REFLECTIVITY MEASUREMENTS ON SEMI-CONDUCTORS

by

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INTRODUCTION

Electromagnetic Theory

Maxwell's equations which govern all macroscopic electromagnetic phenomena, are

$$\nabla \cdot \underline{D} = \rho_t \qquad \nabla \cdot \underline{B} = 0 \tag{1}$$
$$\nabla \times \underline{E} = -\frac{\partial B}{\partial t} \qquad \nabla \times \underline{H} = j_t + \frac{\partial D}{\partial t}.$$

It has been shown that in a region of no net stationary charges, but where there may be a net current given by the relation $j = \sigma \underline{E}$ and $\underline{B}$ is a linear function of $\underline{H}$ with σ, ϵ and μ not explicit functions of time, $\underline{E}$ satisfies the partial differential equation given by

$$\nabla^2 \underline{E} - \epsilon\mu \frac{\partial^2 E}{\partial t^2} - \mu\sigma \frac{\partial E}{\partial t} = 0, \tag{2}$$

and $\underline{H}$ satisfies a similar equation

$$\nabla^2 \underline{H} - \epsilon\mu \frac{\partial^2 H}{\partial t^2} - \mu\sigma \frac{\partial H}{\partial t} = 0. \tag{3}$$

For plane waves, if ∇ is set equal to $\underline{n} \frac{\partial}{\partial \xi}$, the equation becomes

$$\frac{\partial^2 E}{\partial \xi^2} - \epsilon\mu \frac{\partial^2 E}{\partial t^2} - \mu\sigma \frac{\partial E}{\partial t} = 0. \tag{4}$$

A solution of this equation is

$$\underline{E} = \underline{E}_0 e^{iK\xi} e^{-i\omega t} \tag{5}$$

where

$$K^2 = \mu\epsilon\omega^2 + i\omega\mu\sigma. \tag{6}$$

The usual spatial term in a traveling wave equation, however, is not $e^{iK\xi}$, but instead is

$$e^{i\frac{2\pi}{\lambda}\xi} \quad \text{or} \quad e^{i\omega\frac{x}{v}}. \tag{7}$$

Therefore,

$$K = \frac{\omega}{v} \tag{8}$$

But,

$$v = \frac{c}{n} \tag{9}$$

where v is the velocity of light in a medium, c is the velocity of light in vacuum and n is the index of refraction of the medium. Therefore upon substitution

$$K = \frac{n\omega}{c}. \tag{10}$$

The substitutions $\mu = \mu_0 K_m$, $\epsilon = K_\epsilon \epsilon_0$ and $c = \frac{1}{\mu_0 \epsilon_0}$ into equation (6), where K_ϵ is the dielectric constant and K_m is the relative permeability of the medium, yields

$$n^2 = K_m \left(K_\epsilon + \frac{i\sigma}{\omega\epsilon_0}\right). \tag{11}$$

To make an analogy with the case in which there is no conductivity, the quantity

$$K_\epsilon' = K_\epsilon + \frac{i\sigma}{\omega\epsilon_0} \tag{12}$$

is called the complex dielectric constant (3). Since n is a complex quantity we let $n = \alpha + i\beta$.

Then,

$$n^2 = \alpha^2 - \beta^2 + i2\alpha\beta = K_m \left(K_\epsilon + \frac{i\sigma}{\omega\epsilon_0}\right) \tag{13}$$

For optical frequencies with the material which was used, $K_m \doteq 1$ and the following relationships between the complex dielectric constant and the complex index of refraction are found.

$$K_\epsilon = \alpha^2 - \beta^2 \tag{14}$$

The equations may also be solved for α and β separately, yielding

$$\alpha^2 = \frac{K_\epsilon K_m \left[1 + \left\{1 + \left(\frac{\sigma}{\omega K_\epsilon \epsilon_0}\right)^2\right\}^{1/2}\right]}{2}$$

(15)

$$\beta^2 = \frac{K_\epsilon K_m \left[-1 + \left\{1 + \left(\frac{\sigma}{\omega K_\epsilon \epsilon_0}\right)^2\right\}^{1/2}\right]}{2} .$$

The solutions of Maxwell's equations and the wave equations for $\underline{H}$ and $\underline{E}$ show there is a traveling electric wave and an associated traveling magnetic wave $\underline{H}$ of the form

$$\underline{H} = \frac{K(n \times \underline{E})}{\mu \omega} . \tag{16}$$

The Fresnel equations are obtained by applying the boundary conditions inherent in Maxwell's equations to an idealized mathematical surface between media with different physical properties. The boundary conditions are that the tangential components of $\underline{H}$ and $\underline{E}$ must be continuous across a plane interface. (1) These conditions also give Snell's laws. The general Fresnel laws are

$$E_{0\parallel}'' = E_{0\parallel} \left\{ \frac{\frac{n'}{\mu_2}\cos\theta - \frac{n}{\mu_1}\cos\theta'}{\frac{n'}{\mu_2}\cos\theta + \frac{n}{\mu_1}\cos\theta'} \right\} \tag{17}$$

$$E_{0\perp}'' = E_{0\perp} \left\{ \frac{\frac{n}{\mu_1}\cos\theta - \frac{n'}{\mu_2}\cos\theta'}{\frac{n}{\mu_1}\cos\theta + \frac{n'}{\mu_2}\cos\theta'} \right\} .$$

Snell's laws are

$$n'\sin\theta' = n\sin\theta = n''\sin\theta'' . \qquad (18)$$

The notation which is adopted is that $\parallel$ means parallel to the plane of incidence and $\perp$ means perpendicular to the plane of incidence. No prime refers to values of quantities in the incident wave region, one prime refers to refracted quantities in medium 2 and double primes are reflected quantities in medium 1.

Since n' and θ' may both have complex values, the equations are simplified if the substitution

$$n'\cos\theta' = q + i\,p = \left(n'^2 - n^2\sin^2\theta\right)^{1/2} \qquad (19)$$

is made.

With this substitution the following relations exist.

$$R_{\parallel} = \left[\frac{E''_{0\parallel}}{E_{0\parallel}}\right]\left[\frac{E''_{0\parallel}}{E_{0\parallel}}\right]^* = \frac{\left[\mu_1\cos\theta\,(\alpha'^2-\beta'^2) - \mu_2 n q\right]^2 + \left[2\alpha'\beta'\mu_1\cos\theta - \mu_2 n p\right]^2}{\left[\mu_1\cos\theta\,(\alpha'^2-\beta'^2) + \mu_2 n q\right]^2 + \left[2\alpha'\beta'\mu_1\cos\theta + \mu_2 n p\right]^2}$$

$$(20)$$

$$R_{\perp} = \left[\frac{E''_{0\perp}}{E_{0\perp}}\right]\left[\frac{E''_{0\perp}}{E_{0\perp}}\right]^* = \frac{\left[\mu_2 n\cos\theta - q\mu_1\right]^2 + p^2\mu_1^2}{\left[\mu_2 n\cos\theta + q\mu_1\right]^2 + p^2\mu_1^2}$$

It will be shown that these equations can be solved for q and p as functions of $R_{\parallel}$, $R_{\perp}$ and θ. Knowing what q and p are, and the relations between q, p, θ, α and β, the value of K_e' for a certain incident radiation frequency may be found for surfaces in general and for semi-conductor sufaces in particular.

If the approximation $\mu_1 = \mu_2$ is made, the Fresnel equations reduce to the form

$$R = \frac{R_{\parallel}}{R_{\perp}} = \frac{(q - \sin\theta\tan\theta)^2 + p^2}{(q + \sin\theta\tan\theta)^2 + p^2}. \tag{21}$$

Avery's Method of Solution

Avery (2) has solved this problem graphically with equation (21) and the relations

$$\begin{aligned} pq &= \alpha\beta \\ \alpha^2 - \beta^2 &= q^2 - p^2 + \sin^2\theta. \end{aligned} \tag{22}$$

The only difference between Avery's notation and that used here is the equation

$$N = n(1 - ik) \tag{23}$$

Instead of using equation (23) $n = \alpha + i\beta$ is the notation here.

Experimental Methods

Since Avery's graphs were unavailable the equations (21) and (22) were programmed for computation on the IBM 650 computer and graphs were plotted for the values of the angles ($\theta = 60^\circ$, 70° and 80°).

The experiment was performed on Bismuth Telluride and on Germanium. The entire curve for R between 40° and 85° was measured and plotted for Bismuth Telluride. The values for R were then taken from its intersection with the angles 60°, 70° and 80°.

Two different spectroscopes were set up and adjusted to measure the values of R. One spectroscope was set up with Nicol prisms on it and one was set up with polaroid on it. The agreement between values of R measured on the two instruments was better than 0.009 at worst in the regions used for calculations and was better than 0.005 at most points. When measurements were made at the wavelength of the blue mercury line only the Nicol prism was used since the polaroid used at the time of these measurements was ineffective in the blue wavelength region.

A series of five measurements was taken at each of three angles for Germanium and the final value of R was taken as the average of these five values. When making measurements at the wavelengths of the blue mercury and green mercury lines a Bausch and Lomb polaroid was used which was obtained after the Bismuth Telluride measurements were made. It was efficient in the blue wavelength region as well as in the other regions. The measurements at the wavelength of the green line were checked with the Nicol prism and measurement at the wavelength of the yellow line were made using the nicol prism.

The apparatus was arranged so that the incident light was polarized at an angle of 45° to the plane of incidence in order that the incident $R_{\parallel}$ and $R_{\perp}$ components would be of equal intensity. When this is done the ratio of the meter readings yields R because $|E_{0\perp}|^2$ and $|E_{0\parallel}|^2$ cancel each other.

Before reaching the surface and after passing through the first polarizer the width of the beam was narrowed by passing it through a small circular aperture. The beam was then incident on the crystal face and passed through an analyzer which could be rotated from a 0° angle to a 90° angle with the plane of incidence. This separated the $R_\parallel$ and $R_\perp$ components so that they could be measured separately. The beam was then passed into a photomultiplier tube attached to a densitometer for intensity measurements.

The principal difficulty appeared to be due to the possibility of a shift of the beam on the detector surface when the analyzer was rotated. This difficulty was overcome by using a pinhole source and a vertical slit in front of the detector face. Assuming the detector to be fairly uniform over its surface, a slight vertical shift of the beam should not affect the measurements since the whole beam will still fall on the detector surface at each position of the analyzer.

This method allows leeway for vertical beam shift without decreasing angle sensitivity. It was found possible to use the Nicol prisms and certain pieces of polaroid with this method. They did introduce vertical shift, but had negligible lateral shift at the two analyzer positions.

By this means consistent results were obtained, whereas attempts to use a slit for the incoming light in the collimator tube and a pinhole in front of the detector surface failed, presumably because of beam shift over the stationary detector hole.

The angle at which the first polarizer is set must be precise. The method used to set this angle was the use of a piece of black glass in a preliminary experiment to determine the Brewster angle. After finding the angle of the polarizer for minimum reflected light the polarizer then was rotated through 45° to orient it properly for the incoming light.

The analyzer was then crossed with the polarizer by use of the eye. It was found that the eye is more sensitive to very small intensity changes near zero intensity than the densitometer is. After this setting has been made, a rotation of 45° either way should give equal intensities with a straight through beam. It was found that this varied until the slit, pinhole arrangement described above was used.

Another thing which must be adjusted carefully is the focus of the collimator tube so that parallel rays of light come from the collimator. The minimum distance which should be used for this measurement is about one hundred yards.

The apparatus used was: two Gaertner spectroscopes graduated to twenty minutes of arc, two Nicol prisms, two pieces of polaroid, one Bausch and Lomb polaroid, the IBM 650 computer, a densitometer, a Germanium crystal, a Bismuth Telluride crystal, a mercury arc source and a prism to disperse the light into nearly monochromatic beams.

The Bismuth Telluride crystal surface was a peeled surface. It was impossible to peel this surface without slight scratching taking place and a plane surface was also unobtainable.

The Germanium crystal was polished by hand and had some curvature, erosion pits and slight scratches on it.

PROCEDURE

General Expansion of Fresnel Equations

The author expanded the equations in $R_{\parallel}$ to get

$$\mu_1^2 \cos^2\theta\left[\alpha'^2+\beta'^2\right]^2 - 2\mu_1\mu_2 n \cos\theta\left[q(\alpha'^2-\beta'^2)+2p\alpha'\beta'\right]\frac{(1+R_{\parallel})}{(1-R_{\parallel})} + \mu_2 n^2(q^2+p^2) = 0. \quad (24)$$

At this point the equation should be put entirely in terms of q and p or α' and β'. Attempts to put the equation in terms of α' and β' invariably leads to increased complications of the equations. When solved for q and p, however, the equations are simplified somewhat. The following relationships between variables was used.

$$\begin{aligned} \alpha'^2-\beta'^2 &= q^2-p^2+n^2\sin^2\theta \\ \alpha'\beta' &= qp \\ (q^2+p^2)^2 &= 4\alpha'^2\beta'^2+(\alpha'^2-\beta'^2-n^2\sin^2\theta)^2 \end{aligned} \quad (25)$$

Upon substitution of q and p for α' and β' the following equation was obtained. $q^4\left[\mu_1^2\cos^2\theta\right] + p^4\left[\mu_1^2\cos^2\theta\right]$

$$\begin{aligned} &+ q^3\left[-2\mu_1\mu_2 n\cos\theta\frac{(1+R_{\parallel})}{(1-R_{\parallel})}\right] + q^2\left[\mu_2^2 n^2 + 2\mu_1^2 n^2\cos^2\theta\sin^2\theta\right] \\ &+ p^2\left[\mu_2^2 n - 2\mu_1^2 n^2\cos^2\theta\sin^2\theta\right] + q^2p^2\left[2\mu_1^2\cos^2\theta\right] \\ &+ p^2q\left[-2\mu_1\mu_2 n\cos\theta\frac{(1+R_{\parallel})}{(1-R_{\parallel})}\right] + q\left[-2\mu_1\mu_2 n^3\sin^2\theta\cos\theta\frac{(1+R_{\parallel})}{(1-R_{\parallel})}\right] \\ &+ \mu_1^2 n^4\cos^2\theta\sin^4\theta = 0 \end{aligned} \quad (26)$$

This equation contains p to the fourth power and second powers only. An evaluation of q would give a quadratic equation in p which could then be solved. A solution for q was found by using the $R_\perp$ equation with α' and β' eliminated. This yielded the equations

$$
\begin{aligned}
q^2+p^2 &= 2q\frac{\mu_2}{\mu_1} n\cos\theta\frac{(1+R_\perp)}{(1-R_\perp)} - \frac{\mu_2^2}{\mu_1^2} n^2\cos^2\theta \\
q^2-p^2 &= 2q + \frac{\mu_2^2}{\mu_1^2} n^2\cos^2\theta - 2q\frac{\mu_2}{\mu_1} n\cos\theta\frac{(1+R_\perp)}{(1-R_\perp)} \\
(q^2+p^2)^2 &= 4q^2\frac{\mu_2^2}{\mu_1^2} n^2\cos^2\theta\frac{(1+R_\perp)^2}{(1-R_\perp)^2} - 4q\frac{\mu_2^3}{\mu_1^3} n^3\cos^3\theta\frac{(1+R_\perp)}{(1-R_\perp)} + \frac{\mu_2^4}{\mu_1^4} n^4\cos^4\theta.
\end{aligned}
\tag{27}
$$

The general equation was then put in the form

$$
\begin{aligned}
&(q^2+p^2)^2\mu_1^2\cos^2\theta + (q^2+p^2)\mu_2^2 n^2 + (q^2-p^2)\,2\mu_1^2 n^2\cos^2\theta\sin^2\theta \\
&+ q(q^2+p^2)\left[-2\mu_1\mu_2 n\cos\theta\frac{(1+R_\parallel)}{(1-R_\parallel)}\right] + \mu_1^2 n^4\cos^2\theta\sin^4\theta \\
&+ q\left[-2\mu_1\mu_2 n^3\sin^2\theta\frac{(1+R_\parallel)}{(1-R_\parallel)}\cos\theta\right] = 0.
\end{aligned}
\tag{28}
$$

Then p was eliminated by substitution and the equation was solvable as a quadratic in q. The result is

$$
\begin{aligned}
&q^2\left[4\mu_2^2 n^2\cos^4\theta\frac{(1+R_\perp)^2}{(1-R_\perp)^2} + 4\mu_1^2 n^2\cos^2\theta\sin^2\theta - 4\mu_2^2 n^2\cos^3\theta\frac{(1+R_\perp)(1+R_\parallel)}{(1-R_\perp)(1-R_\parallel)}\right] \\
&+q\left[\begin{aligned}&-4\frac{\mu_2^3}{\mu_1} n^3\cos^5\theta\frac{(1+R_\perp)}{(1-R_\perp)} - 4\mu_1\mu_2 n^3\cos^3\theta\sin^2\theta\frac{(1+R_\perp)}{(1-R_\perp)} + 2\frac{\mu_2^3}{\mu_1} n^3\cos\theta\frac{(1+R_\perp)}{(1-R_\perp)} \\ &+ 2\frac{\mu_2^3}{\mu_1} n^3\cos^3\theta\frac{(1+R_\parallel)}{(1-R_\parallel)} - 2\mu_1\mu_2 n^3\sin^2\theta\cos\theta\frac{(1+R_\parallel)}{(1-R_\parallel)}\end{aligned}\right] \\
&+ \frac{\mu_2^4}{\mu_1^2} n^4\cos^6\theta + 2\mu_2^2 n^4\cos^4\theta\sin^2\theta - \frac{\mu_2^4}{\mu_1^2} n^4\cos^2\theta + \mu_1^2 n^4\cos^2\theta\sin^4\theta = 0.
\end{aligned}
\tag{29}
$$

By finding μ_1, μ_2, n, θ, $R_\parallel$ and $R_\perp$, at some point, a solution for q can be found. Knowing a solution for q, a solution for p can be found. When q and p are known at a particular angle θ, the complex index of refraction is determined.

Advantages and Disadvantages of General Method

The advantage of this equation is that no approxmations are made on the permeabilities and a knowledge of the values at any one angle completely determines the complex index of refraction.

The disadvantage of this equation is that it is necessary to measure absolute reflectivities. To do this, accurately, is more difficult than measuring the ratio R since any curvature or imperfection in the surface will affect the absolute reflectivities adversely while, if the ratio is measured, these effects cancel each other in the measurement.

Graphical Method of Solution

The Bismuth Telluride used was observed to be curved and slightly scratched. The Germanium surface was a polished surface with many imperfections. These included haze, slight scratches, and small indentations which were presumed to be erosion spots caused by polishing.

Because of these crystal defects a method similar to Avery's was adopted. A program to solve equations (21) and (22) was devised for the IBM 650 computer.

With θ and β held constant in these equations values of α were substituted into the equation and for each of these values of α the value of R was computed. In the calculations the parameter ranged from one to ten in 0.25 interval steps. The ordinate of the graphs was taken to be α and the abscissa R, with one curve for each value of β. Then β was varied in steps of 0.25 from zero to ten.

Three graphs were plotted, one for each of the angles 60°, 70° and 80°. For each angle there is a measured value of R. At this value of R on the graph, possible values of α and β are read off from the graph. This was done for all three angles and graphs of the three curves of α versus β, one for each angle were made. At the true value of α and β these curves must intersect each other at a point and therefore α

and β are determined.

Since the computed graphs must be large to give the desired accuracy, they are not included in this thesis. They were constructed so that they could be read directly with three place accuracy and four place accuracy could be estimated.

Algebraic Solution with Approximations

A third method which could be used if the approximation $\mu_1 = \mu_2$ is made uses only the values of θ, $R_\perp$ and R. Upon expanding (21) the equation

$$q^2 + p^2 = 2q\cos\theta \frac{(1+R_\perp)}{(1-R_\perp)} \tan^2\theta - \sin^2\theta \tan^2\theta \tag{30}$$

is obtained. Since $\mu_1 = \mu_2$ and if $n = 1$ the equation in $R_\perp$ is reduced to

$$q^2 + p^2 = 2q\cos\theta \frac{(1+R_\perp)}{(1-R_\perp)} - \cos^2\theta .$$

If this equation is then substituted in the equation for R, the R equation becomes an equation in q, but not in p.

$$q = \frac{1}{2} \frac{\cos^2\theta - \sin^2\theta \tan^2\theta}{\cos\theta \frac{(1+R_\perp)}{(1-R_\perp)} - \sin\theta \tan\theta \frac{(1+R)}{(1-R)}} \tag{31}$$

Once q is known p may be found from

$$p = \left[- q^2 + 2q\cos\theta \frac{(1+R_\perp)}{(1-R_\perp)} - \cos^2\theta \right]^{1/2} . \tag{32}$$

From these values and the value of the angle θ, n' may be calculated. The advantage of this formula is that it requires a knowledge of R and $R_\perp$ only. Since $R_\perp$ is the higher curve on the graph, its accuracy should be much greater than $R_{\parallel}$. The principal disadvantage, again, is the necessity for a nearly perfect surface in order to get accurate measurements of $R_{\perp}$.

The dielectric constant K_ϵ' for a particular frequency of radiation may be calculated once q and p or n' is known. The equations are

$$K_\epsilon = \alpha^2 - \beta^2 = q^2 - p^2 + n^2 \sin^2\theta$$

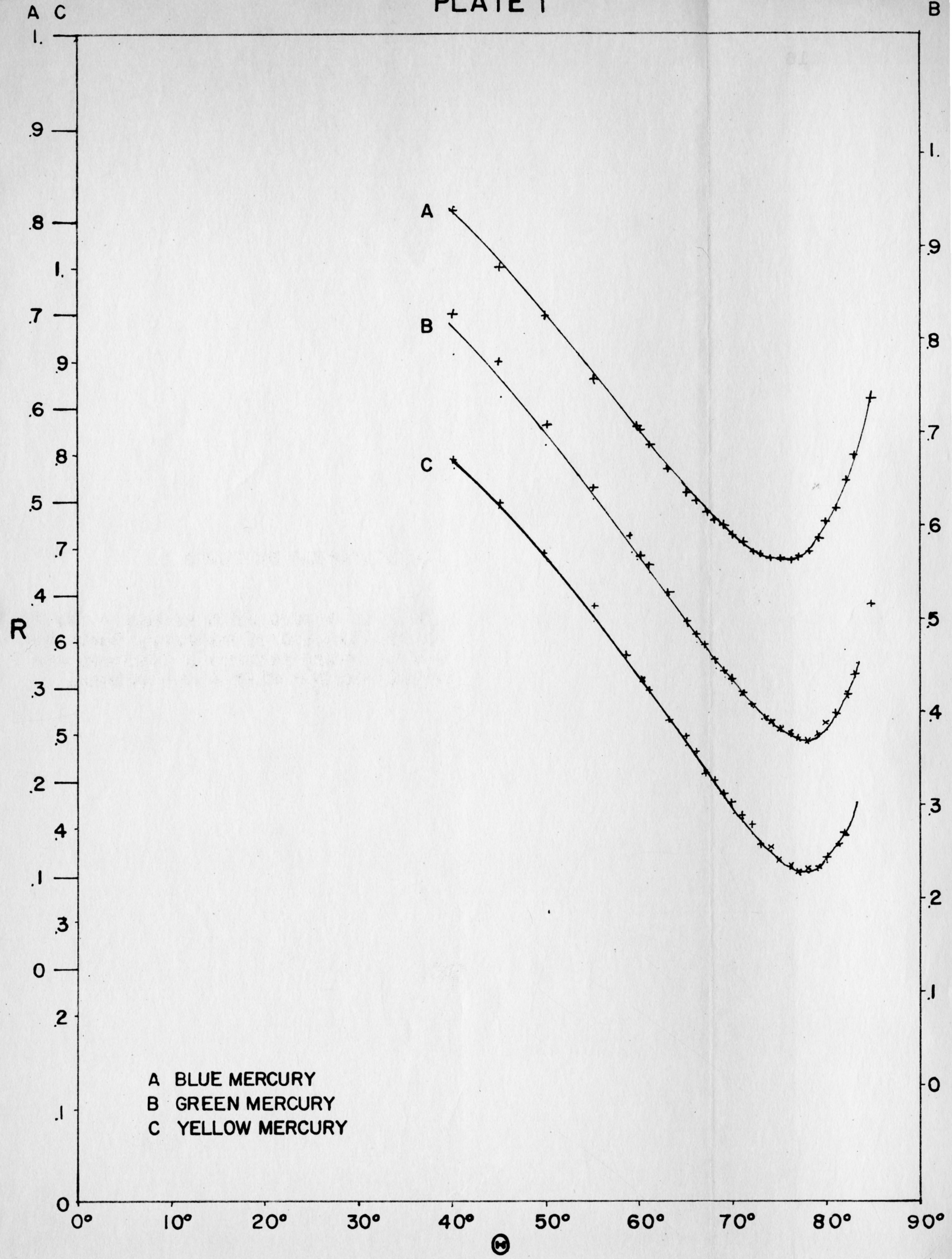
$$2\alpha\beta = \frac{\sigma}{\omega\epsilon_0} \quad . \tag{33}$$

PLATES SHOWING RESULTS

EXPLANATION ON PLATE I

Plate I is three plots of curves of R versus θ for the green, blue, and yellow wavelengths of mercury. Dots indicate experimental results using polaroid. Crosses are for experimental results with Nicol prisms.

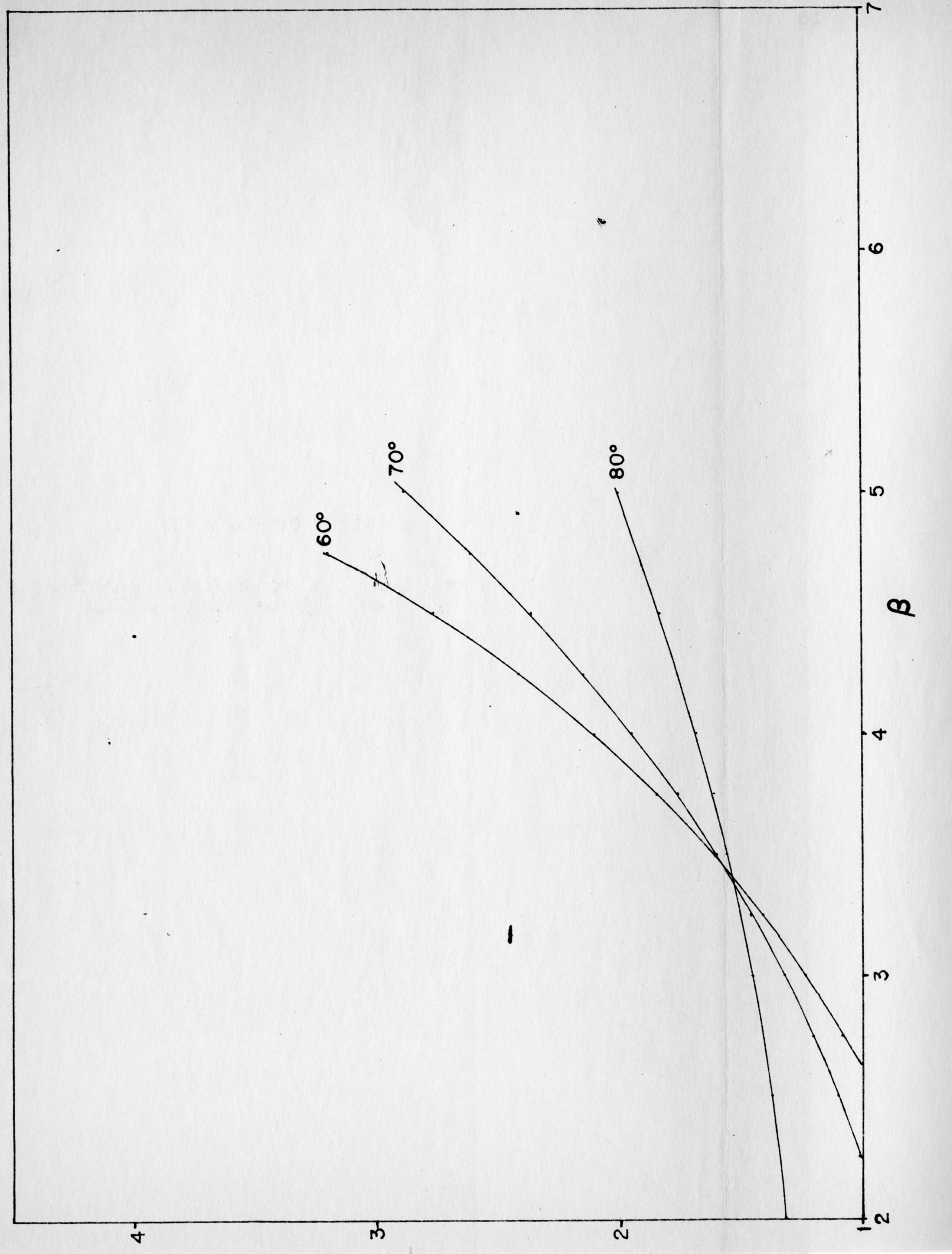
PLATE I


A C
B
R
Θ
0° 10° 20° 30° 40° 50° 60° 70° 80° 90°
A
B
C
A BLUE MERCURY
B GREEN MERCURY
C YELLOW MERCURY

EXPLANATION OF PLATE II

Curves of α versus β for the blue mercury wavelength are plotted on plate II.

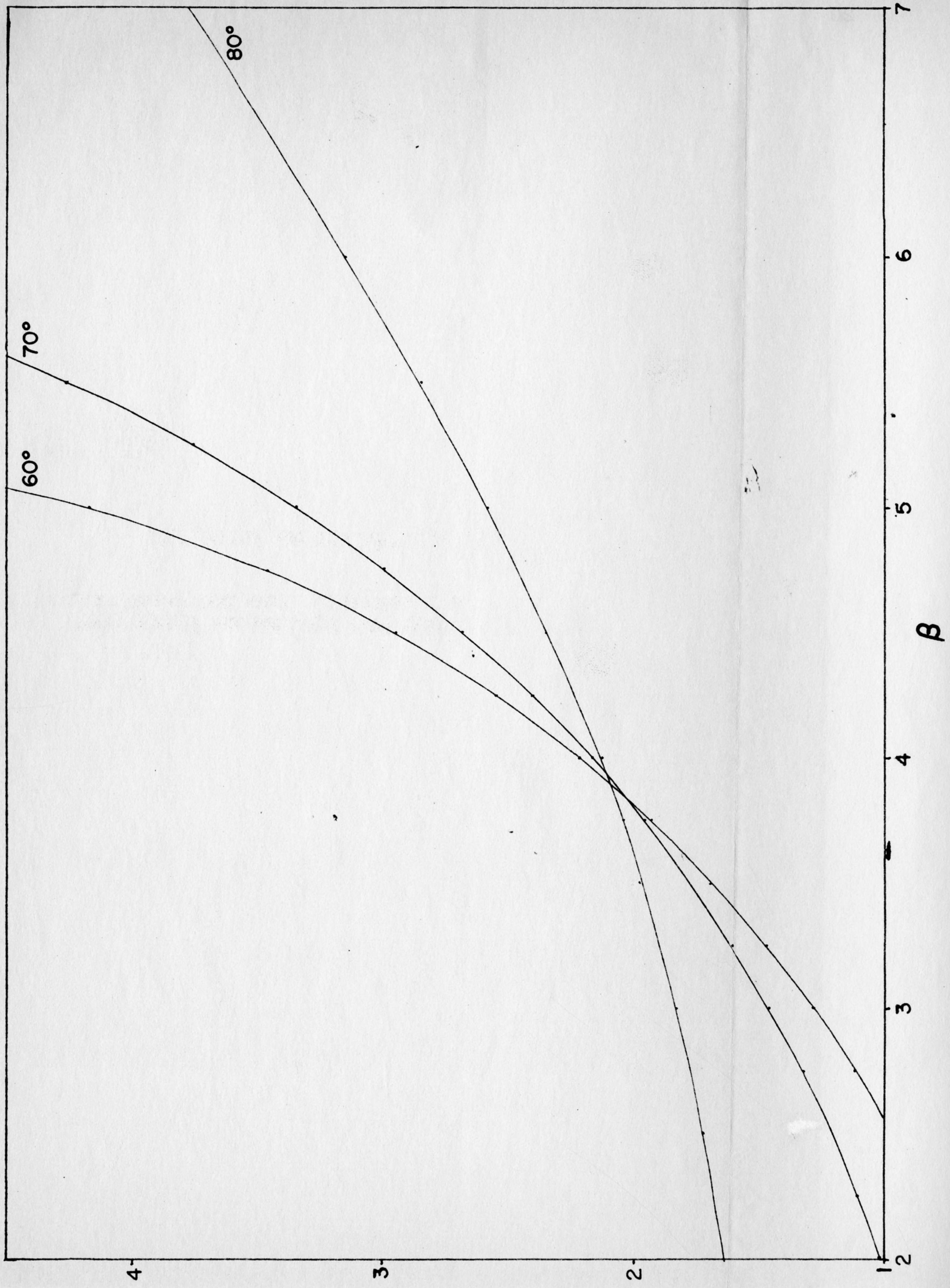
PLATE II



EXPLANATION OF PLATE III

Curves of α versus β for the green mercury wavelength are plotted on plate III.

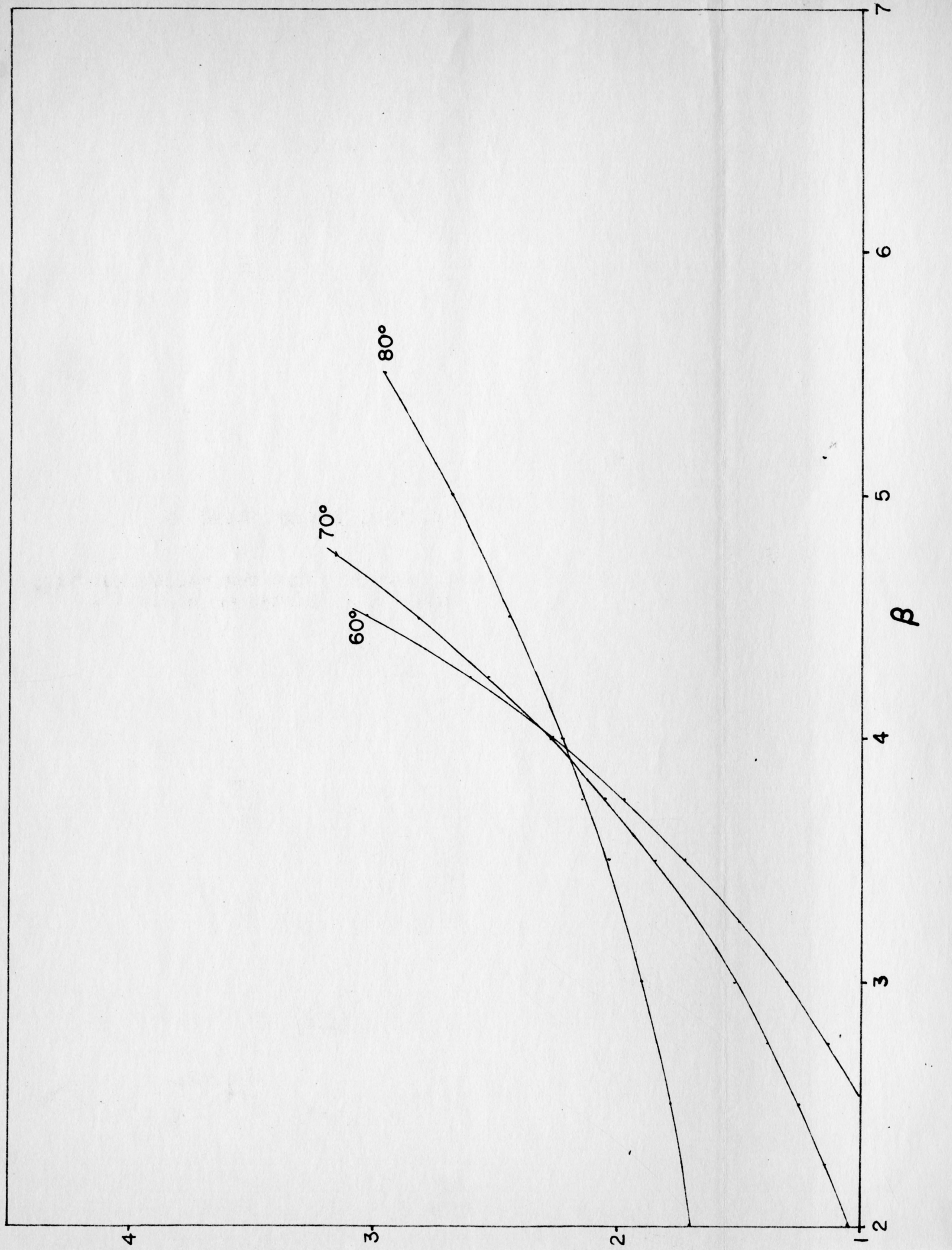
PLATE III



EXPLANATION OF PLATE IV

Curves of α versus β for the yellow mercury wavelength are plotted on plate IV.

PLATE IV



TABLES SHOWING RESULTS

Table 1. Experimental results of measurements on Germanium

Wavelength	Polarizer	Incidence angle	Meter readings $M_\perp$	$M_\parallel$	$M_\parallel/M_\perp$	Average
Blue mercury	B and L	80° 00'	78.0	11.0	.141	
			77.5	10.5	.136	
			77.9	10.5	.133	
			77.6	10.9	.141	
			77.2	10.9	.141	.138
		70° 00'	64.0	12.3	.192	
			62.9	12.0	.191	
			63.2	12.1	.192	
			63.5	12.1	.191	
			63.5	12.1	.191	.191
		60° 00'	55.1	20.0	.363	
			55.2	20.0	.362	
			54.9	19.8	.361	
			54.6	19.7	.361	
			54.5	19.9	.367	.363
Green mercury	B and L	80° 00'	81.2	8.5	.105	
			81.5	8.7	.107	
			81.3	8.3	.102	
			81.7	8.7	.106	
			81.3	8.5	.104	.105
		70° 00'	70.9	12.7	.179	
			71.1	12.8	.180	
			71.5	12.8	.179	
			71.0	12.7	.179	
			70.9	12.5	.176	.179
		60° 00'	62.7	22.8	.364	
			62.8	22.9	.365	
			62.9	23.0	.366	
			63.0	23.0	.365	
			63.2	23.2	.367	.365
	Nicol	80° 00'	83.0	8.6	.104	
		70° 00'	72.0	13.0	.181	
		60° 00'	63.5	23.2	.365	
Yellow mercury	Nicol	80° 00'	77.6	10.2	.131	
			78.0	10.3	.132	
			78.0	10.5	.135	
			78.2	10.5	.134	
			88.0	10.8	.139	.134
		70° 00'	63.5	12.8	.202	
			63.9	12.9	.202	
			64.0	12.8	.200	
			63.4	12.5	.197	
			62.4	12.1	.194	.199
			61.0	22.8	.374	
			60.9	22.9	.376	
			61.0	22.9	.375	
			61.0	22.9	.375	
		60° 00'	60.3	22.9	.380	.376

Table 2. Results of measurements

Material	Wavelength	Complex index of refraction α	β	Complex dielectric const. $\alpha^2-\beta^2$	$2\alpha\beta$
Germanium	Blue mercury	3.6 + .1	2.74 + .03	5 + .9	20 + .7
	Green mercury	4.1 + .3	2.65 + .08	10 + .3	22 + .2
	Yel. mercury	3.8 + .1	2.84 + .03	6 + .9	22 + .8
Bi. Te.	Blue mercury	1.54 + .05	3.42 + .03	-9.3+ .7	10 + .4
	Green mercury	2.08 + .03	3.89 + .03	-10.9+ .4	16 + .3
	Yel. mercury	2.22 + .03	3.96 + .03	-10.8+ .5	17 + .4

Table 3. Comparison of measured values of the dielectric constant and with those measured by Avery.

Wavelength	Avery $\alpha^2-\beta^2$	$2\alpha\beta$	Measured $\alpha^2-\beta^2$	$2\alpha\beta$
Blue mercury	4	17	5 + .9	20 + .7
Green mercury	7	21	10 + 3	22 + 2
Yellow mercury	10	18 - 19	6 + .9	22 + .8

CONCLUSIONS

The experimental values of $\alpha^2-\beta^2$ and $2\alpha\beta$ from the polished Germanium surface compare closely to those values given by Avery for a single crystal Germanium face, as read from his graph published in Moss. (5)

These measurements were to be used as a check on the adjustment of the apparatus. The values are close enough to the previously measured values for differences to be attributed to the method of surface preparation.

Avery made measurements on the (111) plane of a Germanium crystal which was not a polished surface. The author's measurements were along no particular crystal plane and were on a polished surface. The larger error in measurement of α and β for Germanium is also probably due to the surface condition. This is indicated by the intersection area of α and β for the peeled surface of Bismuth Telluride.

A smaller intersection area should occur for Germanium if a plot of the curve of α and β for the angle theta equal to seventy-five degrees is used instead of the curve for seventy degrees. Observation of the graphs of α and β indicates that the plot of seventy degrees does not intersect the sixty and seventy degree curves at a favorable angle for a tight intersection of the curves.

The values for Bismuth Telluride are probably as good as can be obtained with the equipment used as only one value has greater than (1-2) percent deviation. Meter linearity was measured and found to have no greater than 1.5 percent error. An exact evaluation of the effect of meter non-linearity upon the measured values can not be made, until more accurate values of the meter error are measured at specific points on the meter scale.

Since the maxiimum of $2\alpha\beta$ indicates absorbtion the data indicates the approach to an absorption edge in the yellow wavelength region or above in the Bismuth Telluride sample. Further values should be obtained in the longer wavelength region to determine the exact position of the absorption edge. Measurements should be extended into the infra-red region, but at present equipment to carry out this measuremont is not available.

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REFLECTIVITY MEASUREMENTS ON SEMI-CONDUCTORS

by

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Maxwell's equations for macroscopic electromagnetic phenomena are used in two ways. They show the existence of traveling electromagnetic waves and they give the boundary conditions for the waves when they are incident on an interface between media with different physical properties.

Fresnel's equations and Snell's law are a consequence of the boundary conditions. Fresnel's equations provide a means of measurement of the complex index of refraction and the complex dielectric constant.

The purpose of this experiment was to extend Fresnel's equations to a more general form than has been used before without approximations on the permeabilities and to measure the optical constants of Bismuth Telluride.

The procedure was to measure the optical constants of Bismuth Telluride using a Gaertner spectroscope, polaroids, a mercury light source and a photomultiplier tube as a detector for the light. Measurements on a Germanium crystal were used as a check on the apparatus. These values have been measured before by Avery on a (111) Germanium crystal face.

It was necessary to use the approximations $\mu_1 = \mu_2$ and $n = 1$. When these approximations are made a graphical solution is possible. The graphical solution uses values from measurements which may be made with greater accuracy if the crystals to be measured have surface imperfections. The values which were

measured were the values of R at the incidence angles of 60°, 70° and 80°. The IBM 650 computer was used to solve the equations and compute values for the graphs.

Graphs were drawn and measurements made on Germanium and Bismuth Telluride. The measurements on Germanium checked with those measured by Avery. Results of measurements of Bismuth Telluride give values for the blue, green and yellow mercury wavelengths. With only one value having greater than 1-2 percent deviation. The values of the complex dielectric constant indicate an absorption peak in the yellow wavelength region or above. Measurements should be extended to the longer wavelength region to determine the exact position of the absorption peak.