB1+2.*DYB                                                    KIKU5368
      XB4=XB1+3.*DXB                                                    KIKU5369
      YB4=YB1+3.*DYB                                                    KIKU5370
      IF(H1) 7061,7060,7060                                             KIKU5372
 7061 CALL FPLOT(-2,XB1,YB1)                                            KIKU5374
      CALL FPLOT (-1,XB2,YB2)                                           KIKU5375
 7060 IF(K1) 7071,7070,7070                                             KIKU5376
 7071 CALL FPLOT(-2,XB2,YB2)                                            KIKU5377
      CALL FPLOT(-1,XB3,YB3)                                            KIKU5378
 7070 IF(L1)7081,40,40                                                  KIKU5379
 7081 CALL FPLOT(-2,XB3,YB3)                                            KIKU5380
      CALL FPLOT(-1,XB4,YB4)                                            KIKU5381
  500 CONTINUE                                                          KIKU53C0
   40 CONTINUE                                                          KIKU5400
   30 CONTINUE                                                          KIKU5500
   20 CONTINUE                                                          KIKU5600
      CALL EXIT
      END

VARIABLE ALLOCATIONS
      U(R )=000E-0000      V(R )=001E-0010      W(R )=002E-0020     CX(R )=0032-0030     CY(R )=0036-0034    RKC(R )=003A-003
      X(R )=009E-003C      Y(R )=0102-00A0     XP(R )=0166-0104     YP(R )=01CA-0168     SF(R )=161C-01CC      R(R )=161E
     X0(R )=1620          Y0(R )=1622          R1(R )=1624          F1(R )=1626          F2(R )=1628       THET(R )=162A
      A(R )=162C           F(R )=162E       XSCAL(R )=1630       YSCAL(R )=1632          S0(R )=1634       SMS0(R )=1636
    XHS(R )=1638         XKS(R )=163A         XLS(R )=163C         X11(R )=163E         X12(R )=1640        X13(P )=1642
    X21(R )=1644         X22(R )=1646         X23(R )=1648         X31(R )=164A         X32(R )=164C        X33(R )=164E
     S1(R )=1650          S2(R )=1652          S3(R )=1654         A11(R )=1656         A12(R )=1658        A13(R )=165A
    A21(R )=165C         A22(R )=165E         A23(R )=1660         A31(R )=1662         A32(R )=1664        A33(R )=1666
     XH(R )=1668          XK(R )=166A          XL(R )=166C         XI1(R )=166E         XI2(R )=1670       RDX1(R )=1672
   ARDX(R )=1674          FH(R )=1676          PN(R )=1678          RM(R )=167A         RMN(R )=167C         A1(R )=167E
    PHI(R )=1680           C(R )=1682           S(R )=1684          TH(R )=1686          A2(R )=1688      ARG12(R )=168A
    SI2(R )=168C         C12(R )=168E        XHI2(R )=1690        XK12(R )=1692        XL12(R )=1694      ARG21(R )=1696
    S21(R )=1698         C21(R )=169A        XH21(R )=169C        XK21(R )=169E        XL21(R )=16A0      ARG11(R )=16A2
    S11(R )=16A4         C11(R )=16A6        XH11(R )=16A8        XK11(R )=16AA        XL11(R )=16AC      ARG22(R )=16AE
    S22(R )=16B0         C22(R )=16B2        XH22(R )=16B4        XK22(R )=16B6        XL22(R )=16B8      GAM12(R )=16BA
  TAN12(R )=16BC         F12(R )=16BE         A1X(R )=16C0         A1Y(R )=16C2       GAM21(R )=16C4      TAN21(R )=16C6
    F21(R )=16C8         B1X(R )=16CA         B1Y(R )=16CC       GAM11(R )=16CE       TAN11(R )=16D0        F11(R )=16D2
    A2X(R )=16D4         A2Y(R )=16D6       GAM22(R )=16D8       TAN22(R )=16DA         F22(R )=16DC        B2X(R )=16DE
    B2Y(R )=16E0        ABX1(R )=16E2        ABY1(R )=16E4        ABX2(R )=16E6        ABY2(R )=16E8        SCH(R )=16EA
    R11(R )=16EC        SCH1(R )=16EE        SCH2(R )=16F0         SOS(R )=16F2          X1(R )=16F4         X2(R )=16F6
     Y1(R )=16F8          Y2(R )=16FA          T1(R )=16FC         T1A(R )=16FE          T2(R )=1700        T2A(R )=1702
     RY(R )=1704         X1S(R )=1706         X2S(R )=1708         Y1S(R )=170A         Y2S(R )=170C       ALFB(R
```

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                                                                02 JAN 70
                                                                 PAGE 009

     ALF2(R )=1710      DALF(R )=1712      AX(R )=1714      AY(R )=1716      DY(R )=1718      DX(R )=171A
      DEL(R )=171C        X8(R )=171E      Y8(R )=1720     XB1(R )=1722     YB1(R )=1724     DXB(R )=1726
      DYB(R )=1728       XB2(R )=172A     YB2(R )=172C     XB3(R )=172E     YB3(R )=1730     XB4(R )=1732
      YB4(R )=1734         H(I )=1740      H1(I )=1741     H1A(I )=1742      HA(I )=1743       I(I )=1744
        K(I )=1745        K1(I )=1746       L(I )=1747      L1(I )=1748       M(I )=1749     K1A(I )=174A
      L1A(I )=1748        IH(I )=174C     IH1(I )=174D      IK(I )=174E     IK1(I )=174F      IL(I )=1750
      IL1(I )=1751         N(I )=1752     IH5(I )=1753     IK5(I )=1754     IL5(I )=1755      IG(I )=1756
        J(I )=1757        M1(I )=1758      JJ(I )=1759      KA(I )=175A      LA(I )=1758

 STATEMENT ALLOCATIONS
 7    =179E  8    =17A1  6968 =17A3  6962 =17AA  7099 =17AE  10   =17C4  50   =184A  39   =1873  29   =187C  19   =1885
 60   =18E3  140  =1917  141  =191E  130  =1A2C  101  =1A70  46   =1AA4  45   =1AA8  43   =1AD7  111  =1AE8  41   =1AF
 110  =1812  100  =1818  90   =1824  80   =182D  252  =1836  255  =183D  254  =184A  256  =184F  257  =1859  253  =1864
 258  =1869  260  =1878  261  =1883  259  =188D  262  =1894  263  =189A  265  =18B0  266  =18CA  264  =18D0  271  =1C86
 272  =1C91  2710 =1C9A  273  =1C9E  274  =1CE9  275  =1CF4  2740 =1CFD  276  =1D01  278  =104C  279  =1D57  2780 =1D6
 280  =1064  281  =1DAF  282  =1DBA  2810 =10C3  283  =1DC7  401  =1EE4  402  =1EF1  410  =1EF5  420  =1F6C  430  =1F7
 440  =1FA7  441  =1FAE  449  =1FC0  450  =1FC5  515  =1FEF  516  =1FF4  517  =2001  510  =2010  526  =2017  523  =201D
 520  =2023  505  =2029  528  =2036  535  =203D  536  =2042  537  =204F  530  =205E  546  =2065  543  =2068  540  =207
 525  =2077  5450 =2084  54   =2089  5453 =208E  5454 =2095  5456 =209A  5455 =20A2  5458 =20A7  5451 =20AD  5501 =20C2
 5502 =20C8  5503 =20CE  550  =212D  580  =2134  600  =2152  699  =2162  700  =2188  7000 =21D7  7010 =21FC  7011 =2209
 7012 =220F  7020 =221C  7061 =22A3  7060 =2287  7071 =228C  7070 =22D0  7081 =22D5  500  =22E9  40   =22F2  30   =22F8
 20   =2304

 FEATURES SUPPORTED
  TRANSFER TRACE
  ARITHMETIC TRACE
  ONE WORD INTEGERS
  IOCS

 CALLED SUBPROGRAMS
  FSQRT  FCOS   FSIN   ROUND  SCALF  IABS   FABS   FATAN  FPLOT  FCHAR  FAOD   FADDX  FSUB   FSUBX  FMPY
  FMPYX  FDIV   FLD    FLDX   FSTO   FSBR   FSBRX  FDVR   FAXI   MFAR   MFARX  MIAR   FLOAT  MIIF   MFIF
  MRED   MWRT   MCOMP  MIOFX  MIOF   MIOI   SUBSC  SNR    FCHRI  HOLEB  PRNTN  EBPRT  CARDN

 REAL CONSTANTS
  .125000E 02=1760   .000000E 00=1762   .628000E 01=1764   .390000E 00=1766   .100000E 01=1768   .230000E-02=176A
  .500000E 01=176C   .500000E 00=176E   .100000E 05=1770   .100000E 03=1772   .100000E 00=1774   .400000E 01=1776
  .314159E 01=1778   .157079E 01=177A   .200000E 01=177C   .785398E 00=177E   .500000E-04=1780   .100000E-01=1782
  .628318E 01=1784   .471239E 01=1786   .157000E 01=1788   .500000E 02=178A   .120000E 00=178C   .350000E 00=178E
  .250000E 00=1790   .300000E 01=1792

 INTEGER CONSTANTS
     1=1794      8=1795      2=1796      9=1797     17=1798      5=1799      0=179A     50=179B     51=179C     11=179D

 CORE REQUIREMENTS FOR PROG
  COMMON        0  INSKEL COMMON       0
  VARIABLES     5984  PROGRAM     2992


 END OF COMPILATION
```

```
// FOR PROG   02 JAN 70 20.079 HRS
*IOCS(CARD, 1443 PRINTER)
*IOCS (PLOTTER)
*TRANSFER TRACE
*ARITHMETIC TRACE
*LIST ALL
*ONE WORD INTEGERS
      INTEGER HZ,HZ1,HZ11,HZA                                           KIKU6000
C
C  RADIUS R OF PROJ. SPHERE
C
      R=11.
      XSCAL=0.39
      YSCAL=XSCAL
      CALL SCALF(XSCAL,YSCAL,0.0,0.0)
C
C  SIZE OF MAP 2*X0*2*Y0 CM*CM
C
      X0=11.                                                            KIKU5901
      Y0=11.                                                            KIKU5902
      DO 300 HZ=7,17                                                    KIKU6000
      HZ1=HZ-9                                                          KIKU6010
      DO 310 KZ=7,17                                                    KIKU6020
      KZ1=KZ-9                                                          KIKU6030
      DO 320 LZ=7,17                                                    KIKU6040
      LZ1=LZ-9                                                          KIKU6041
      SQ=SQRT(FLOAT(HZ1*HZ1+KZ1*KZ1+LZ1*LZ1))                           KIKU6045
C
C  REJECT HIGH INDEX POLES
C
      SMSQ=4.                                                           KIKU6046
      IF(SMSQ-SQ) 320,320,329                                           KIKU6047
  329 IF(SQ-0.5) 320,320,351                                            KIKU6048
  351 FZ=R/SQ                                                           KIKU6049
      XHZS=HZ1*FZ                                                       KIKU6050
      XKZS=KZ1*FZ                                                       KIKU6051
      XLZS=LZ1*FZ                                                       KIKU6052
C
C  TRANSITION TO DESIRED ORIENTATION WITH COORD. X31,X32,X33
C
      X11=1.                                                            KIKU6055
      X12=0.                                                            KIKU6056
      X13=0.                                                            KIKU6057
      X21=0.                                                            KIKU6058
      X22=1.                                                            KIKU6059
      X23=-1.                                                           KIKU6060
      X31=0.                                                            KIKU6061
      X32=1.                                                            KIKU6062
      X33=1.                                                            KIKU6063
      S1=SQRT(X11*X11+X12*X12+X13*X13)                                  KIKU6065
      S2=SQRT(X21*X21+X22*X22+X23*X23)                                  KIKU6066
      S3=SQRT(X31*X31+X32*X32+X33*X33)                                  KIKU6067
      A11=X11/S1                                                        KIKU6068
      A12=X12/S1                                                        KIKU6069
      A13=X13/S1                                                        KIKU6070
      A21=X21/S2                                                        KIKU6071
      A22=X22/S2                                                        KIKU6072
      A23=X23/S2                                                        KIKU6073
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      A31=X31/S3                                              KIKU6074
      A32=X32/S3                                              KIKU6075
      A33=X33/S3                                              KIKU6076
      XHZ=A11*XHZS+A12*XKZS+A13*XLZS                          KIKU6080
      XKZ=A21*XHZS+A22*XKZS+A23*XLZS                          KIKU6081
      XLZ=A31*XHZS+A32*XKZS+A33*XLZS                          KIKU6082
      IF(XLZ) 320,301,301                                     KIKU6085
C
C  REJECT HIGH ORDER POLES
C
  301 HZA=IABS(HZ1)                                           KIKU6090
      KZA=IABS(KZ1)                                           KIKU6052
      LZA=IABS(LZ1)                                           KIKU6053
      XI1=10000.*HZA+100.*KZA+LZA                             KIKU6054
      DO 340 IH=1,5                                           KIKU6055
      IH1=IH-1                                                KIKU6056
      DO 341 IK=1,5                                           KIKU6057
      IK1=IK-1                                                KIKU6058
      DO 342 IL=1,5                                           KIKU6059
      IL1=IL-1                                                KIKU6060
      DO 343 N=2,8                                            KIKU6061
      IF(IH1+IK1+IL1) 344,342,344                             KIKU6062
  344 XI2=N*(10000.*IH1+100.*IK1+IL1)                         KIKU6063
      RX1=XI1-XI2                                             KIKU6064
      IF(RX1) 342,320,343                                     KIKU6064
  343 CONTINUE                                                KIKU6065
  342 CONTINUE                                                KIKU6066
  341 CONTINUE                                                KIKU6067
  340 CONTINUE                                                KIKU6068
C
C  CALCULATE COORD. IN PROJECTION PLANE
C
      AZ=SQRT((R/XLZ)**2-1.)                                  KIKU6110
      IF (XLZ) 354,353,352                                    KIKU6112
  354 GAMZ=(3.14193-ATAN(AZ))/2.                              KIKU6114
      GO TO 356                                               KIKU6116
  352 GAMZ=ATAN(AZ)/2.                                        KIKU6118
      GO TO 356                                               KIKU6120
  353 GAMZ=0.785398                                           KIKU6122
  356 TANZ=SIN(GAMZ)/COS(GAMZ)                                KIKU6130
      SORA=SQRT(XHZ*XHZ+XKZ*XKZ)                              KIKU6135
      IF (SORA-0.5) 359,359,355                               KIKU6138
  355 FZ1=2.*R*TANZ/SORA                                      KIKU6140
      PXZ=XHZ*FZ1                                             KIKU6150
      PYZ=XKZ*FZ1                                             KIKU6160
      GO TO 358                                               KIKU6162
  359 AXLZ=ABS(XLZ)                                           KIKU6164
      IF(AXLZ-0.5) 320,320,357                                KIKU6166
  357 PXZ=0.0                                                 KIKU6168
      PYZ=0.0                                                 KIKU6169
  358 APXZ=ABS(PXZ)                                           KIKU6170
      APYZ=ABS(PYZ)                                           KIKU6171
C
C  SLECT POLES WITHIN THE PLOTTED AREA
C
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      IF(XO-APXZ) 320,321,321                                          KIKU6172
  321 IF(YO-APYZ) 320,324,324                                          KIKU6173
C
C  PLOT + AND NUMBER (HZ1,KZ1,LZ1) AT COORDINATES (PXZ,PYZ)
C
  324 CALL FPLOT (-2,PXZ,PYZ)                                          KIKU6182
      CALL POINT (0)                                                   KIKU6184
      CALL FPLOT (-1,PXZ,PYZ)                                          KIKU6186
      HZ11=IABS(HZ1)                                                   KIKU6175
      KZ11=IABS(KZ1)                                                   KIKU6176
      LZ11=IABS(LZ1)                                                   KIKU6177
      IF(APXZ-0.1) 326,326,325                                         KIKU6187
  325 CALL FCHAR (PXZ-0.06*XSCAL,PYZ+0.1*YSCAL,.1,.12,1.571)           KIKU6188
      WRITE (11,390) HZ11,KZ11,LZ11                                    KIKU6194
  390 FORMAT (3I1)                                                     KIKU6195
      IF(HZ1) 361,360,360                                              KIKU6200
  361 CALL FPLOT (-2,PXZ-0.40,PYZ+0.04)                                KIKU6205
      CALL FPLOT (-1,PXZ-0.40,PYZ+0.24)                                KIKU6210
  360 IF (KZ1) 371,370,370                                             KIKU6215
  371 CALL FPLOT (-2,PXZ-0.40,PYZ+0.25)                                KIKU6220
      CALL FPLOT (-1,PXZ-0.40,PYZ+0.50)                                KIKU6225
  370 IF (LZ1) 381,320,320                                             KIKU6230
  381 CALL FPLOT (-2,PXZ-0.40,PYZ+0.55)                                KIKU6235
      CALL FPLOT (-1,PXZ-0.40,PYZ+0.80)                                KIKU6240
      GO TO 320                                                        KIKU6250
  326 CALL FCHAR(PXZ+0.06*XSCAL,PYZ+0.1*YSCAL,.1,.12,0.0)              KIKU6300
      WRITE(11,391)HZ11,KZ11,LZ11                                      KIKU6310
  391 FORMAT(3I1)                                                      KIKU6320
      IF(HZ1)366,365,365                                               KIKU6330
  366 CALL FPLOT(-2,PXZ+0.03,PYZ+0.4)                                  KIKU6340
      CALL FPLOT(-1,PXZ+0.24,PYZ+0.4)                                  KIKU6350
  365 IF(KZ1)376,375,375                                               KIKU6360
  376 CALL FPLOT(-2,PXZ+0.25,PYZ+0.4)                                  KIKU6370
      CALL FPLOT(-1,PXZ+0.50,PYZ+0.4)                                  KIKU6380
  375 IF(LZ1)386,320,320                                               KIKU6390
  386 CALL FPLOT(-2,PXZ+0.55,PYZ+0.4)                                  KIKU6400
      CALL FPLOT(-1,PXZ+0.80,PYZ+0.4)                                  KIKU6410
  320 CONTINUE                                                         KIKU8000
  310 CONTINUE                                                         KIKU8001
  300 CONTINUE                                                         KIKU8002
      CALL EXIT
      END

VARIABLE ALLOCATIONS
      R(R )=0000      XSCAL(R )=0002      YSCAL(R )=0004         XO(R )=0006         YO(R )=0008         SQ(R )=000A
   SMSQ(R )=000C         FZ(R )=000E       XHZS(R )=0010       XKZS(R )=0012       XLZS(R )=0014        X11(R )=0016
    X12(R )=0018        X13(R )=001A        X21(R )=001C        X22(R )=001E        X23(R )=0020        X31(R )=0022
    X32(R )=0024        X33(R )=0026         S1(R )=0028         S2(R )=002A         S3(R )=002C        A11(R )=002E
    A12(R )=0030        A13(R )=0032        A21(R )=0034        A22(R )=0036        A23(R )=0038        A31(R )=003A
    A32(R )=003C        A33(R )=003E        XHZ(R )=0040        XKZ(R )=0042        XLZ(R )=0044        XI1(R )=0046
    XI2(R )=0048        RX1(R )=004A         AZ(R )=004C       GAMZ(R )=004E       TANZ(R )=0050       SQRA(R )=005[illegible]
    FZ1(R )=0054        PXZ(R )=0056        PYZ(R )=0058       AXLZ(R )=005A       APXZ(R )=005C       APYZ(R )=005E
     HZ(I )=006A        HZ1(I )=0068       HZ11(I )=006C        HZA(I )=006D         KZ(I )=006E        KZ1(I )=006F
     LZ(I )=0070        LZ1(I )=0071        KZA(I )=0072        LZA(I )=0073         IH(I )=0074  [illegible](I )=[illegible]
     IK(I )=0076        IK1(I )=0077         IL(I )=0078        IL1(I )=0079          N(I )=007A       KZ11(I )=[illegible]
```

```
LZ11(I )=007C

STATEMENT ALLOCATIONS
 390  =0083  391  =0086  329  =011F  351  =0126  301  =0234  344  =0285  343  =0280  342  =0289  341  =02C2  340  =02C8
 354  =02EA  352  =02F5  353  =02FE  356  =0302  355  =0328  359  =0340  357  =034C  358  =0354  321  =0365  324  =036C
 325  =0399  361  =03BF  360  =03E9  371  =03F0  370  =041C  381  =0421  326  =044F  366  =0475  365  =04A1  376  =04AC
 375  =04D2  386  =04D7  320  =0503  310  =050C  300  =0515

FEATURES SUPPORTED
 TRANSFER TRACE
 ARITHMETIC TRACE
 ONE WORD INTEGERS
 IOCS

CALLED SUBPROGRAMS
 SCALF   FSQRT   IABS    FATAN   FSIN    FCOS    FABS    FPLOT   POINT   FCHAR   FADD    FSUB    FMPY    FDIV    FLD
 FSTO    FSBR    FDVR    FAXI    MFAR    MIAR    FLOAT   MIIF    MFIF    MWRT    MCOMP   MIOI    SNR     FCHRI   HOLEB
 PRNTN   EBPRT   CARDN

REAL CONSTANTS
  .110000E 02=007E   .390000E 00=0080   .000000E 00=0082   .400000E 01=0084   .500000E 00=0086   .100000E 01=0088
  .100000E 05=008A   .100000E 03=008C   .314193E 01=008E   .200000E 01=0090   .785398E 00=0092   .100000E 00=0094
  .600000E-01=0096   .120000E 00=0098   .157100E 01=009A   .400000E 00=009C   .400000E-01=009E   .240000E 00=00A0
  .250000E 00=00A2   .550000E 00=00A4   .800000E 00=00A6   .300000E-01=00A8

INTEGER CONSTANTS
     7=00AA     17=00AB      9=00AC      1=00AD      5=00AE      2=00AF      8=00B0      0=0081     11=0082

CORE REQUIREMENTS FOR PROG
 COMMON      0  INSKEL COMMON      0
  VARIABLES    126  PROGRAM   1186


END OF COMPILATION
```

Chapter 2

ELECTRICAL CHARACTERIZATION OF QUASI MOS STRUCTURES ON SILICON

by

W. R. Fahrner, E. F. Gorey, and C. P. Schneider

INTRODUCTION

Junctions are present in important devices, e.g., in buried-channel charge-coupled devices (CCDs) or in silicon on sapphire (SOS)-based integrated circuits. In order to optimize the performance of such a device--speed, transfer efficiency, etc.--the characterization of the electrical properties of the material is desirable. For homogeneous silicon, there are some standard techniques based on metal oxide semiconductor (MOS) capacitance measurements for this purpose. The presence of underlying junctions requires important precautions to be made with the use of MOS-CV measurement techniques.

Owing to the junction, the number of components of the equivalent network increases and the analysis is impeded. It will be shown in this paper how this problem can be solved. When one side of a junction described above is oxidized, a quasi MOS structure results. The equivalent network of such a structure is discussed in this paper, and the conditions for MOS C-V and G-V measurements are given. In the case where the MOS admittance can be measured, the following information can be obtained:

1. The surface-state density N_{ss} (1), the corresponding capture cross sections (2), the charge density in the oxide (3), and deep energy levels (4).
2. The doping concentration N_D.
3. The lifetime of the minority carriers (5).

Measurements on epitaxial junctions according to (3) have already been carried out (6) without an adequate theoretical basis.

In this investigation, we are primarily interested in the measurement of lifetime, since this parameter is more sensitive to defects and impurities in the crystal than any other electrical parameter (7). Thus, in the section "Range of Quasi MOS Capacitance Technique," the values for layer and substrate resistivity, dot diameter, oxide thickness, etc., refer to ranges in which such lifetime measurements can be carried out.

ANALYSIS OF EQUIVALENT NETWORK

In Fig. 1, a cross section of an oxidized n epitaxial layer on a p^- substrate is shown. The network of the structure consists of the oxide capacitance C_{ox}, the distributed layer resistance R of the n-layer, the distributed junction admittance $Y_J = G_J + j\omega C_J$, and the distributed substrate resistance R_s. A net consisting of buried layers each of 2.5 times 2.5 mm^2 area with a spacing of 8 mm is diffused into the substrate prior to epitaxy. The doping profiles underneath A (off the

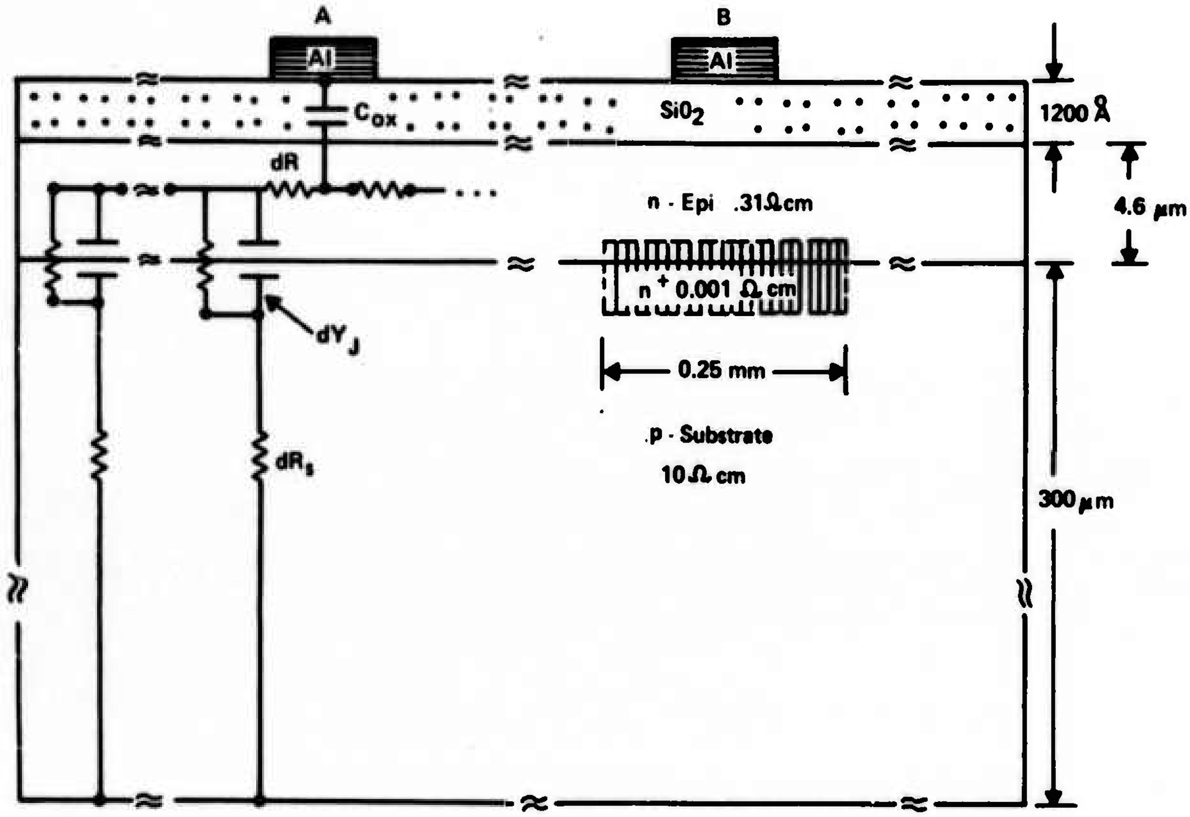

Fig. 1. Cross section of a n-p^- junction. The n layer was grown by regular gas phase epitaxy. It is covered by 1200 Å thermal oxide.

buried layer) and B (on the buried layer) are obtained by the spreading resistance technique (Fig. 2). The C-V curves for two dots off the buried layer are shown in Fig. 3. The dots have areas of 0.01765 and 0.00196 cm^2. The same measurements are repeated for a <115> and a <100> oriented wafer with epitaxial layer resistivity of approximately 0.9 ohm-cm and of approximately 4-μm epitaxial thickness. The substrate resistivity is 8 and 6 ohm-cm respectively (Fig. 4a,b). In these wafers, no buried layer is present.

The analysis of the data given in Fig. 3 reveals that the measured low-frequency capacitance in accumulation is identical with the oxide capacitance. This is confirmed through measurements on control wafers, by measuring the oxide thickness and the capacitances for different dot areas and comparing the ratios with the area ratios.

The dc voltage drop (v_J) across the junction is 0 since there is no dc current flow through the MOS structure.

The ac admittance is given by $G_J (v_J) + j\omega C_J (v_J)$ with $v_J = 0$. G_J can be derived as $G_J = dI_J/dv_J = I_o \times (q/kT) \times \exp(qv_J/kT)$. In anticipation of the results, the lifetime of the epitaxial layer (which is heavily doped compared with the substrate and can be expected to give the major contribution to the dark current) is measured now to be approximately 1 μsec. With this

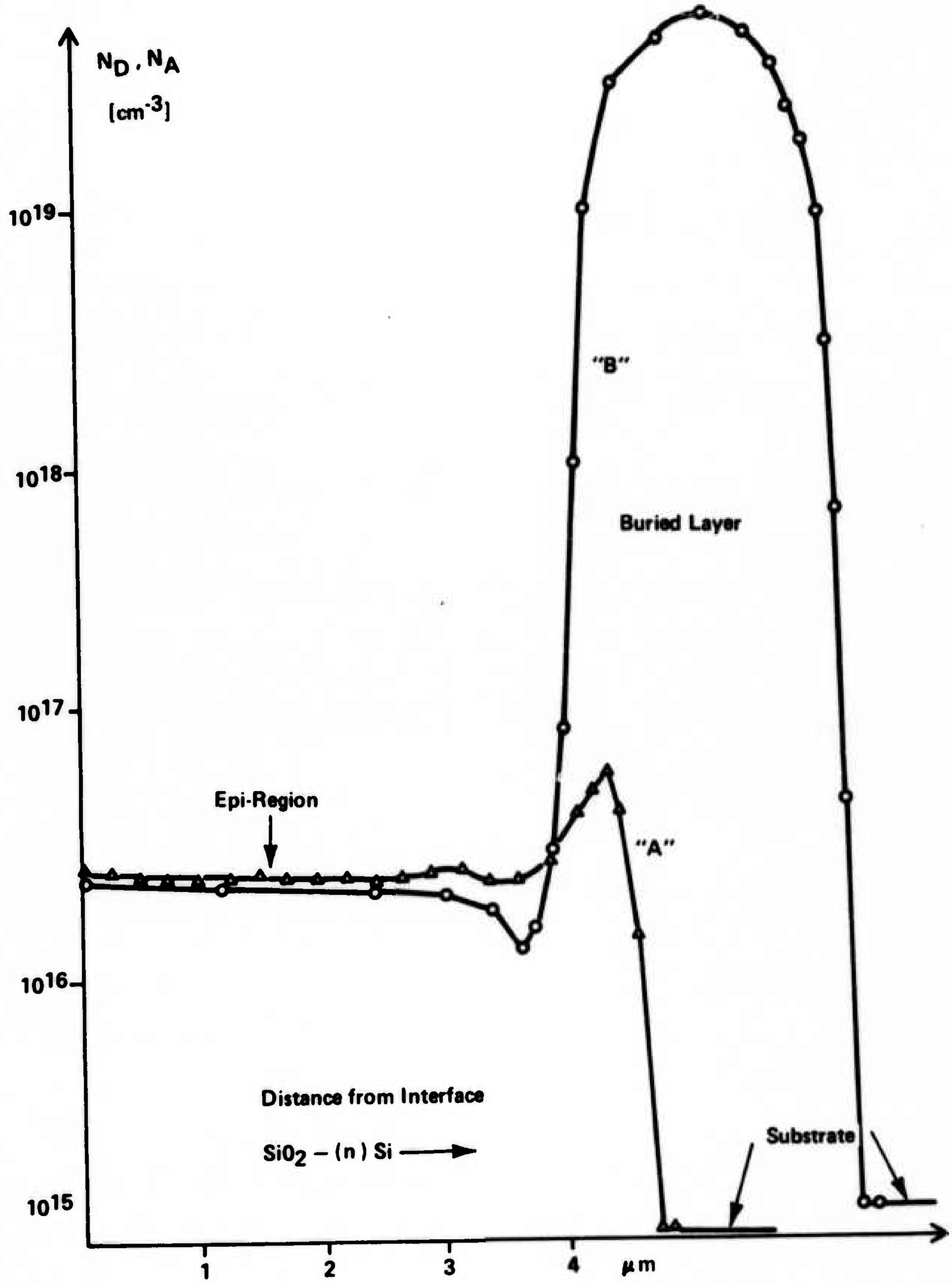

Fig. 2. Doping profiles underneath the dots A (triangles) and B (circles) in Fig. 1.

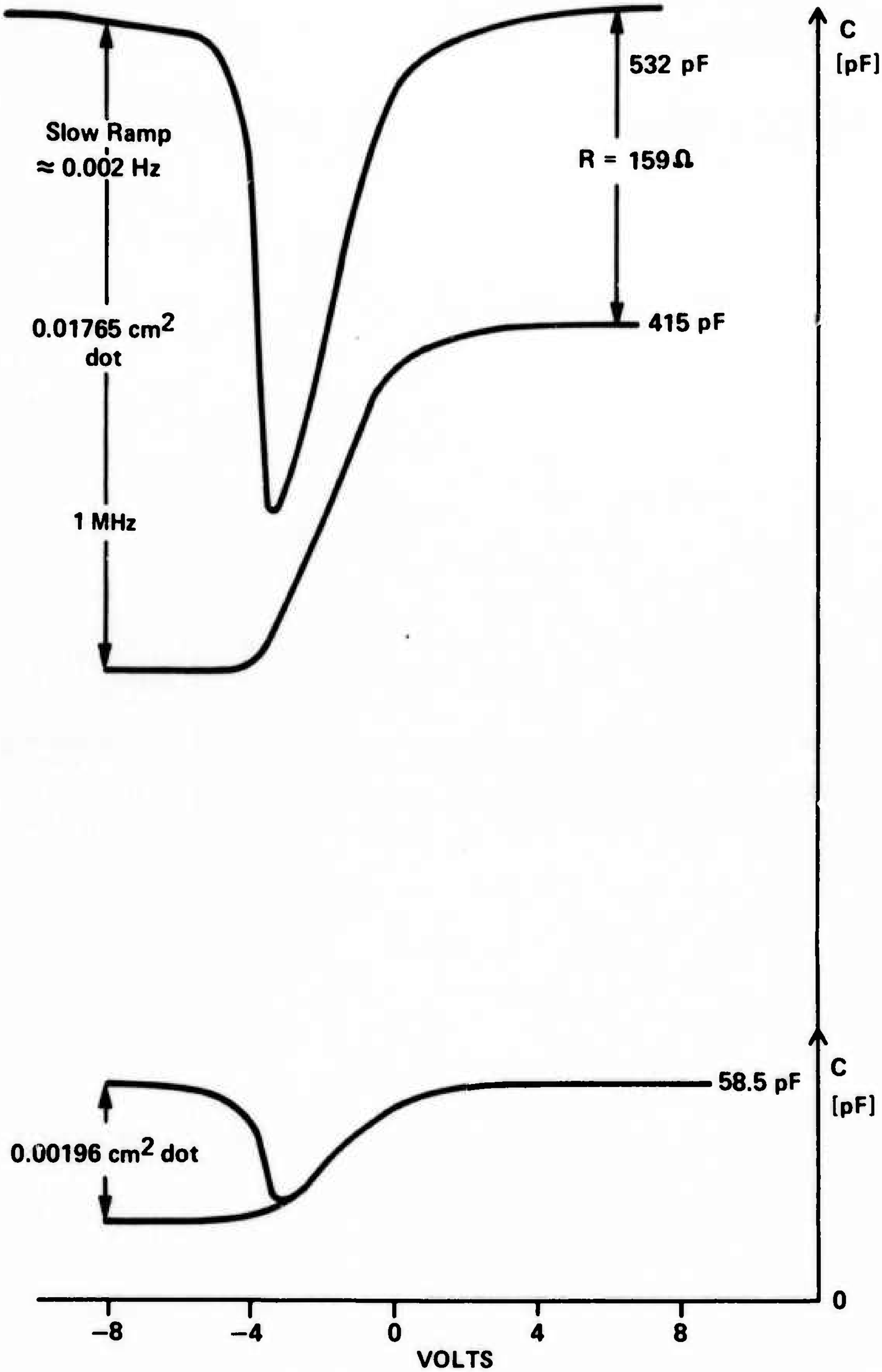

Fig. 3. C-V curves for two dots off the buried layer (A in Fig. 1). Note that for the smaller dot no dispersion is seen.

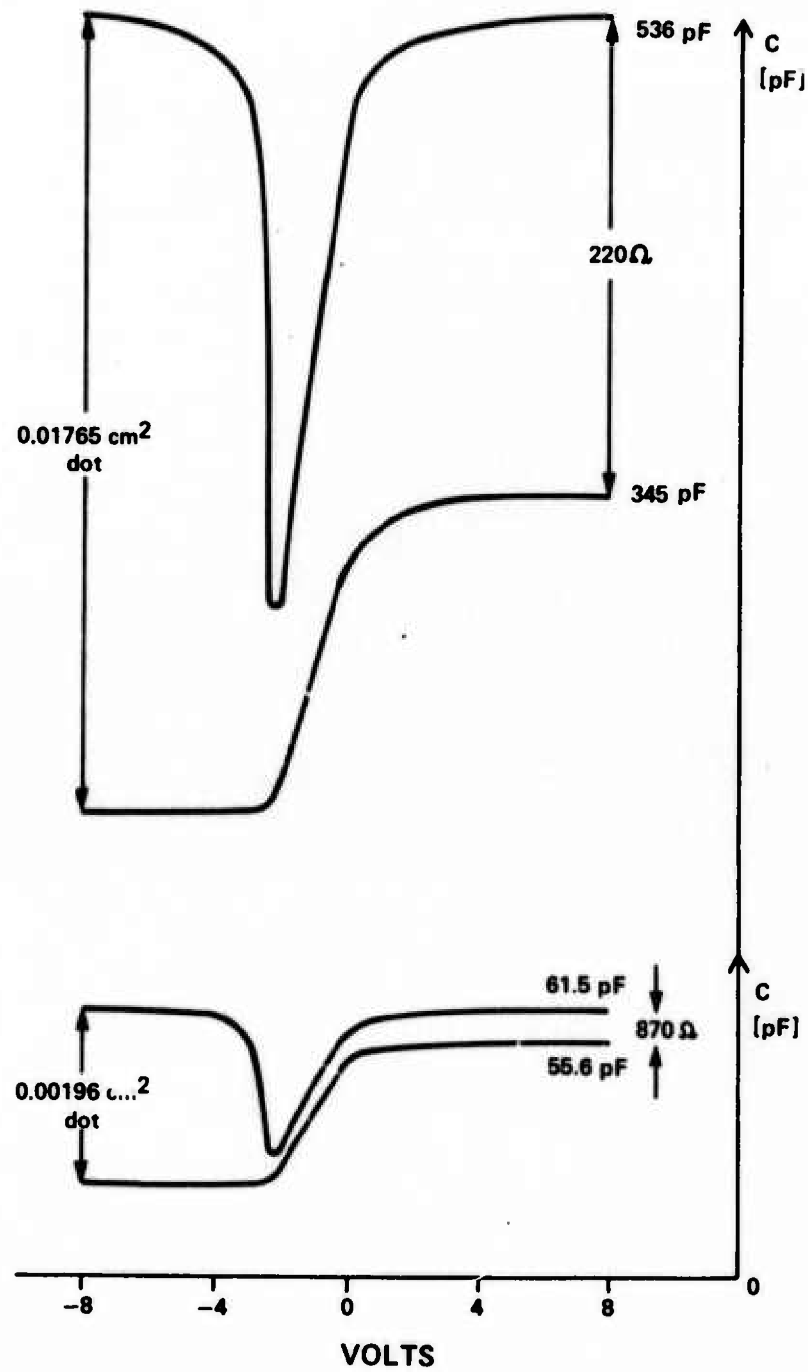

Fig. 4a. The same C-V curves as in Fig. 3 for a ⟨115⟩ oriented substrate wafer. The epitaxial resistivity is three times larger than that in the samples characterized in Fig. 3.

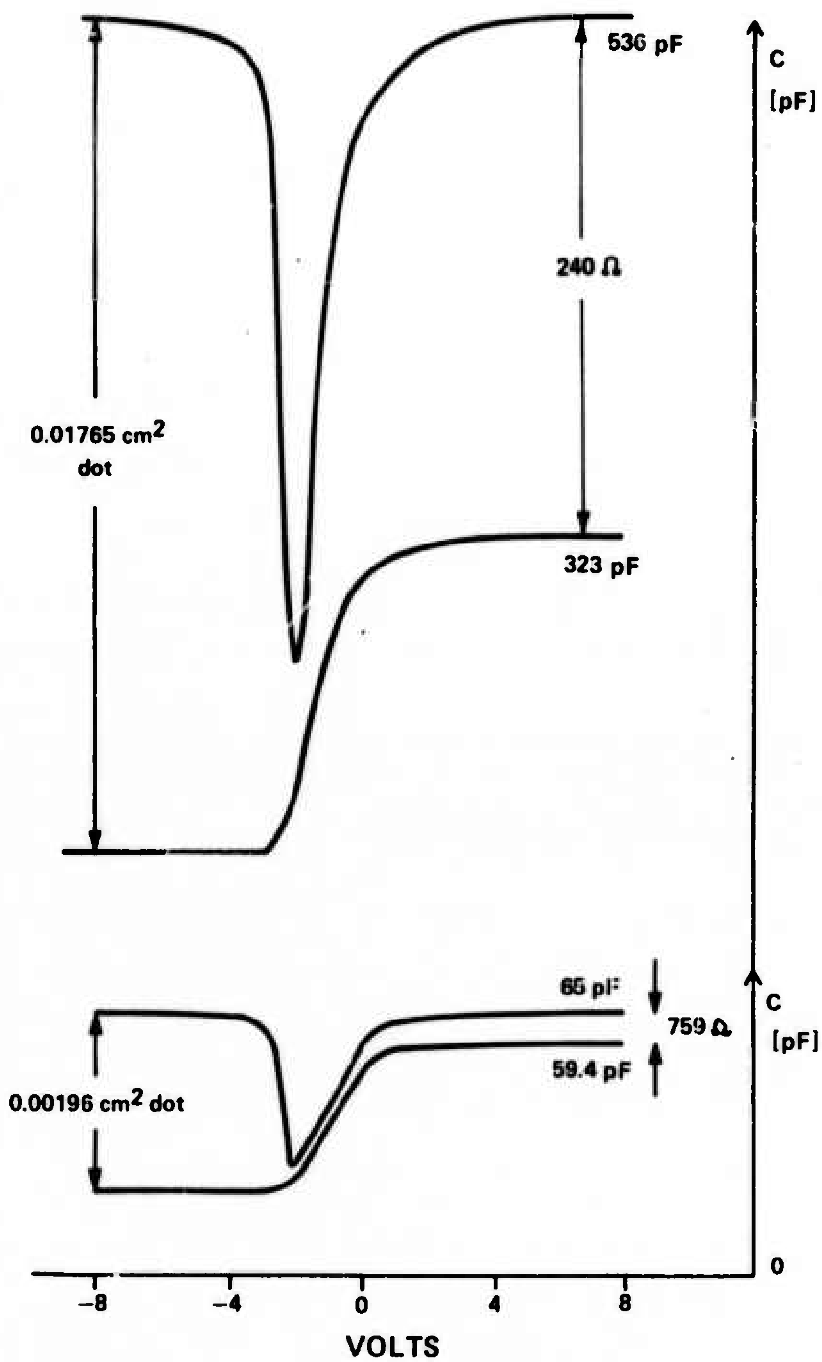

Fig. 4b. The same C-V curves as in Fig. 3 for a ⟨100⟩ oriented substrate wafer. The epitaxial resistivity is three times larger than that in the samples characterized in Fig. 3.

value and the given wafer data, one obtains $I_o \sim 10^{-9}$ A, and thus $G_J \sim 4 \times 10^{-8} \exp(qv_J/kT)$ mhos. The capacitance C_J is $\sim$ 20 nf at 0 Volt and $\omega C_J \sim 10^{-10}$ mhos for a frequency of 2×10^{-3} Hz. (I_o and C_J have been calculated by means of Shockley's equation $I_o = qA\,(p_n \sqrt{D_p/\tau_p} + n_p \sqrt{D_n/\tau_n})$ and the depletion approximation $C_J = \varepsilon A \left(\frac{q}{2\varepsilon v_D} \cdot \frac{N_D \cdot N_A}{N_D + N_A}\right)^{1/2}$. v_D is the diffusion potential. The other symbols have the usual meaning.) The ac admittance is resistance-controlled up to $\sim$ 1 Hz. Even in range f > 1 Hz, there is no influence of the junction admittance, since $\omega C_J \gg \omega C_{ox}$. These considerations explain why a voltage-independent accumulation capacitance is measured over the usual frequency and bias range. The validity of the assumption on G (v_J), C (v_J), and the numeric values are found in good agreement with C (v_J) and differentiated I (v_J) curves measured after oxide removal and ultrasonic cutting (e.g., C_J = 35 and 40 nf for dots cut at A and B, respectively).

The bulk resistance R_s of the substrate can be neglected as long as the resistivity is not too large. Experimentally, the upper limit was found to be approximately 50-100 ohm-cm and is theoretically given by the comparison of the RC_{ox} time constant with the measurement frequency of 1 MHz.

From the data given in Fig. 3 (i.e.: C_{ox} = 532 pf, C_{HF} (acc). = 415 pf), the lumped series resistance can be determined:

$$C_{HF}\ (acc) = C_{ox}/(1 + \omega^2\tau^2) \qquad [1]$$

$$\tau = RC_{ox} \qquad [2]$$

This gives R = 159 ohms. For the case of a buried layer underneath the dot, this value is reduced to R = 88 ohms. (Note that in Fig. 2 the buried layer extends into the epitaxial layer due to outdiffusion.) When the dot area is reduced to 0.00196 cm^2 and the capacitance to 58 pf, no dispersion is observed in accumulation up to 1 MHz. With the same values of R, one obtains now $(\omega\tau)^2 = (2\pi\cdot 10^6\cdot R\cdot C_{ox})^2 =$ 3.4×10^{-3} and 1×10^{-3}, respectively; C_{ox} can be measured with 1 MHz.

Since the time constant of the surface states is usually observed in the kHz range, G(V) and G(ω) measurements (2) are also feasible. (A G(V) and a G(ω) curve is a plot of the total conductance G vs voltage or frequency at a fixed frequency or voltage respectively.) This is roughly checked by measuring G(V) in the kHz range. The typical peak due to surface states and its shift with frequency is observed.

From Fig. 4, one obtains R values of 220 ohms and 240 ohms for $N_D = 5 \times 10^{15}$ and 4.8×10^{15} cm^{-3}, respectively.

SPREADING RESISTANCE VS DOT DIAMETER

For frequencies $\omega \leq 1/RC_{ox}$, the equipotential lines of the structure are schematically drawn in Fig. 5a. Therefore, one can assume a disk-like volume representing the epitaxial layer, in which the current flows (Fig. 5b). The voltage v_o is applied at the inner area $2\pi r_o \cdot d_{epi}$, d_{epi} being the epitaxial layer thickness; the outer area at r_1 is grounded. A voltage dv drops across a volume increment $2\, r\, \pi\, dr \cdot d_{epi}$:

$$dv = -i_o\, dR$$

(i_o is the current caused by v_o).

dR is defined by

$$dR = \rho \cdot dr/A(r) = \rho \cdot dr/(2 \cdot \pi \cdot r \cdot d_{epi})$$

$$dv = -i_o \cdot \rho \cdot dr/(2 \cdot \pi \cdot r \cdot d_{epi})$$

$$v = -(i_o \cdot \rho/2 \cdot \pi \cdot d_{epi}) \ln (r/r_1).$$

Since $v(r_o) = v_o$:

$$(v_o/i_o) = R = -(\rho/2\, d_{epi}) \ln (r_o/r_1) \qquad [3]$$

As a result, one obtains an increase of the spreading resistance for smaller dot diameters. For the epitaxial wafers of Figs. 2 and 3, we are not able to observe this change, first because the spreading resistance is too small, second, because the existence of the junction and oxide capacitance heavily interferes with the assumption of a simple radial current. For the SOS wafers shown here, however, the effect is clearly visible. For an oxide of 1300 Å, and an ∿ 10-μm-thick epitaxial layer of 1 ohm-cm, one obtains R = 500, 1380, and ∿ 2450 ohms for dots of 0.01765, 0.00196, and 0.00049 cm^2,

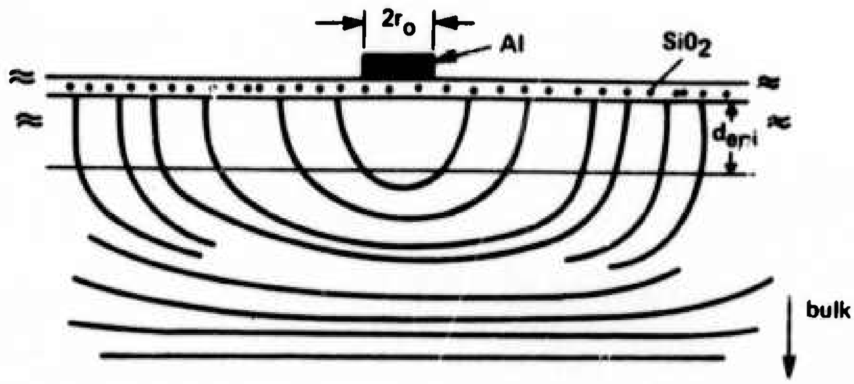

Fig. 5a. Equipotential lines for frequencies $\ll$ 1 MHz. The current flow in the epitaxial layer is practically radial.

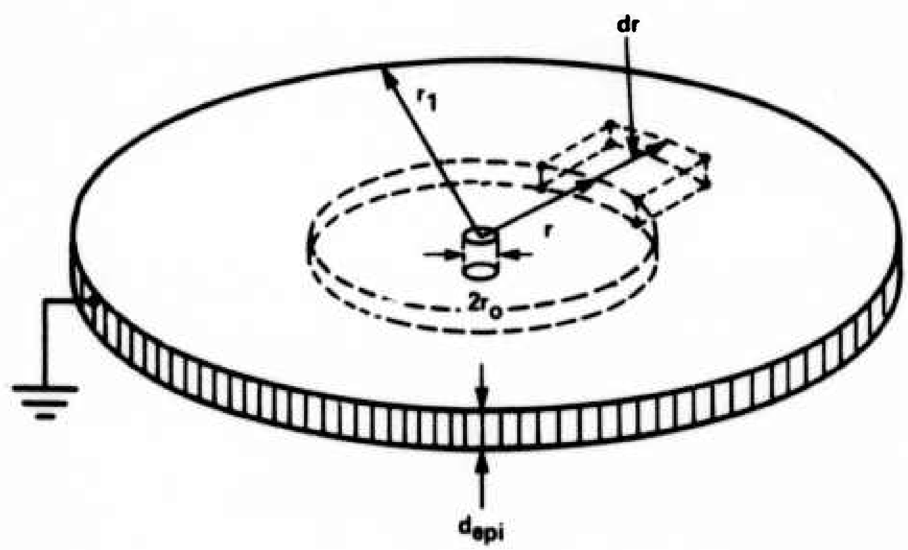

Fig. 5b. The epitaxial layer in a simplified disk-like geometry. For $r < r_o$, the potential is assumed to be constant ($= v_o$).

respectively. Since, for these structures, contact with the backside is made by overlapping Al at the edge of the wafer, the spreading resistance is measured without distortion by the junction capacitance. Though we do not observe an $R \propto (-\ln r_o)$ dependence but, rather, an $R \propto 1/r_o$ one, the model qualitatively describes the behavior of the spreading resistance.

RANGE OF QUASI MOS CAPACITANCE TECHNIQUE

In the preceding sections, we have shown that the contribution of the junction impedance can be neglected, if appropriate values for the resistivities, oxide thickness, dot diameter, etc., are selected. In the following, we give approximate ranges for those parameters. Within these ranges, the junction impedance is small compared with the interface, oxide, and layer impedance.

For a 5-μm layer of $\rho \sim 0.3$ ohm-cm resistivity and 1200 Å SiO_2, a dot of $d \leq 0.5$-mm diameter should be used. The substrate might have $\rho \leq 20$ ohm-cm. For other oxide thicknesses d_{ox}, d can be chosen to be $d = \frac{0.5}{1200} d_{ox}$. For higher layer resistivities, the layer thickness should be increased according to the resistivity ratio. For epitaxial ρ values ≥ 15 ohm-cm, care must be taken that the condition $C_{ox} << C_J$ is still valid, e.g., by increasing the wafer area. For the insulator-silicon structure, with an oxide thickness of 1300 Å and a layer of

$\sim$ 10 μm and N_D, N_A $\sim$ $1\text{-}2 \times 10^{16}$ cm^{-3}, we consider a dot of 0.25-mm diameter as appropriate. The same changes in dot diameter and epitaxial layer thickness should be done for a variation in oxide thickness and layer resistivity. The diameter of the wafer should be at least 1-1/4 inches. Since these values refer to the oxide capacitance ($\tau = RC_{ox}$) and the lifetime measurements are carried out with the inversion and deep depletion capacitance (8), the accuracy increases by $(C_{ox}/C_f)^2$. (Cf. Eq. [1].)

COMPARISON WITH OTHER TECHNIQUES

Finally, this technique should be compared with some alternatives, namely, the MOS emitter device and the buried-layer SOS structure, described, for example, in Refs. (9) and (10). Though some restricting conditions are implied in our technique, such as dot diameter, epitaxial layer thickness, etc., its advantages are greater versatility and measurement without distortion of a conduction layer. For example, the technique of Jones and Barber (9) is restricted to lifetimes, whereas a buried conduction layer (10) might cause outdiffusion and thus a reduction of lifetimes even in the epitaxial bulk.

Measurements using a guard ring as a counterelectrode were made. The substrate was at the same potential as the guard ring. The equivalent network consists of the oxide and space charge capacitance, C_{ox} and C_{sc}, respectively, of the dot in series with the oxide capacitance C_{oxR}, the space charge capacitance C_{scR} of the ring, and the spreading resistance of the layer. The network is shunted by the coupling capacitance C_c between the dot and the ring. (We neglect here the shunt to the substrate, because this has been discussed above.) The condition $C_{ox} << \frac{C_{oxR} \cdot C_{scR}}{C_{oxR} + C_{scR}}$ can be fulfilled by the appropriate choice of the ring area. The condition $C_c << \frac{C_{ox} \cdot C_{sc}}{C_{ox} + C_{sc}}$ is always valid since oxide thicknesses of 500...5000 Å are used. For a dot diameter of 60 mils, an oxide of 1000 Å, and a spacing of 150 μm, one obtains $C_c = 10^{-4}$ pf. Thus dispersion-free C-V curves are feasible. This was confirmed by the experiment. However, a disadvantage is encountered: with the present state of the art, photoresist deteriorates the oxide and silicon properties, especially the lifetimes and the oxide stability. We observed reductions in lifetimes from 500 μsec to 0.1 μsec and flatband shifts. (The lifetime data of the paper were obtained by the technique given in Ref. 8.)

RESULTS AND DISCUSSION

The results of the measurements can be summarized as follows: Flatband voltages and surface-state densities are found in the usual ranges of $\sim$ -1V and $\leq 1.4 \times 10^{10}$ eV^{-1} cm^{-2}, respectively.

Since the peak of the G-V curves is found at depletion surface potentials for frequencies in the kHz range, the capture cross section can be expected to be 10^{-13} to 10^{-15} cm^2. No deviation compared with "normal" MOS structures can be seen. Lifetimes are measured to be 1 μsec in the epitaxial wafers, 10^{-3} μsec in the n-SOS wafers, and 0.1 μsec in the p-SOS wafers.

The SOS low-frequency curves for wafers of layer thicknesses between 1 and 10 μm do not show any trace of a donor or an acceptor level (Fig. 6). This is in contradiction to earlier reports (11, 12), where an acceptor and a donor level at $E_c - E_A = 0.25$ eV and $E_D - E_v = 0.30$ eV were published. This might be attributed to different measurement techniques. The densities of the levels are reported to be 10^{17} to 10^{18} cm^{-3}. A good resolution for surface states (or bulk impurities seen as surface states) for the slow ramp technique is 10^{11} cm^{-2}. If this value is divided by an effective distribution width of 10 to 100 Å, one obtains bulk concentrations of 10^{17} to 10^{18} cm^{-3}. The slow ramp technique, however, measures states localized at the surface, whereas the techniques used in Refs. (11) and (12) cover the total depth of the film. Thus, it might be concluded that the reported levels are located near the Si-Al_2O_3 interface.

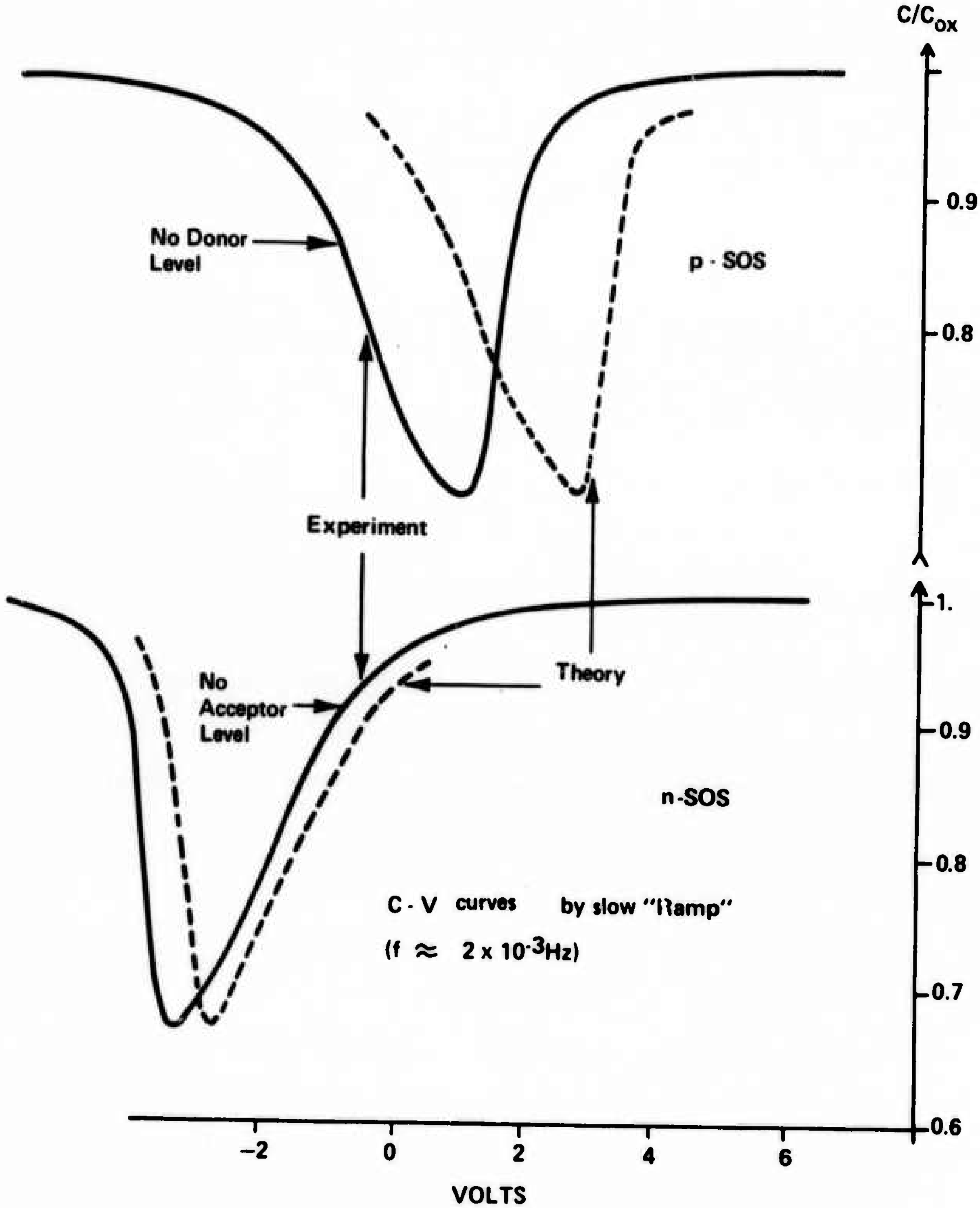

Fig. 6. Enlarged portion of the low frequency C-V curve of a p- and an n- SOS wafer. No indication of a deep lying level is visible. For comparison, the ideal low frequency curves are shown too.

Another possible explanation is the fact that one deals with extremely deep levels. Their time constant is controlled by the surface potential u_s:

$$\tau_p = (\sigma \cdot v_{th} \cdot N_A)^{-1} \exp(-u_s)$$

Since the levels are defined to be either acceptor or donor levels, they exchange carriers only with the valence or conductance band, respectively. With the given data and an assumption of a capture cross section $\sigma = 10^{-15}$ cm^2 and a thermal velocity $v_{th} = 10^7$ cm/sec, one obtains for the hole dispersion time constant in the n-type wafer $\tau_p = 2 \times 10^2$ sec. This value is comparable to our measurement frequency of 2×10^{-3} Hz. Capture cross sections of 10^{-15} cm^2 have been measured (13); in this case, however, higher values are more likely, and the first explanation should be preferred.

SUMMARY AND CONCLUSIONS

The measurement of the admittance of an MOS structure over a p-n junction or on SOS devices is discussed. It is shown that by appropriate choice of the wafer data, the contribution of the junction to the total admittance can be neglected and lifetime measurement can be carried out.

No deep levels can be seen for the SOS system.

REFERENCES

1. R. Castagne, C. R. Acad. Sc. (Paris), 267, Serie B, 866 (1968).
2. E. H. Nicollian and A. Goetzberger, Bell System Tech. J., 46, 1055 (1967).
3. D. R. Kerr, Int. Conf. on Properties and Use of MIS Structures, J. Borel, Editor, CNRS-LETI, Grenoble, 303 (1969).
4. W. R. Fahrner and A. Goetzberger, Appl. Phys. Lett., 21, 329 (1972).
5. M. Zerbst, Z. Angew. Phys., 22, 30 (1966).
6. P. Rai-Choudhury and D. K. Schroder, J. Electrochem. Society, 119, 1580 (1972).
7. Technical Report No. 4.
8. W. R. Fahrner and C. P. Schneider, ESSDERC, Nottingham, England (1974).
9. J. E. Jones and H. D. Barber, IInd Int. Symp. on Silicon Materials Science and Technology, March 13-18, Chicago, 561 (1973).
10. D. K. Schroder and P. Rai-Choudhury, Appl. Phys. Lett., 22, 455 (1973).
11. F. P. Heiman, ibid., 11, 132 (1967).
12. D. J. Dumin, Solid-State Electron., 13, 415 (1970).
13. W. Fahrner and A. Goetzberger, Appl. Phys. Lett., 17 16 (1970).