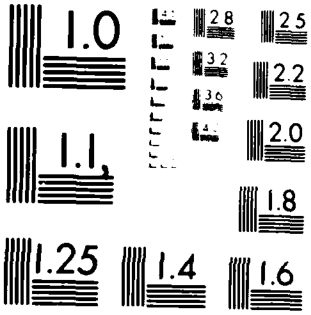
AD-A131 844 THE STUDY OF THIN FILMS ON SEMI-INSULATING GALLIUM ARSENIDE BY ELLIPSOMETRY(U) AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH 1/1

UNCLASSIFIED N T MCDEVITT ET AL. JUN 83 AFWAL-TR-83-4034 F/G 14/2 NL

END
DATE
FILMED
9 83
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

ADA131844

AFWAL-TR-83-4034

# THE STUDY OF THIN FILMS ON SEMI-INSULATING GALLIUM ARSENIDE BY ELLIPSOMETRY

Neil T. McDevitt
William L. Baun

Mechanics and Surface Interactions Branch
Nonmetallic Materials Division

June 1983

Final Report for Period January 1982 to December 1982

DTIC
ELECTE
AUG 26 1983
S D

Approved for public release; distribution unlimited.

DTIC FILE COPY

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AFB, OHIO 45433

83 08 26 049

## *NOTICE*

*When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.*

*This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.*

*This technical report has been reviewed and is approved for publication.*

NEIL T. MCDEVITT
Materials Research Engineer
Mechanics & Surface Interactions Branch

STEPHEN W. TSAI, Chief
Mechanics and Surface Interactions Branch
Nonmetallic Materials Division

*FOR THE COMMANDER*

FRANKLIN D. CHERRY, Chief
Nonmetallic Materials Division

*"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify* AFWAL/MLBM*, W-PAFB, OH 45433 to help us maintain a current mailing list".*

*Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.*

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| | | |
|---|---|---|
| **REPORT DOCUMENTATION PAGE** | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
| 1. REPORT NUMBER<br>AFWAL-TR-83-4034 | 2. GOVT ACCESSION NO.<br>AD-A131 844 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>THE STUDY OF THIN FILMS ON SEMI-INSULATING GALLIUM ARSENIDE BY ELLIPSOMETRY | | 5. TYPE OF REPORT & PERIOD COVERED<br>Internal<br>Jan 82 to Dec 82 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Neil T. McDevitt and William L. Baun | | 8. CONTRACT OR GRANT NUMBER(s)<br>In-House Report |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Materials Laboratory<br>Air Force Systems Command<br>Wright-Patterson AFB, Ohio 45433 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>Project 2303<br>Task 2303Q108 WUD #50 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Air Force Wright Aeronautical Laboratories<br>Materials Laboratory (AFWAL/MLBM)<br>Wright-Patterson AFB, Ohio 45433 | | 12. REPORT DATE<br>June 1983 |
| | | 13. NUMBER OF PAGES<br>34 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ellipsometry Gallium Arsenide Dielectric Films Epitaxial Films
Metal Films

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer-grid procedure is discussed where delta and psi values obtained from a thin filmed surface are used to estimate the optical constants of the film-free surface. Thin films can be measured with reasonable accuracy on gallium arsenide; however, the optical constants of these films cannot be obtained.

# FOREWORD

This technical report was prepared by N. T. McDevitt and W. L. Baun of the Mechanics and Surface Interactions Branch, Nonmetallic Materials Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories. The work was initiated under Project 2303, "Surface Phenomena" and WUD #50, "Surface and Interface Properties," monitored by Dr. T. W. Haas.

This report covers work performed in-house during the period January 1982 to December 1982.

The authors are grateful to Mr. Gary Griffin for his technical assistance with the computer program.

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

# LIST OF TABLES

# SECTION I

# INTRODUCTION

Optical methods have for a long time been extensively employed in surface studies and one of the more sensitive techniques used in this field is ellipsometry. Ellipsometry is virtually the only method for the direct determination of the optical constants of a large number of materials, and for the detection and quantitative thickness measurement of films deposited on these materials. The mathematical equations used in ellipsometry were formulated at the end of the last century; however, due to the cumbersome trigonometric equations involved in the analyses of these data, the technique, through the use of computers, has only been utilized in the last decade. This particular study was mainly accomplished through the use of McCrackin's (Reference 1) computer program for ellipsometry.

In principle, ellipsometry involves directing a monochromatic beam of linearly polarized light, at oblique incidence, onto a clean, flat reflecting surface and analyzing the state of polarization of the reflected beam. We can be a little more specific by referring to Figure 1. The plane polarized light has been rotated into s and p components, where the s component vibrates perpendicular to the plane of incidence and the p component parallel to it. The interaction of this light beam with a surface is unique and computation of the differing phase and amplitude of the orthogonal components enables the optical constants of a material to be determined. However, the application of electromagnetic theory to the reflection of light from materials containing free electrons requires the use of a complex refractive index. The free electrons cause an absorption of the incident light and the complex portion of the refractive index is justified by the fact that the imaginary part permits an easier solution to the absorption problem. The complex refractive index $\bar{n}$ is usually written $\bar{n} = n-ik$. Both n and k are positive numbers with the negative sign an arbitrary choice for the direction of propagation of the electromagnetic wave.

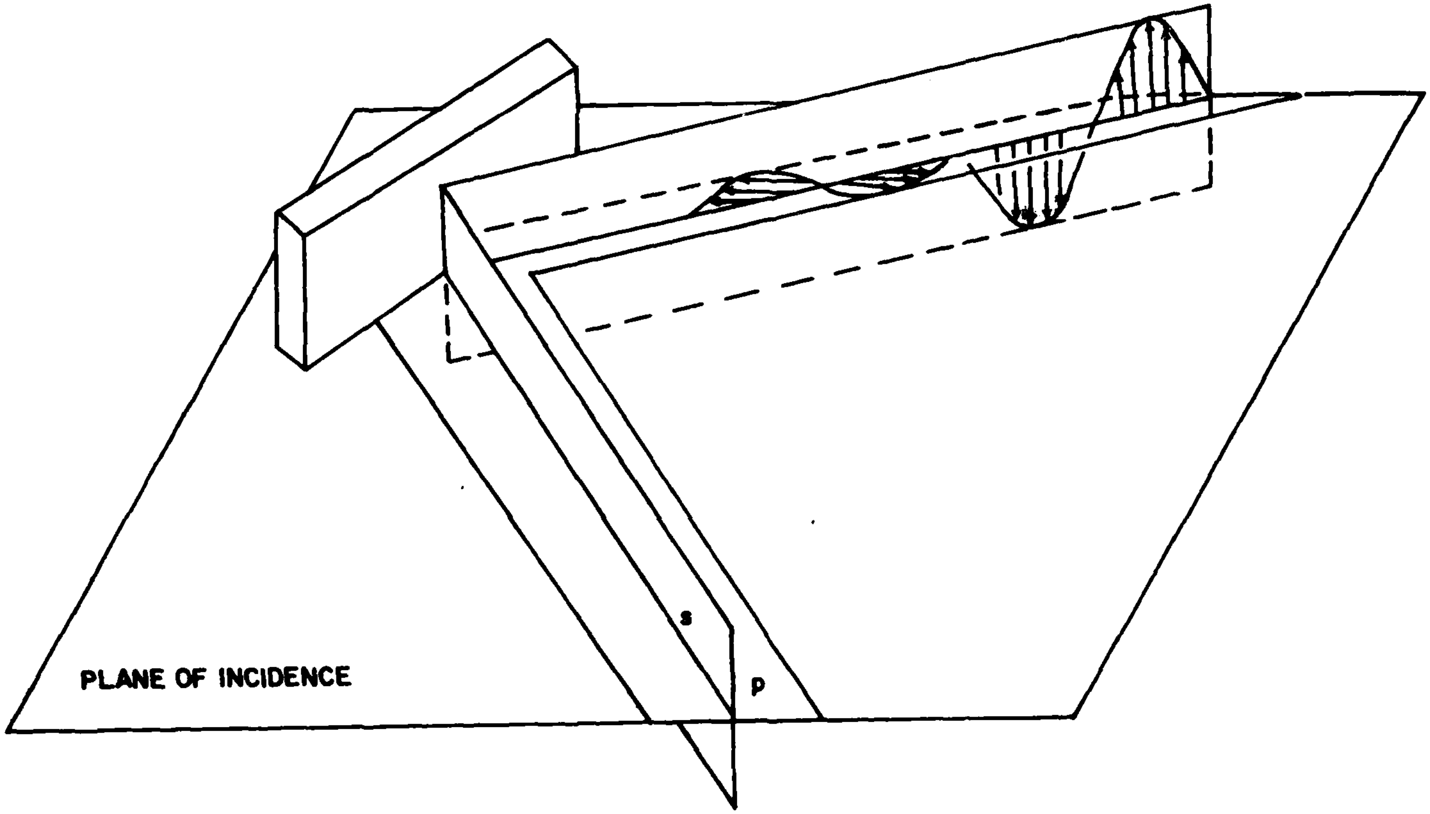


Figure 1. Reflection of Polarized Light into its Orthogonal Components

Interaction of light with this same surface when it is covered with a continuous, transparent (to the wavelength of light used) isotropic film is also unique, and often allows for the determination of the thickness of the film or its refractive index. In the case of a non-absorbing film or substate, k will be zero and the film or substrates optical constant will be designated only by n.

Our interest in ellipsometry is aimed at the study of thin films on semiconductors, in particular gallium arsenide (GaAs). Ellipsometry appears quite suitable for the study of these films for several reasons: (1) it is nondestructive by nature; (2) it can be utilized at ambient conditions; and (3) substrates can be studied under realistic processing procedures.

Thin films on semiconducting or semi-insulating GaAs are essential in device and circuit fabrication, particularly in FET (Field Effect Transistors) devices. These films help establish the appropriate properties of the GaAs surface for fabrication purposes. The determination of whether the GaAs surface is clean or contains a film, and the thickness of the film, is an important aspect of this technology. The main emphasis of this report will be on the optical characteristics of the <100> surface of the GaAs and the affects dielectrics and metal overlayers have on these properties.

# SECTION II

## EXPERIMENTAL

A Rudolph ellipsometer (Model 43702) was used for this study. The experimental details are described in a previous report (Reference 2). A mercury light source was used (546.1nm) and all measurements were performed at an angle of incidence of 70°. Extinction points were obtained from the polarizer and analyzer settings in Zones 1 and 3. All computations were performed on a PRIME 550+ computer. The program is capable of performing nine different ellipsometric computations. Our main use of the program in this study was centered on the computation of delta and psi for the purpose of studying the refractive index and film thickness of semiconductor materials.

All of the semi-insulating GaAs wafers used in this study were obtained commercially. The wafers were cut from boules grown by the liquid encapsulated Czochralski process. The polished wafers are 50mm in diameter, 0.5mm thick, and are oriented on the <100> plane. No dopants were added intentionally.

# SECTION III

# PROCEDURE

It is necessary to have access to a computer to facilitate the computation of the ellipsometric data. Also it must be remembered that the foundation of ellipsometry is buried deeply in theoretical models. These models require the surface of the substrate to be optically smooth and film free to obtain a true refractive index. The film must be optically isotropic, homogeneous, and transparent to the wavelength of the light source. The light source has to be monochromatic. Other problems that may arise, such as precision of measurement or instrumental errors, can be found in the literature (References 3-6). Consequently, data acquisition from real surfaces still leaves the interpretation aspect of the computed data fairly subjective.

In this report we will be dealing primarily with the ellipsometric parameters delta and psi and their dependence on the values of the refractive index of the substrate ($n_s$), the imaginary part ($k_s$), and the thickness (d) of the film. All of these are referenced to an angle of incidence of 70° and 546.1nm incident light. As mentioned previously, the complex refractive index is written

$$\bar{n}_s = n_s - ik_s \tag{1}$$

where $k_s$ is usually referred to as the extinction coefficient. However, the input into the computer program we are using will not take the value of the extinction coefficient ($k_s$), rather it requires the parameter called the absorption coefficient ($k_s^\star$). $k_s^\star$ is related to $k_s$ by the following:

$$k_s^\star = \frac{k_s}{n_s} \tag{2}$$

the complex refractive index may then be written as

$$\bar{n}_s = n_s(1-ik_s^\star) \tag{3}$$

Hereafter, this report will always use $k_s^\star$ when referring to the imaginary part of the refractive index.

Ellipsometry is noted for its sensitivity to changes in the surface of materials. The sensitivity of the technique can be estimated from the following equation that defines the penetration depth of the light as

$$d_p = \frac{\lambda}{4\pi n_s k_s^*} \tag{4}$$

the distance of penetration into the material which is measured in a direction normal to the surface and is dependent on the product of $n_s k_s^*$. For light of 5461Å, and several values obtained from the literature for $n_s$ and $k_s^*$ for gallium arsenide, the calculated penetration depth will be between 800 and 1000Å.

# SECTION IV

# RESULTS

## 1. DIELECTRIC FILMS

Ellipsometric measurements were performed on five semi-insulating gallium arsenide wafers. These wafers were cut from the same boule. Delta and psi values were obtained from five areas on each two inch wafer. These experimental data points are plotted (solid dots) on the graph (Figure 2). The grid shown in Figure 2 was computer generated. It was formed by using a series of n and $k^*$ values for gallium arsenide which were obtained from the literature. Each intersection on the grid represents a delta-psi value that would be obtained from a film-free surface (d=o). The spread of the data points is small and indicates the surfaces of the wafers are optically homogeneous. Because of the small spread in the data we can see from the graph that a reasonable average value for these points would be $\bar{n}_s = 3.98(1-i0.14)$. However, every gallium arsenide wafer, under ambient conditions, will have a film on the surface. The refractive index obtained from the graph will then be an apparent refractive index and not represent a film-free surface. In order to accurately obtain the thickness of a film on a surface the refractive index of the film-free surface must be known with some accuracy. This usually requires the measurement of the optical constants of a film-free surface while in an ultra-high vacuum environment. Other difficulties involved in this type of measurement are the possible damage to the surface while removing the ambient film while under vacuum, and the presence of the windows of the chamber between the light source, sample, and detector.

The following ellipsometric method is proposed as an easy and quick determination, under ambient conditions, to obtain the optical constants of a film-free surface. However, we are not proposing that this method is capable of predicting the absolute value of a film-free surface, but only a method to obtain the refractive index of a reasonably film-free surface of a particular substrate being studied.

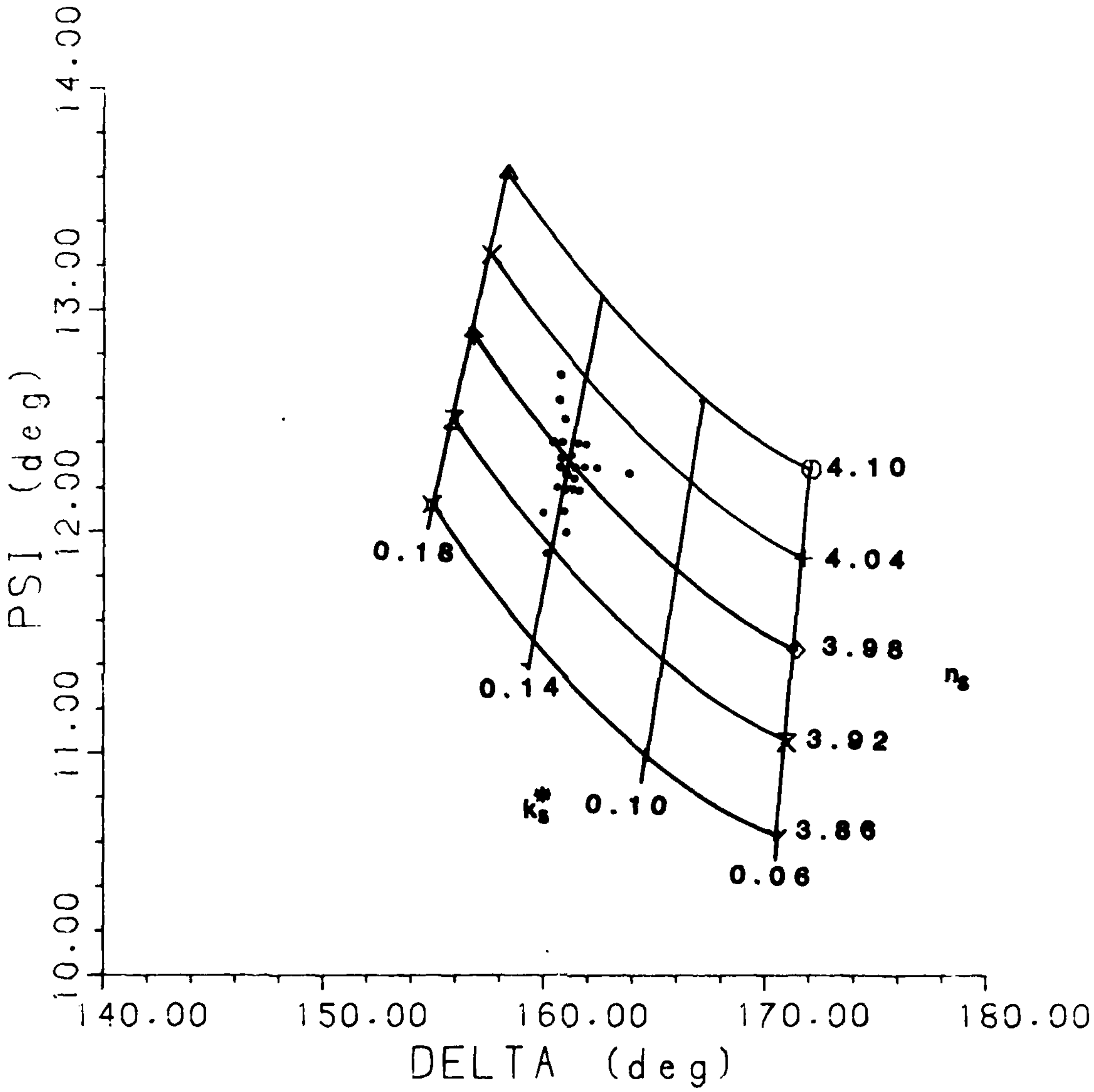


Figure 2. Computed Delta and Psi Relation for Various Complex Refractive Index Values of GaAs at Zero Film Thickness

It has been shown empirically that a nonabsorbing film on an absorbing substrate will lower the value of the real part of the refractive index while increasing the value of the imaginary part. Taking this into consideration and knowing that the data in Figure 2 represents a film covered surface, we can obtain the optical constant of a surface with a thinner film by moving to the right on the grid in Figure 2. Arbitrarily, we chose the next intersection on the grid and read $\bar{n}_s = 4.04(1-i0.1)$. We can now generate another set of curves in the following manner. Since $k_s^*$ is very small compared to $n_s$, delta and psi values will be insensitive to small changes in $k_s^*$. Curves may then be obtained by varying the real part of the refractive index, $4.04\pm3\%$, and keeping the imaginary part (0.1) constant. The film growth will be 0 to 50Å with a refractive index, $n_f = 1.90$. With a film of this thickness the refractive index can vary by ±5% and no error will be introduced into the readings (Figure 3). From the above data a second grid can be constructed as shown in Figure 4. Plotting the experimental data on this graph (solid points) show the GaAs wafers to have a film approximately 15Å thick with the optical constants for the film-free surface being 4.04(1-i0.1). Further indications show in Figure 4 that we have a reasonable value for $n_s$ which can be seen by the position of the open dots. These data points represent delta-psi values for several of the wafers after they have been chemically etched. The points indicate that some of the original surface film has been removed. These same wafers were subjected to a study by X-ray photoelectron spectroscopy and the corrected cross sections for the 1s line of oxygen and the Auger LMM line of gallium indicating only a small amount of oxygen is present on the surface.

By this comparison between the experimental data points and the calculated delta-psi grid diagrams, formed by varying the real part of the refractive index ($4.04\pm3\%$) for a 50Å film, we have demonstrated a method that should reveal the optical constants of a film-free substrate that are within the experimental error range of the unique value. The rest of the film data presented in this report will be referenced to the substrate optical constant obtained from Figure 4 where $\bar{n}_s = 4.04(1-i0.1)$. The assumption that the GaAs surface has a continuous film under ambient

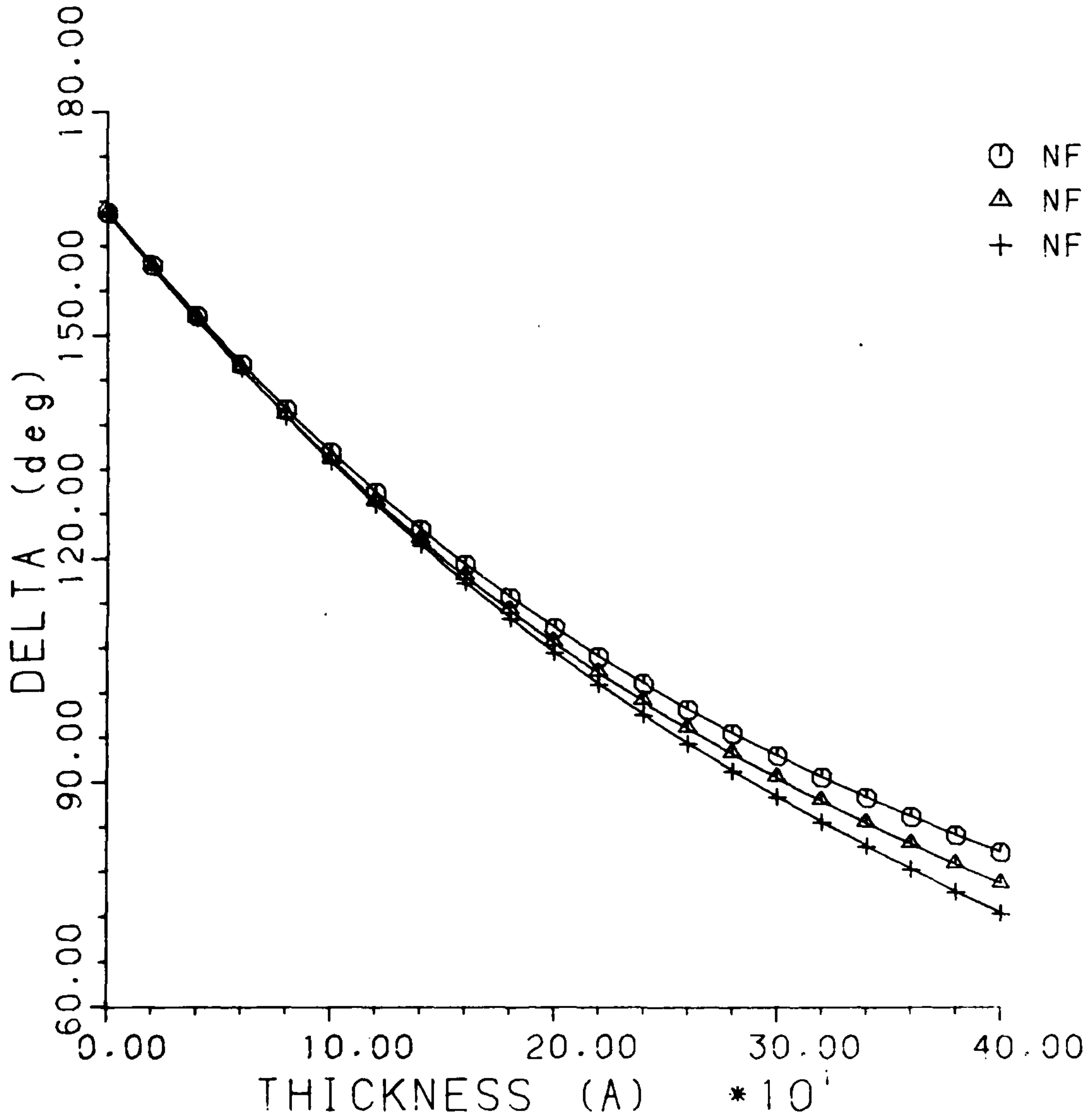


Figure 3. Computed Delta and Thickness Relation for Various Refractive Index Values of $Ga_2O_3$ on GaAs

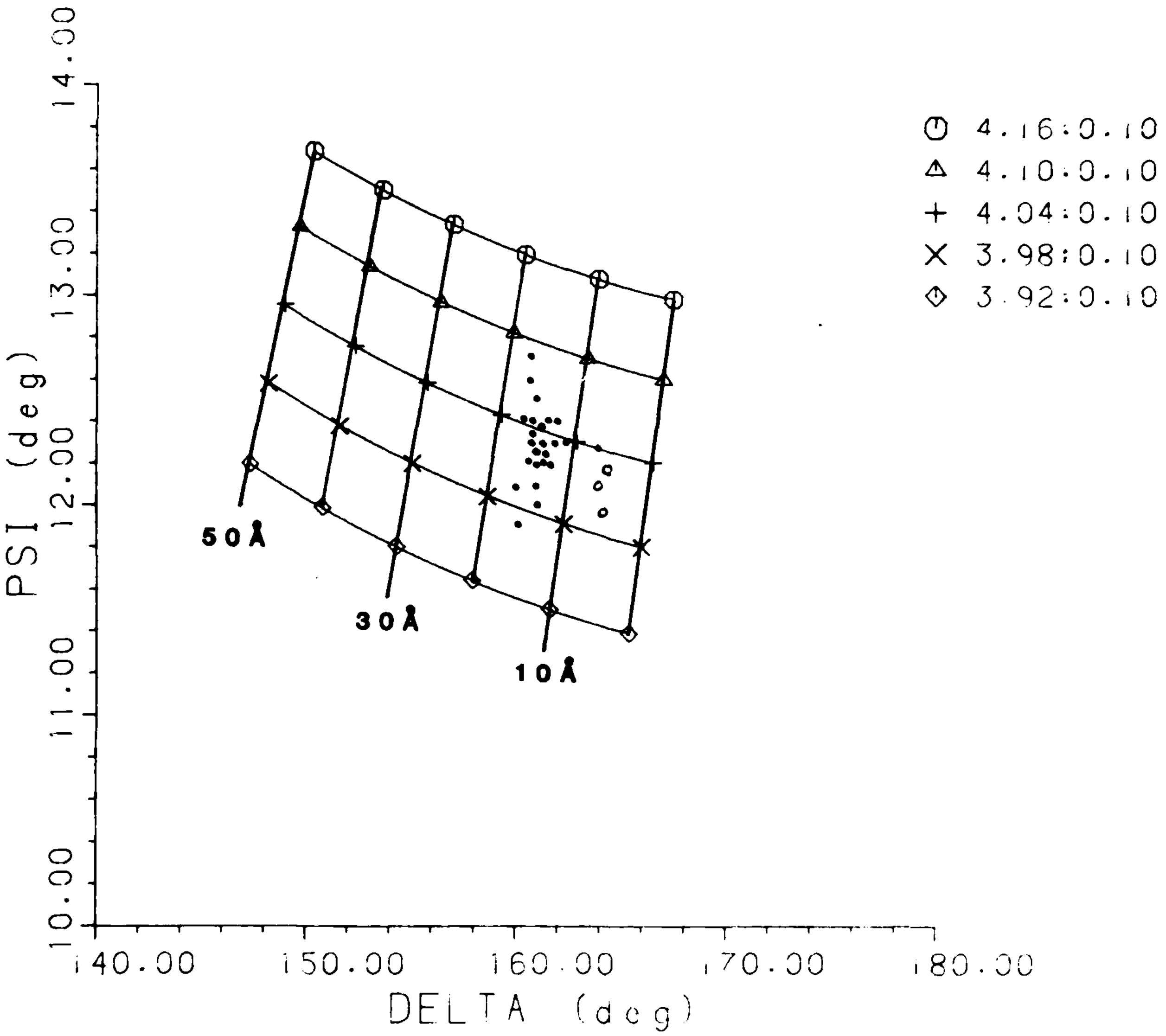


Figure 4. Computer Generated Delta and Psi Grid for GaAs for Film Thicknesses to 50Å

conditions seems valid when compared to the work (Reference 7) reported on GaAs at reduced pressures of oxygen where coverage is obtained around three monolayers. The stoichiometry of the film may be $As_2O_3$, $Ga_2O_3$ or $GaAsO_4$ but when dealing with a thin film these differences are not crucial (Figure 3) to this procedure. We also assumed that $k_f^* = 0$, however, the film may be slightly absorbing and the variations of delta and psi for thin films will not be large enough (Figure 5) to make this procedure invalid.

When a value has been established for a particular surface then delta and psi curves may be calculated for thicker films. Figure 6 shows the effect the refractive index of various films will have on the substrate being studied. A film with an index of 2.50 on this substrate will lose its sensitivity with the psi parameter and will require a fit primarily with the delta parameter. These curves were calculated using $\bar{n}_s = 4.04(1-i0.1)$, keeping the real part of the film refractive index constant and $k_f^* = 0$, while varying the thickness of the film. Figure 7 shows a similar series of curves for films that are commonly used or found on GaAs. The film was calculated for a film of 1600Å. Values for these films and several others are presented in Tables 1-5. The delta and psi values will repeat themselves after an increment of one wavelength of the light source used. This type of curve is considered closed. Comparison of delta with film thickness for a system of $Ga_2O_3$ on GaAs is shown in Figure 8. This figure shows the repeat pattern of a closed curve.

## 2. EPITAXIAL FILMS

Ternary and quaternary compounds are becoming increasingly important as CVD films on GaAs. Problems that are usually encountered in this type of film growth are lattice mismatch and dislocations. The use of ellipsometry in connection with vapor-phase film growth has been studied (Reference 8). Most of these films will have some free electron character, thus $k_f^* \neq 0$. When films become slightly absorbing the effect of the substrate on the reflected light becomes less pronounced as the film becomes thicker. The delta and psi curves will no longer be closed

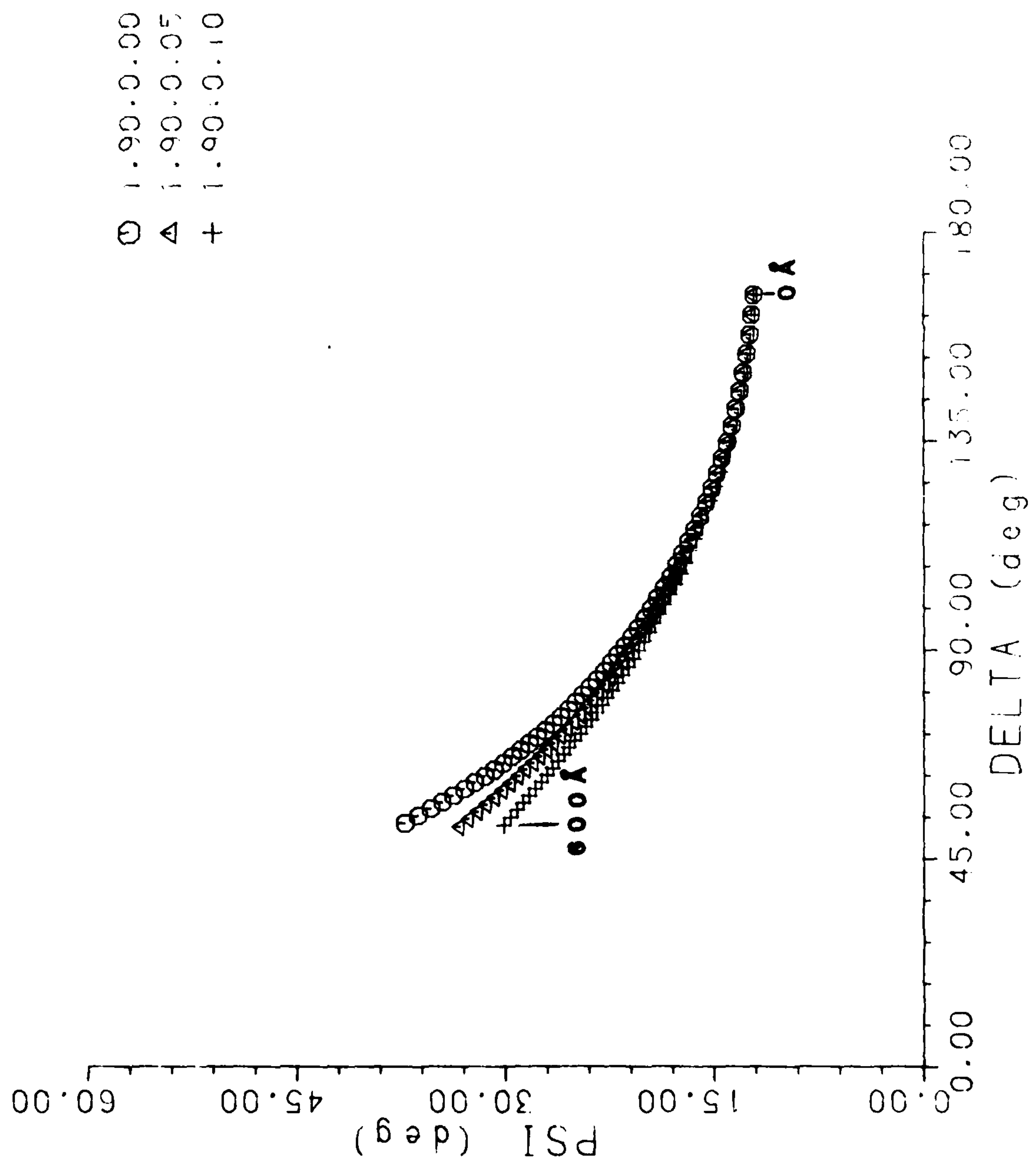


Figure 5. Computer Generated Delta and Psi Relation for a $Ga_2O_3$ Film Having an Imaginary Part

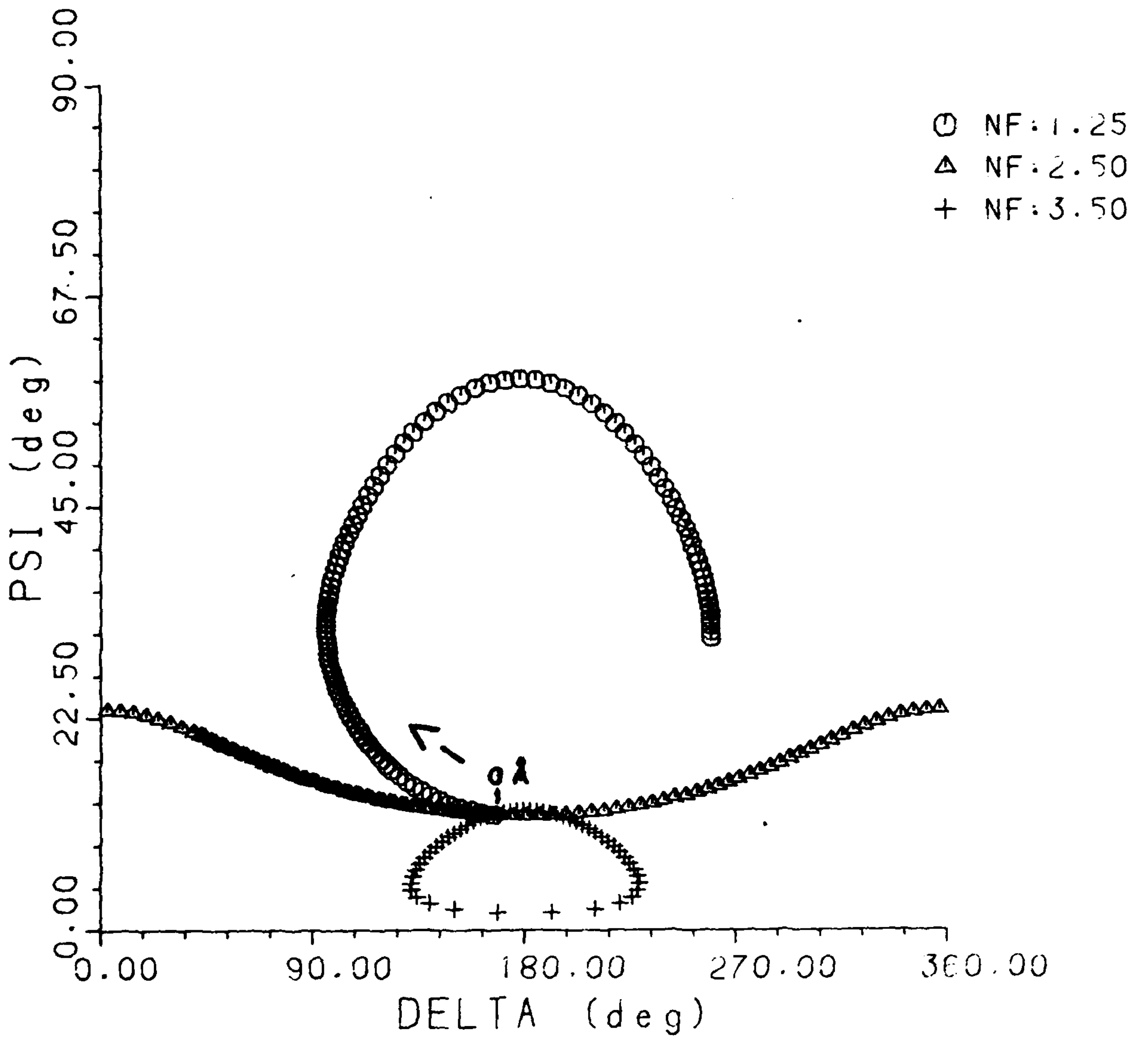


Figure 6. Relationship of Delta and Psi for Films of Varying Refractive Index on GaAs for Thicknesses up to 2400Å

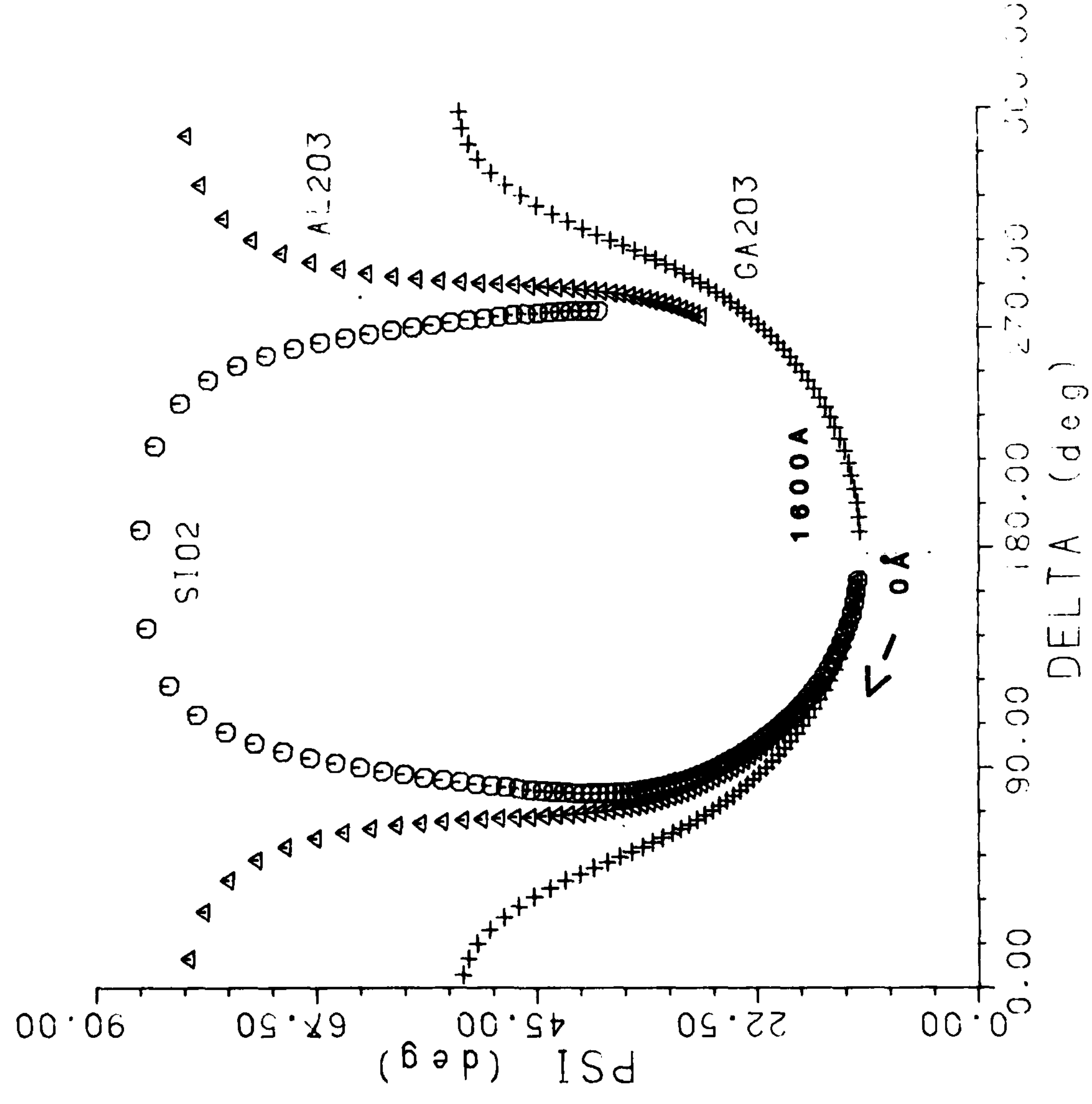


Figure 7. Relationship of Delta and Psi for Dielectric Films on GaAs

## TABLE 1

## CALCULATED VALUES FOR DELTA AND PSI FOR VARIOUS THICKNESSES OF $Si_3N_4$ ON GaAs

```
SI3N4//GAAS
NF          1.99
NS          4.04                                      0.10

   THICK     DEL       PSI      RF.CF.PARALLEL        RF.CF.NORMAL
     0.0  166.534    12.202   0.18198   -14.516   0.84153   179.050
    50.0  148.954    12.948   0.19255   -33.076   0.83913   177.070
   100.0  133.381    14.135   0.21096   -51.465   0.83415   175.164
   150.0  120.609    15.758   0.23352   -66.775   0.82759   173.216
   200.0  108.592    17.538   0.25842   -80.157   0.81772   171.211
   250.0   96.766    19.442   0.28357   -92.549   0.80482   169.135
   300.0   90.195    21.424   0.30897  -102.826   0.78741   166.979
   350.0   82.606    23.483   0.33259  -112.649   0.76512   164.744
   400.0   75.776    25.649   0.35428  -121.774   0.73710   162.451
   450.0   69.492    27.992   0.37366  -130.355   0.70359   160.153
   500.0   63.508    30.621   0.39052  -138.512   0.65978   157.900
   550.0   57.465    33.690   0.40472  -146.338   0.60728   156.197
   600.0   50.767    37.369   0.41617  -153.910   0.54493   155.322
   650.0   42.390    41.748   0.42485  -161.294   0.47653   156.516
   700.0   30.712    46.516   0.43073  -168.847   0.40852   160.741
   750.0   14.100    50.407   0.43382  -175.701   0.35679   170.179
   800.0  353.672    51.331   0.43406   177.184   0.34739  -176.538
   850.0  334.708    48.606   0.43156   169.970   0.38039  -164.732
   900.0  329.693    43.979   0.42623   162.737   0.44170  -157.056
   950.0  310.880    39.269   0.41811   155.343   0.51140  -155.496
  1000.0  303.458    35.189   0.40722   147.853   0.57748  -155.005
  1050.0  297.109    31.790   0.39355   140.083   0.63457  -157.026
  1100.0  291.050    28.919   0.37720   131.998   0.68277  -159.252
  1150.0  284.919    26.407   0.35832   123.510   0.72158  -161.310
  1200.0  278.119    24.124   0.33704   114.533   0.75263  -163.016
  1250.0  270.717    21.983   0.31377   104.833   0.77705  -165.484
  1300.0  262.384    19.940   0.28699    94.334   0.79601  -168.090
  1350.0  252.853    17.984   0.26347    82.659   0.81164  -170.195
  1400.0  241.801    16.140   0.23832    69.567   0.82308  -172.234
  1450.0  228.859    14.506   0.21514    54.651   0.83149  -174.208
  1500.0  213.737    13.178   0.19603    37.694   0.83726  -176.133
  1550.0  196.511    12.312   0.18348    18.487   0.84067  -178.024
  1600.0  177.979    12.044   0.17962    -1.918   0.84187  -179.857
  1650.0  159.590    12.421   0.18521   -22.180   0.84091   176.230
  1700.0  142.712    13.373   0.19917   -40.945   0.83775   176.342
  1750.0  127.994    14.757   0.21922   -57.563   0.83225   174.422
  1800.0  115.414    16.422   0.24291   -72.132   0.82415   172.454
  1850.0  104.651    18.258   0.26823   -84.926   0.81306   170.423
  1900.0   95.343    20.194   0.29369   -96.340   0.79846   168.317
  1950.0   87.178    22.205   0.31824  -106.692   0.77962   166.130
  2000.0   79.906    24.299   0.34117  -116.226   0.75563   163.868
  2050.0   73.311    26.523   0.36201  -125.126   0.72535   161.563
  2100.0   67.175    28.968   0.38045  -133.532   0.68747   159.293
  2150.0   61.220    31.738   0.39630  -141.551   0.64070   157.229
  2200.0   55.015    35.022   0.40944  -149.272   0.58428   155.714
  2250.0   47.825    38.971   0.41983  -156.764   0.51859   155.411
  2300.0   38.402    43.574   0.42744  -164.091   0.44905   157.507
  2350.0   24.960    48.223   0.43224  -171.308   0.38616   163.732
  2400.0    6.477    51.212   0.43424  -178.465   0.34699   175.059
```

# TABLE 2

## CALCULATED VALUES FOR DELTA AND PSI FOR VARIOUS THICKNESSES OF $Ga_2O_3$ ON GaAs

```
GA2O3//GAAS
NF        1.90
NS        4.04                                0.19

  THICK     DEL       PSI      RF.CF.PARALLEL        RF.CF.NORMAL
    0.0  166.534   12.202   0.18198   -14.516   0.84153   179.551
   50.0  149.007   12.955   0.19307   -33.034   0.83709   177.559
  100.0  133.508   14.202   0.21127   -51.752   0.83443   175.342
  150.0  120.227   15.795   0.23406   -66.566   0.82704   173.183
  200.0  108.913   17.576   0.25921   -79.991   0.81831   171.165
  250.0   99.197   19.487   0.28504   -91.738   0.80349   169.075
  300.0   90.742   21.475   0.31033  -102.317   0.78665   166.772
  350.0   83.278   23.532   0.33427  -112.079   0.76600   164.442
  400.0   76.588   25.689   0.35630  -121.101   0.74172   162.411
  450.0   70.470   28.010   0.37606  -129.578   0.70906   159.852
  500.0   64.699   30.603   0.39332  -137.627   0.66449   157.674
  550.0   58.955   33.617   0.40795  -145.342   0.61162   155.733
  600.0   52.711   37.233   0.41986  -152.709   0.55549   154.466
  650.0   45.041   41.587   0.42904  -160.062   0.48346   154.596
  700.0   34.396   46.509   0.43546  -167.157   0.41669   156.416
  750.0   18.844   50.968   0.43911  -174.206   0.35549   160.132
  800.0  358.443   52.824   0.44000   178.774   0.33549  -175.665
  850.0  338.181   50.747   0.43814   171.766   0.35511  -166.416
  900.0  322.861   46.170   0.43352   164.702   0.41617  -158.159
  950.0  312.359   41.203   0.42614   157.545   0.48672  -154.624
 1000.0  304.729   36.829   0.41600   150.211   0.55549  -154.514
 1050.0  298.452   33.194   0.40313   142.671   0.61619  -155.781
 1100.0  292.622   30.155   0.38757   134.848   0.66711  -157.774
 1150.0  285.720   27.532   0.36941   126.661   0.70767  -160.160
 1200.0  280.427   25.176   0.34882   118.068   0.74209  -162.419
 1250.0  273.508   22.986   0.32608   108.760   0.76449  -164.748
 1300.0  265.749   20.902   0.30155    98.747   0.78571  -167.003
 1350.0  256.912   18.899   0.27599    87.740   0.80615  -169.172
 1400.0  246.709   16.994   0.25024    75.441   0.81382  -171.259
 1450.0  234.757   15.242   0.22570    61.484   0.82431  -173.274
 1500.0  220.728   13.743   0.20424    45.498   0.83508  -175.031
 1550.0  204.471   12.649   0.18825    27.325   0.83944  -177.146
 1600.0  186.424   12.084   0.18017     7.398   0.84158  -179.036
 1650.0  167.813   12.172   0.18153   -13.135   0.84161   179.082
 1700.0  150.171   12.885   0.19204   -32.657   0.83552   177.192
 1750.0  134.516   14.102   0.20982   -50.207   0.83521   175.077
 1800.0  121.086   15.667   0.23237   -65.592   0.82550   173.321
 1850.0  109.647   17.447   0.25742   -79.045   0.81506   171.308
 1900.0   99.831   19.351   0.28324   -90.546   0.80650   169.023
 1950.0   91.297   21.334   0.30862  -101.647   0.79015   167.056
 2000.0   83.772   23.386   0.33266  -111.425   0.76926   164.603
 2050.0   77.034   25.534   0.35484  -120.481   0.74080   162.475
 2100.0   70.883   27.841   0.37476  -129.031   0.70957   160.116
 2150.0   65.096   30.410   0.39220  -137.077   0.66621   157.827
 2200.0   59.364   33.389   0.40701  -144.813   0.61763   155.923
 2250.0   53.179   36.957   0.41912  -152.286   0.55706   154.535
 2300.0   45.651   41.259   0.42849  -159.560   0.48843   154.788
 2350.0   35.278   46.162   0.43509  -166.693   0.41700   158.028
 2400.0   20.114   53.713   0.43694  -173.737   0.35510   166.150
```

## TABLE 3

## CALCULATED VALUES FOR DELTA AND PSI FOR VARIOUS THICKNESSES OF $As_2O_3$ ON GaAs

AS2O3//GAAS
NF 1.80
AS 4.04 .10

| THICK | DEL | PSI | RF.CF.PARALLEL | | RF.CF.NORMAL | |
|---|---|---|---|---|---|---|
| 0.0 | 166.534 | 12.202 | 0.18198 | -14.516 | 0.84153 | 179.959 |
| 50.0 | 149.371 | 12.980 | 0.19352 | -33.622 | 0.83558 | 177.607 |
| 100.0 | 134.301 | 14.259 | 0.21237 | -50.662 | 0.83169 | 175.637 |
| 150.0 | 121.500 | 15.876 | 0.23597 | -65.476 | 0.82569 | 173.225 |
| 200.0 | 110.694 | 17.696 | 0.26296 | -78.355 | 0.82173 | 170.952 |
| 250.0 | 101.503 | 19.627 | 0.28856 | -89.656 | 0.81127 | 168.661 |
| 300.0 | 93.592 | 21.618 | 0.31545 | -99.852 | 0.79571 | 166.556 |
| 350.0 | 86.708 | 23.653 | 0.34073 | -109.098 | 0.77793 | 164.202 |
| 400.0 | 80.631 | 25.750 | 0.36426 | -117.638 | 0.75521 | 161.731 |
| 450.0 | 75.228 | 27.952 | 0.38568 | -125.624 | 0.72941 | 159.147 |
| 500.0 | 70.346 | 30.342 | 0.40476 | -133.172 | 0.69449 | 156.462 |
| 550.0 | 65.813 | 33.040 | 0.42139 | -140.771 | 0.64788 | 153.816 |
| 600.0 | 61.372 | 36.218 | 0.43549 | -147.293 | 0.59463 | 151.536 |
| 650.0 | 56.574 | 40.096 | 0.44705 | -153.997 | 0.53097 | 149.429 |
| 700.0 | 50.577 | 44.894 | 0.45605 | -160.574 | 0.45774 | 148.689 |
| 750.0 | 41.760 | 50.626 | 0.46252 | -166.951 | 0.37556 | 151.289 |
| 800.0 | 27.338 | 56.499 | 0.46646 | -173.218 | 0.30075 | 159.374 |
| 850.0 | 5.092 | 60.076 | 0.46788 | -179.545 | 0.26070 | 175.323 |
| 900.0 | 340.326 | 58.697 | 0.46679 | 174.121 | 0.29384 | -166.295 |
| 950.0 | 322.091 | 53.476 | 0.46319 | 167.792 | 0.34704 | -154.300 |
| 1000.0 | 310.933 | 47.428 | 0.45705 | 161.388 | 0.41987 | -149.546 |
| 1050.0 | 303.791 | 42.089 | 0.44838 | 154.868 | 0.49143 | -148.923 |
| 1100.0 | 298.491 | 37.739 | 0.43716 | 148.199 | 0.56501 | -150.302 |
| 1150.0 | 293.670 | 34.188 | 0.42375 | 141.299 | 0.62428 | -152.971 |
| 1200.0 | 289.320 | 31.229 | 0.40710 | 134.141 | 0.67143 | -155.179 |
| 1250.0 | 284.504 | 28.656 | 0.38833 | 126.644 | 0.71960 | -157.859 |
| 1300.0 | 279.211 | 26.325 | 0.36722 | 118.722 | 0.74219 | -160.489 |
| 1350.0 | 273.279 | 24.138 | 0.34395 | 110.263 | 0.76753 | -163.016 |
| 1400.0 | 266.547 | 22.038 | 0.31887 | 101.121 | 0.78775 | -165.427 |
| 1450.0 | 258.821 | 19.997 | 0.29250 | 91.098 | 0.80378 | -167.723 |
| 1500.0 | 249.850 | 18.023 | 0.26560 | 79.932 | 0.81632 | -169.918 |
| 1550.0 | 239.305 | 16.159 | 0.23931 | 67.279 | 0.82594 | -172.026 |
| 1600.0 | 226.808 | 14.489 | 0.21527 | 52.742 | 0.83305 | -174.066 |
| 1650.0 | 212.056 | 13.142 | 0.19564 | 36.002 | 0.83754 | -176.054 |
| 1700.0 | 195.141 | 12.278 | 0.18300 | 17.152 | 0.84092 | -178.008 |
| 1750.0 | 176.928 | 12.038 | 0.17951 | -3.018 | 0.84180 | -179.945 |
| 1800.0 | 158.955 | 12.464 | 0.18588 | -22.927 | 0.84093 | 178.118 |
| 1850.0 | 142.622 | 13.477 | 0.20086 | -41.212 | 0.83816 | 176.166 |
| 1900.0 | 128.540 | 14.920 | 0.22206 | -57.280 | 0.83338 | 174.180 |
| 1950.0 | 116.641 | 16.639 | 0.24697 | -71.216 | 0.82641 | 172.143 |
| 2000.0 | 106.573 | 18.515 | 0.27359 | -83.387 | 0.81654 | 170.039 |
| 2050.0 | 97.968 | 20.476 | 0.30043 | -94.182 | 0.80457 | 167.850 |
| 2100.0 | 90.522 | 22.486 | 0.32649 | -103.918 | 0.78877 | 165.560 |
| 2150.0 | 84.004 | 24.544 | 0.35107 | -112.839 | 0.76880 | 163.156 |
| 2200.0 | 78.239 | 26.678 | 0.37372 | -121.126 | 0.74378 | 160.635 |
| 2250.0 | 73.078 | 28.949 | 0.39416 | -128.911 | 0.71258 | 158.010 |
| 2300.0 | 68.370 | 31.454 | 0.41220 | -136.300 | 0.67397 | 155.330 |
| 2350.0 | 63.916 | 34.333 | 0.42775 | -143.371 | 0.62627 | 152.713 |
| 2400.0 | 59.393 | 37.782 | 0.44076 | -150.193 | 0.56859 | 150.414 |

## TABLE 4

## CALCULATED VALUES FOR DELTA AND PSI FOR VARIOUS THICKNESSES OF $Al_2O_3$ ON GaAs

AL2O3//GAAS
NF 1.55
NS 4.04 .31

| THICK | DEL | PSI | RF.CF.PARALLEL | | RF.CF.NORMAL | |
|---|---|---|---|---|---|---|
| 0.0 | 166.534 | 12.002 | 0.18158 | -14.516 | .84157 | [illegible] |
| 50.0 | 150.901 | 12.962 | 0.19339 | -32.106 | 0.84200 | [illegible] |
| 100.0 | 137.225 | 14.191 | 0.21175 | -47.947 | 0.84071 | 174.532 |
| 150.0 | 125.671 | 15.741 | 0.23495 | -61.616 | 0.83345 | 172.277 |
| 200.0 | 116.002 | 17.484 | 0.26170 | -73.477 | .82772 | [illegible] |
| 250.0 | 107.876 | 19.227 | 0.28770 | -83.296 | .82033 | [illegible] |
| 300.0 | 100.987 | 21.012 | 0.31475 | -93.078 | .81099 | [illegible] |
| 350.0 | 95.099 | 23.108 | 0.34110 | -101.330 | .79938 | 167.071 |
| 400.0 | 90.041 | 25.007 | 0.36624 | -108.963 | 0.77914 | 161.096 |
| 450.0 | 85.693 | 26.917 | 0.39981 | -116.092 | 0.74978 | 159.[illegible] |
| 500.0 | 81.474 | 28.864 | 0.41153 | -122.643 | .74469 | 155.[illegible] |
| 550.0 | 78.629 | 30.592 | 0.43145 | -128.859 | 0.70112 | 150.[illegible] |
| 600.0 | 76.216 | 33.066 | 0.44932 | -134.854 | 0.66619 | 148.[illegible] |
| 650.0 | 74.102 | 35.476 | 0.46516 | -140.559 | 0.65270 | 145.736 |
| 700.0 | 72.445 | 38.251 | 0.47898 | -146.057 | 0.60156 | 141.[illegible] |
| 750.0 | 71.174 | 41.568 | 0.49081 | -151.365 | 0.55143 | 137.446 |
| 800.0 | 70.152 | 45.668 | 0.50046 | -156.575 | 0.48411 | 133.[illegible] |
| 850.0 | 69.080 | 50.661 | 0.50557 | -161.654 | 0.41194 | 129.066 |
| 900.0 | 67.267 | 57.489 | 0.51457 | -166.649 | 0.32755 | 126.[illegible] |
| 950.0 | 62.821 | 65.751 | 0.51869 | -171.592 | 0.23364 | 125.096 |
| 1000.0 | 48.741 | 75.655 | 0.52095 | -176.478 | 0.13905 | 134.281 |
| 1050.0 | 357.432 | 80.754 | 0.52136 | 178.641 | 0.08487 | -178.790 |
| 1100.0 | 307.836 | 74.709 | 0.51992 | 173.755 | 0.14215 | -134.081 |
| 1150.0 | 294.362 | 65.354 | 0.51663 | 168.841 | 0.23704 | -125.921 |
| 1200.0 | 290.044 | 57.080 | 0.51146 | 163.876 | 0.33113 | -126.165 |
| 1250.0 | 288.236 | 50.438 | 0.50449 | 158.878 | 0.41471 | -129.299 |
| 1300.0 | 287.119 | 45.224 | 0.49541 | 153.750 | 0.49196 | -133.419 |
| 1350.0 | 286.023 | 41.093 | 0.48447 | 148.437 | 0.55149 | -137.085 |
| 1400.0 | 284.656 | 37.736 | 0.47153 | 143.018 | 0.60099 | -141.637 |
| 1450.0 | 282.880 | 34.915 | 0.45659 | 137.415 | 0.65414 | -145.473 |
| 1500.0 | 280.623 | 32.452 | 0.43961 | 131.571 | 0.69134 | -149.352 |
| 1550.0 | 277.941 | 30.021 | 0.42063 | 125.456 | 0.72210 | -152.585 |
| 1600.0 | 274.493 | 28.133 | 0.39965 | 119.086 | 0.74750 | -155.469 |
| 1650.0 | 270.530 | 26.126 | 0.37699 | 112.147 | 0.76145 | -158.587 |
| 1700.0 | 265.883 | 24.158 | 0.35242 | 104.785 | 0.78069 | -161.099 |
| 1750.0 | 260.452 | 22.209 | 0.32655 | 96.793 | 0.79983 | -163.559 |
| 1800.0 | 254.091 | 20.075 | 0.29973 | 88.093 | 0.81175 | -166.088 |
| 1850.0 | 246.596 | 18.376 | 0.27261 | 78.189 | 0.82062 | -168.407 |
| 1900.0 | 237.691 | 16.555 | 0.24611 | 67.054 | 0.82795 | -170.636 |
| 1950.0 | 227.043 | 14.886 | 0.22158 | 54.245 | 0.83357 | -172.298 |
| 2000.0 | 214.340 | 13.482 | 0.20082 | 39.436 | 0.83763 | -174.505 |
| 2050.0 | 199.527 | 12.484 | 0.18603 | 22.552 | 0.84027 | -176.074 |
| 2100.0 | 183.142 | 12.032 | 0.17978 | 4.120 | 0.84156 | -179.022 |
| 2150.0 | 166.430 | 12.005 | 0.18202 | -14.633 | 0.84153 | 178.437 |
| 2200.0 | 150.808 | 12.969 | 0.19349 | -32.303 | 0.84019 | 176.089 |
| 2250.0 | 137.145 | 14.200 | 0.21190 | -48.036 | 0.83749 | 174.018 |
| 2300.0 | 125.604 | 15.752 | 0.23506 | -61.087 | 0.83337 | 172.716 |
| 2350.0 | 115.946 | 17.495 | 0.26089 | -73.508 | 0.82769 | 170.547 |
| 2400.0 | 107.829 | 19.339 | 0.28766 | -83.058 | 0.82028 | 168.313 |

## TABLE 5

## CALCULATED VALUES FOR DELTA AND PSI FOR VARIOUS THICKNESSES OF $SiO_2$ ON GaAs

```
SIO2//GAAS
NF         1.45
NS         4.04                                   0.16

   THICK      DEL       PSI     RF.CF.PARALLEL         RF.CF.NORMAL
     0.0  166.534    12.202   0.18198   -14.016    0.84153   178.950
    50.0  152.321    12.901   0.19252   -30.808    0.84051   176.851
   100.0  139.796    14.016   0.20930   -45.471    0.83645   174.733
   150.0  129.133    15.425   0.23047   -58.293    0.83539   172.583
   200.0  120.168    17.019   0.25437   -69.444    0.83190   171.388
   250.0  112.625    18.716   0.27965   -79.243    0.82443   169.132
   300.0  106.241    20.458   0.30533   -87.956    0.81047   165.991
   350.0  100.904    22.211   0.33072   -95.019    0.80596   163.576
   400.0   96.158    23.958   0.35533  -103.013    0.79567   160.039
   450.0   92.190    25.693   0.37889  -109.642    0.78734   156.169
   500.0   88.923    27.424   0.40091  -115.918    0.77164   155.338
   550.0   86.008    29.168   0.42156  -121.470    0.75518   152.423
   600.0   83.715    30.952   0.44049  -127.197    0.73447   149.069
   650.0   81.932    32.817   0.45782  -132.467    0.70994   145.501
   700.0   80.662    34.614   0.47349  -137.591    0.68190   141.417
   750.0   79.919    37.014   0.48747  -142.391    0.64655   137.189
   800.0   79.730    39.513   0.49981  -147.105    0.60603   133.164
   850.0   80.135    42.436   0.51053  -151.608    0.55149   128.178
   900.0   81.189    45.946   0.51966  -156.161    0.50278   122.850
   950.0   82.983    50.252   0.52723  -160.543    0.43847   116.474
  1000.0   85.679    55.599   0.53328  -164.887    0.36515   109.466
  1050.0   89.655    62.228   0.53782  -169.157    0.28522   101.236
  1100.0   96.090    70.549   0.54088  -173.323    0.19421    90.587
  1150.0  110.756    79.310   0.54248  -177.514    0.10241    71.731
  1200.0  187.410    85.425   0.54262   178.354    0.04342    -9.106
  1250.0  249.452    78.088   0.54132   174.116    0.11419   -75.336
  1300.0  262.122    69.053   0.53851   169.906    0.20614   -92.016
  1350.0  268.070    61.145   0.53425   165.660    0.29478  -102.410
  1400.0  271.803    54.625   0.52849   161.362    0.37524  -110.441
  1450.0  274.318    49.359   0.52121   156.955    0.44738  -117.523
  1500.0  275.947    45.103   0.51238   152.541    0.51053  -123.406
  1550.0  276.838    41.616   0.50196   147.980    0.56596  -128.858
  1600.0  277.073    38.692   0.48992   143.253    0.61170  -133.760
  1650.0  276.704    36.172   0.47625   138.454    0.65137  -138.250
  1700.0  275.767    33.936   0.46090   133.437    0.68497  -142.329
  1750.0  274.283    31.891   0.44389   128.210    0.71339  -146.072
  1800.0  272.260    29.970   0.42521   122.775    0.73738  -149.625
  1850.0  269.694    28.122   0.40492   116.966    0.75764  -152.728
  1900.0  266.562    26.312   0.38309   110.844    0.77471  -155.718
  1950.0  262.821    24.515   0.35986   104.295    0.78907  -158.526
  2000.0  258.401    22.720   0.33544    97.224    0.80112  -161.178
  2050.0  253.202    20.926   0.31017    89.503    0.81117  -163.699
  2100.0  247.075    19.145   0.28449    80.965    0.81947  -166.111
  2150.0  239.821    17.409   0.25907    71.390    0.82623  -168.431
  2200.0  231.188    15.768   0.23483    60.510    0.83163  -170.678
  2250.0  220.895    14.099   0.21302    48.029    0.83578  -172.867
  2300.0  208.745    13.105   0.19526    33.733    0.83878  -175.012
  2350.0  194.827    12.307   0.18341    17.700    0.84070  -177.126
  2400.0  179.758    12.012   0.17907     0.534    0.84159  -179.224
```

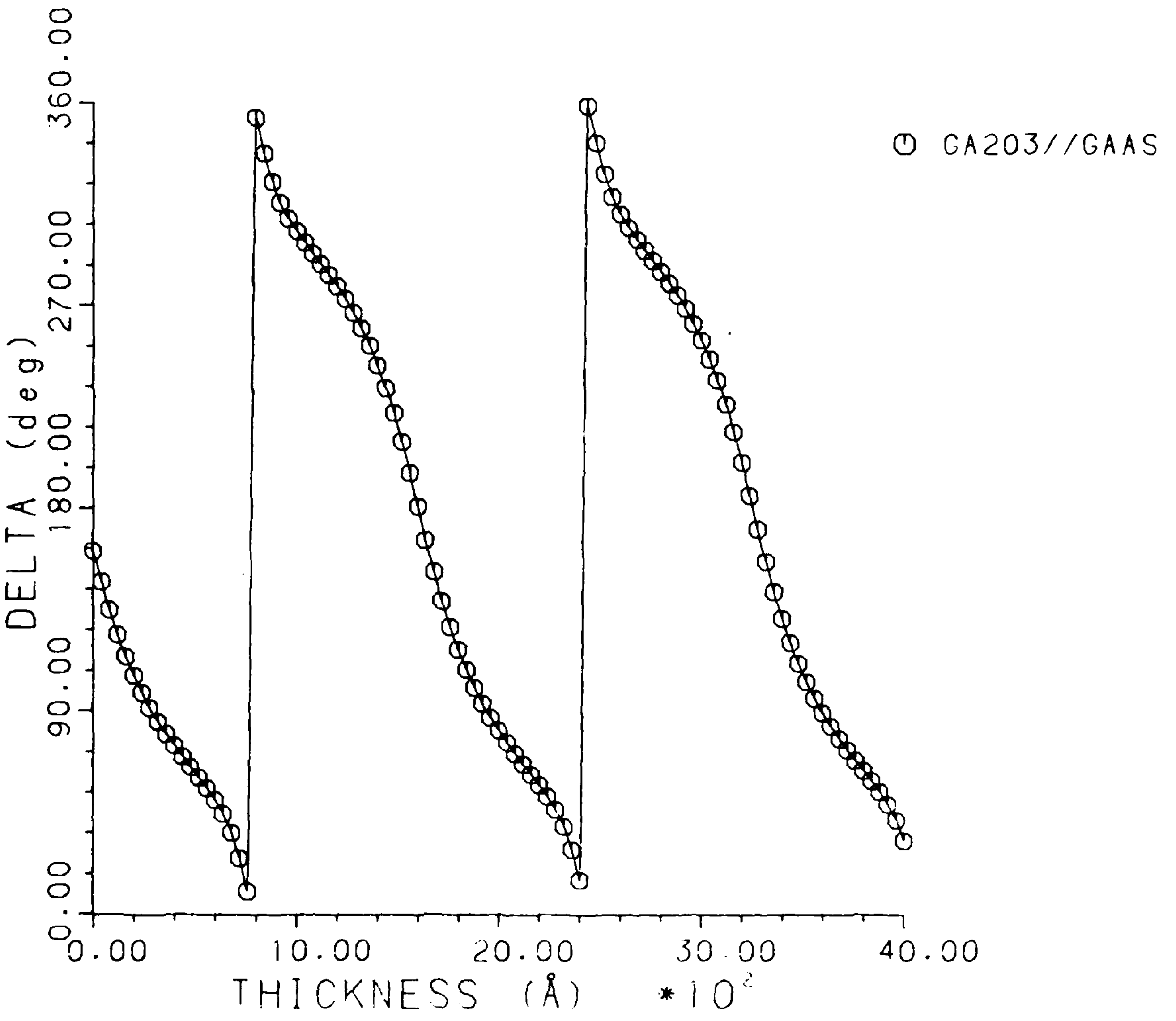


Figure 8. Relationship of Delta and Thickness for a Closed Curve of $Ga_2O_3$ on GaAs

for this type of film. The delta and psi values will approach the values representative of the bulk film with increasing film thickness. This type of curve, shown in Figure 9, is calculated for GaAlAs/GaAs where $\bar{n}_f = 4.2(1-i0.067)$. A comparison of delta and thickness values for this system (Figure 10) shows a dampened curve as the substrate becomes increasingly obscured by the film. The magnitude of the absorption character of the film would determine the usefulness of ellipsometry for each epitaxial film studied. For the film data shown in Figure 10 information could be reasonably obtained from a 200Å film and possibly up to 600Å. Thicker films would become increasingly difficult to interpret using null ellipsometry.

## 3. METAL FILMS

The use of ellipsometry in connection with programs dealing with contacts and interconnects on compound semiconductors was reviewed. A short study was performed looking at a small number of metal films on GaAs. The absorption character ($k_f^*$) of metallic films is usually greater than 0.25. The limitation of the sensitivity of ellipsometry will depend primarily on the value of $k_f^*$ of each film studied. Knowing this limitation will be an important aspect of a study concerning metal films. The metal films looked at in this study were, nickel 1.4-(1-i1.8), gold 0.43(1-i5.12), and germanium 5.46(1-i0.32). The delta and psi curves (Figure 11) are characteristic of metal films and show an entirely different response when compared to dielectric and epitaxial films. These data were generated for 400Å thick films and a comparison of delta and thickness is reported in Figure 12. Sensitivity for the GaAs surface will become obscure for nickel and gold around 150Å, while germanium films may be studied to 300Å. However, the germanium film will suffer in sensitivity where the maximum occurs in the curve.

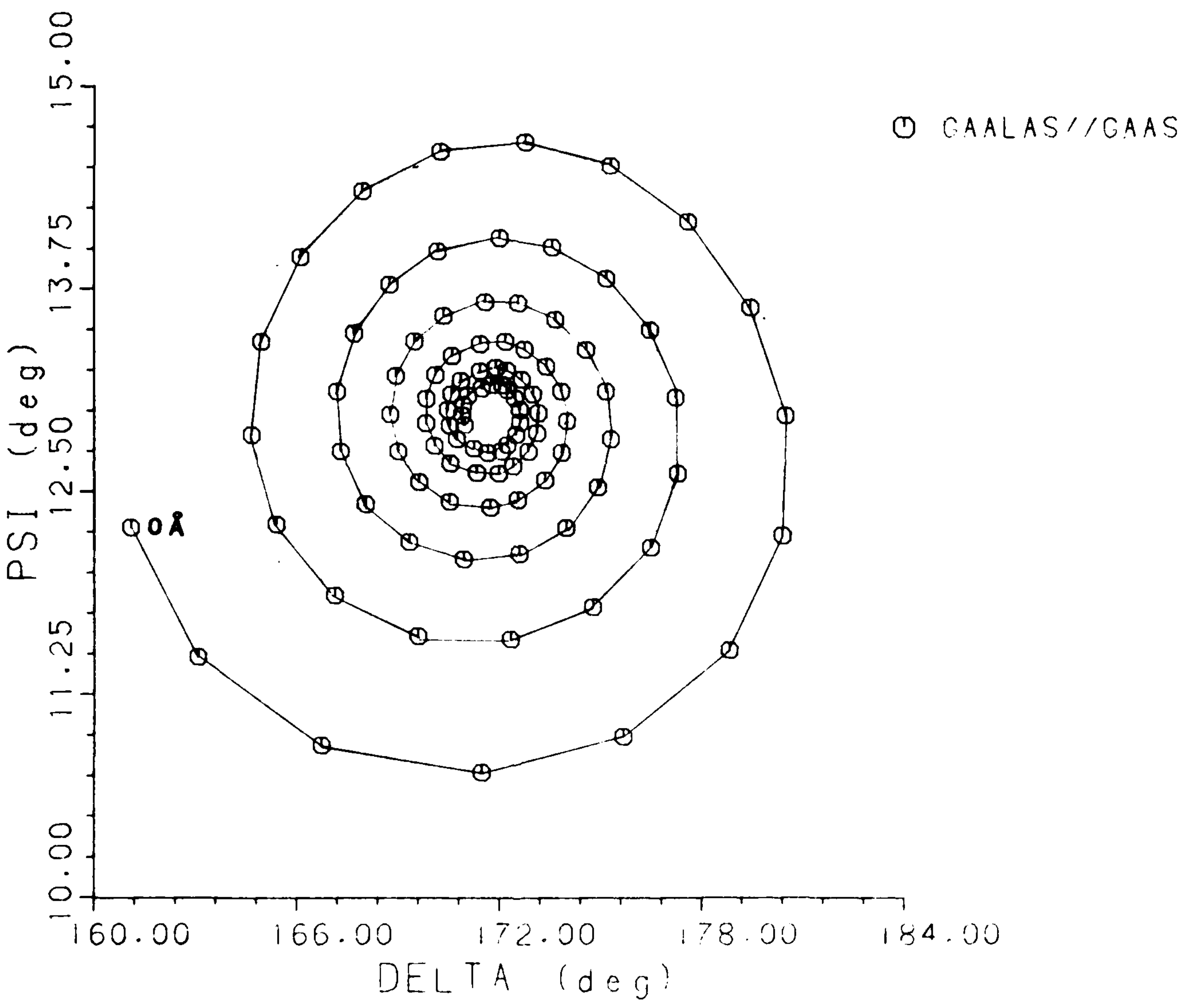


Figure 9. Computed Delta and Psi Relation for Epitaxial Film GaAlAs on GaAs for a Thickness of 2500Å

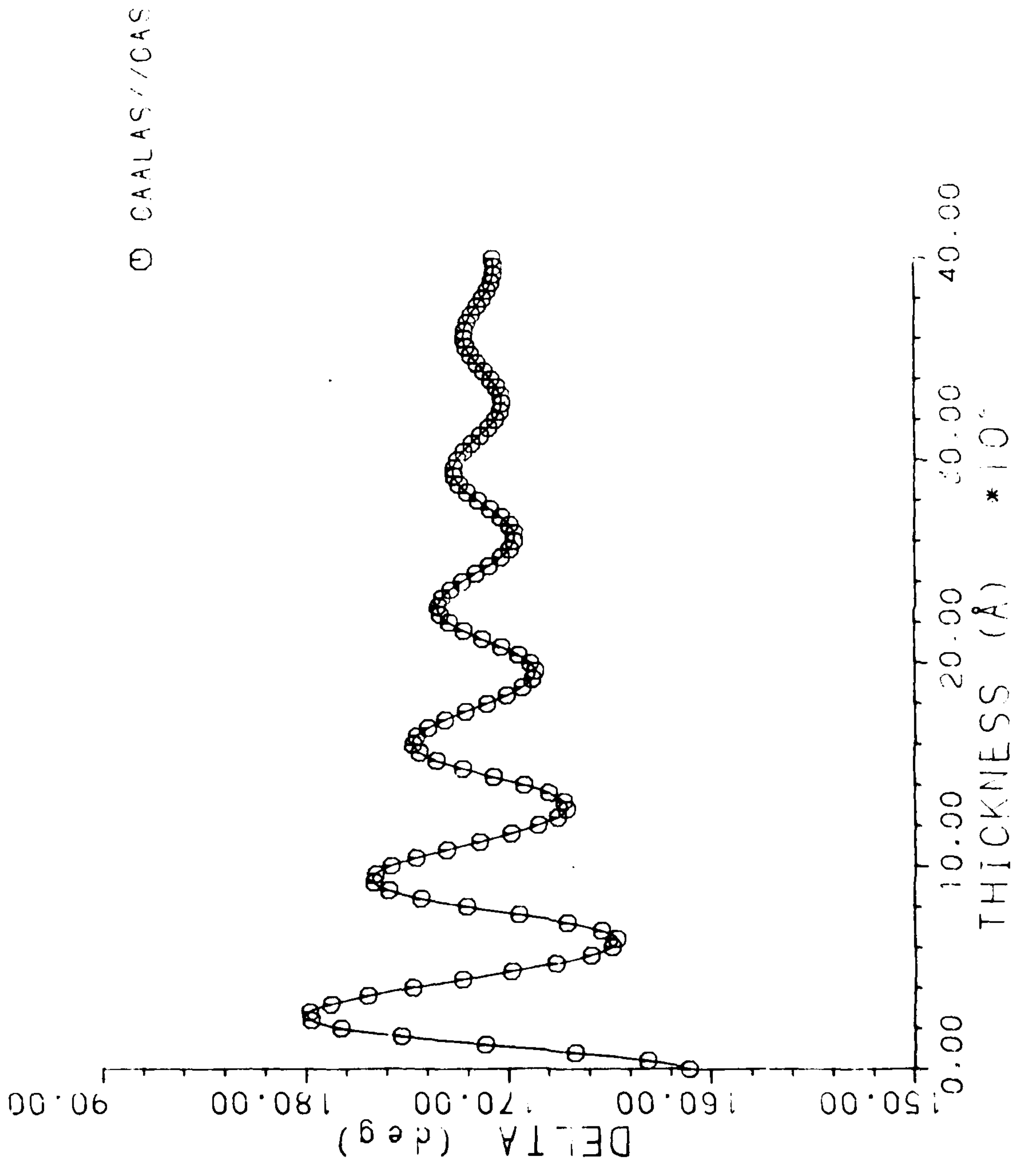


Figure 10. Relationship of Delta and Thickness Showing a Dampened Curve for GaAlAs

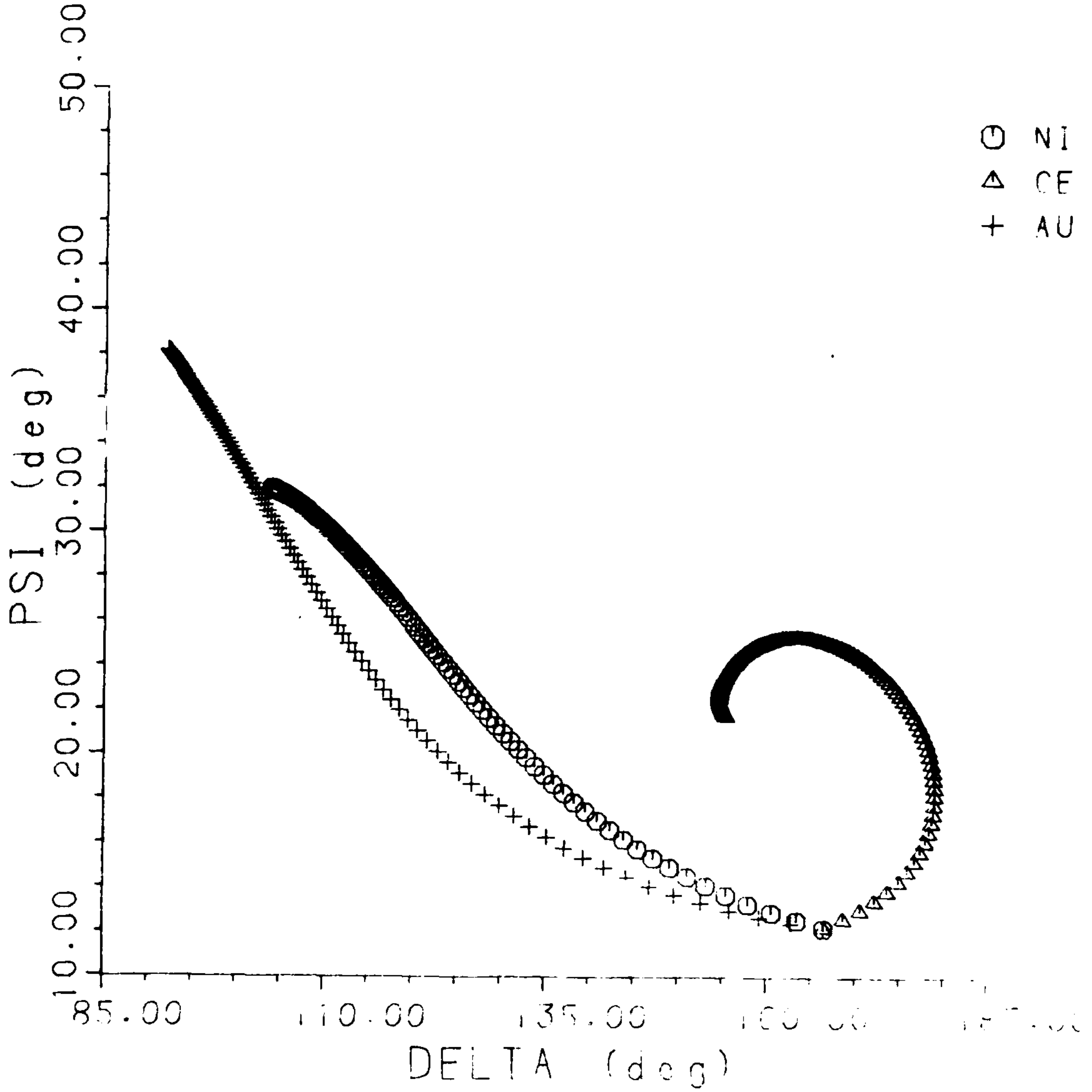


Figure 11. Relationship of Delta and Psi for Metal Films on GaAs for a Thickness of 400Å

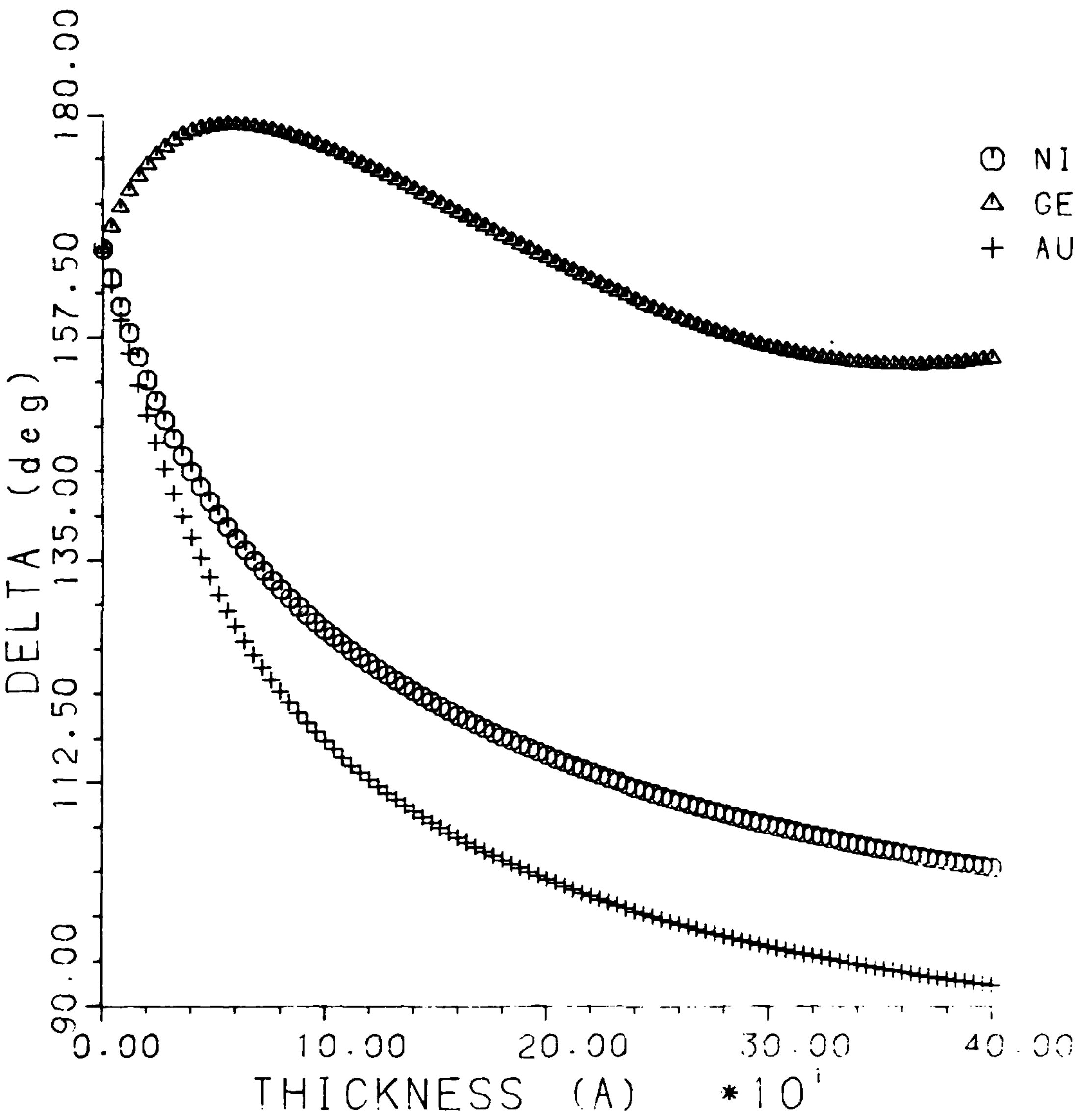


Figure 12. Computed Delta and Thickness Relationship for Metal Films Ni, Ge, and Au

# SECTION V

# DISCUSSION AND SUMMARY

Ellipsometric data has been obtained from a number of commercially prepared gallium arsenide wafers. The wafers were 50mm in diameter and had a polished surface. The optical constants were measured from the as-received surfaces. A grid procedure consisting of the as-received delta and psi readings and literature values for $n_s$ and $k_s^*$ is proposed for finding the optical constants of a film-free surface.

Using the optical constant for the film-free surface a series of experimental and computer studies were performed for dielectric, epitaxial, and metal films on gallium arsenide. When dealing with very thin dielectric films, good fits can be obtained between observed and calculated data giving a reasonable measure of film thickness. However, the optical constants for these thin films cannot be obtained with any accuracy by ellipsometry, because delta and psi approach the same values regardless of the optical constants of the film as the thickness tends towards zero.

# REFERENCES

1. F. McCrackin, A Fortran Program for Analysis of Ellipsometer Measurements, Natl. Bur. of Std. Technical Note 479, U.S. Government Printing Office, Washington D. C. (1969).
2. N. T. McDevitt, Air Force Materials Laboratory, Technical Report AFML-TR-73-245, January 1974, Wright-Patterson AFB, Ohio.
3. E. Schmidt, J. Opt, Soc. Am. 60, 490(1970).
4. F. L. McCrackin, J. Opt. Soc, Am. 60, 57(1970).
5. R. J. Archer and C. V. Shank, J. Opt. Soc, Am. 57, 191(1967).
6. H. T. Yolken, R. M. Waxler, and J. Kryger, J. Opt. Soc. Am 57, 283(1967).
7. I. Lindau and W. E. Spicer, in "Electron Spectroscopy: Theory, Techniques and Applications," C. Brundle and A. Baker, Eds., Vol. 4, Chapter 4, Academic Press, New York 1981.
8. J. B. Theeten, Surface Sci. 96, 275(1980).

ATE

LME