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A mathematical model for a reversible tri-layer optical memory disk

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**A MATHEMATICAL MODEL FOR A REVERSIBLE TRI-LAYER
OPTICAL MEMORY DISK**

ARIEL SHAW

April 13, 1984

**A MATHEMATICAL MODEL FOR A REVERSIBLE TRI-LAYER
OPTICAL MEMORY DISK**

by

Ariel Shaw

**A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in the School of
Photographic Arts and Sciences in the
College of Graphic Arts and Photography
of the Rochester Institute of Technology**

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**Accepted by..... Illegible Signature
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ROCHESTER INSTITUTE OF TECHNOLOGY
COLLEGE OF GRAPHIC ARTS AND PHOTOGRAPHY

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Date: 13 April 1984

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Submitted to the
Imaging and Photographic Science Division
in partial fulfillment of the requirements
for the Bachelor of Science degree
at the Rochester Institute of Technology

ABSTRACT

A research project has been performed, in which a mathematical model for a reversible tri-layer optical memory disk was generated. The disk's reversibility properties are based on the polycrystalline to amorphous physical phase transition that takes place in the disk's top chalcogenide layer. Given the disk's defining parameters, complex indices of refraction, and layer thicknesses, the model predicts the disk's output in terms of a contrast ratio. The output, the contrast ratio, is simply the reflectivity of the chalcogenide in its amorphous state divided by the reflectivity of the chalcogenide material in its polycrystalline state.

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A thank you must be given to the PPHS class of 1984. The impression they made on me and my work will never be forgotten.

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DEDICATION

To my mother, father, and girlfriend, Lori Skoniecki, whose spiritual support and drive made the completion of this project and the past four years a realized goal.

Table of Contents

I. Introduction.....	1
1. Historical.....	1
2. Theoretical.....	4
II. Experimental.....	10
1. Approach.....	10
2. Test Materials.....	11
3. Ellipsometry.....	11
4. Model Building.....	16
5. Apparatus.....	17
III. Results and Discussion.....	19
1. Ellipsometry.....	19
2. Computer Model.....	26
IV. Conclusions.....	29
V. References.....	32
VI. Appendices.....	34
1. Appendix A. Ellipsometry Computer Program.....	34
2. Appendix B. Ellipsometry Equations.....	37
3. Appendix C. Mathematical Model for a Reversible Tri-layer Optical Memory Disk.....	38
Appendix D. Summation Techniques.....	45
VII. Vita.....	46

List of Tables

1. Comparison of Optical Memory and Magnetic Memory	2
2. E.C.D. Ellipsometry Data.....	20
3. R.I.T. Ellipsometry Data.....	21
4. R.I.T. Ellipsometry Data:After Platen Modification	23
5. Ellipsometry Callibration Results.....	24
6. Ellipsometry Data:After Polarizer Calibration.....	25
7. First Order Contrast Ratios.....	27

List of Figures

1. Disk Reflectivity.....	5
2. Energy Interactions.....	6
3. Ellipsometer Schematic.....	13
4. Spectral Profile of Ellipsometer Source.....	22

Historical

Magnetic memory is the standard storage medium for the television, record, and the computer industries. Optical memory, a medium that can store the same type of information as the magnetic medium, has great potential to become the industries' new standard storage medium. As a thesis subject, it was proposed to generate a mathematical model for a reversible tri-layer optical memory disk.

The magnetic tape used in the computer industry has a very long (30 second) access time [1]. The reason being that the tape must be reeled to the desired access point. It also must be stated that magnetic tape has a lifetime for reliable data of about two years [2]. The magnetic disk has both a rapid 0.01 second access time and a greater, ten years, reliable data lifetime [3].

Optical memory disks have a rapid access time of 0.10 seconds and an estimated data lifetime of over ten years [4]. Both disks have a comparable storage capacity of forty Gbits/disk [5]. Optical disks offer a lower cost per bit, much improved accessing characteristics, higher volumetric efficiency, and improved archival characteristics [6].

Table 1 clearly illustrates optical memory's attributes and its shortcomings as compared to the magnetic medium. While the optical disk cannot presently compete with the

magnetic disk in access time, it surpasses the magnetic medium in cost per bit and volumetric efficiency [7].

Table One

Comparison of Optical Memory and Magnetic Memory [8].

	Media Unit Capacity (Gbits)		Media Cost (£/Mbit)		Media Volumetric Efficiency (in ³ /Gbit)		Access Time (sec)	Data Life (Years)
	Now	Later	Now	Later	Now	Later		
Magnetic Disk	40	100	5.0	2.0	40.0	16.0	0.01	> 10
Optical Disk	40	100	0.4	0.1	2.1	1.2	0.1	> 10
Computer Compatible Tape	1	4	2.0	0.5	95.0	24.0	30	> 2

There exists three types of optical memory disks. They are the photographically processed disk, the thermally processed disk and the magneto-optical disk. The magneto-optical memory disk's readout is accomplished by a polarized spot that is about the same size as the magnetic domains [9]. These spots are then detected by utilizing the polar Kerr magneto optic effect [10]. This effect changes the polarization of the light upon reflection from a perpendicularly magnetized medium. The Faraday effect, which polarizes transmitted radiation, can also be used.

The photographically processed disk also uses either reflected or transmitted laser energy for data retrieval.

The laser's radiation is either transmitted through the disk or reflected off of the the disk to create the binary signals. If the corresponding sensor picks up the laser's radiation, then an "on" signal is created. If the sensor does not pick up the laser's radiation, then the signal can be considered to be an "off" signal.

The usage of optical memory will increase as industry develops better systems. One such system, currently being researched, is the reversible (erasable) tri-layer optical memory disk. This system utilizes the physical phase transition from a polycrystalline to an amorphous state of a chalcogenide material [11]. The material is deposited on a substrate in its polycrystalline form. It is then recorded on by using a laser to melt spots, usually one micron in size [12]. The laser's power should range from 4mW to 8mW [13]. Due to rapid cooling rate, the material then resolidifies to its amorphous state. Note that the laser's energy is not enough to ablate or melt a pit in the material. To erase the written data, the disk must then be scanned with a laser of lower energy. The energy usually required to do this is 3mW [14]. This will recrystallize the amorphous spot. The disk is read with a 2mW laser [15].

The read mechanism of the reversible disk utilizes the destructive interference that occurs due to the dielectric layer. The index of refraction of the chalcogenide changes as the material changes from its polycrystalline state to its

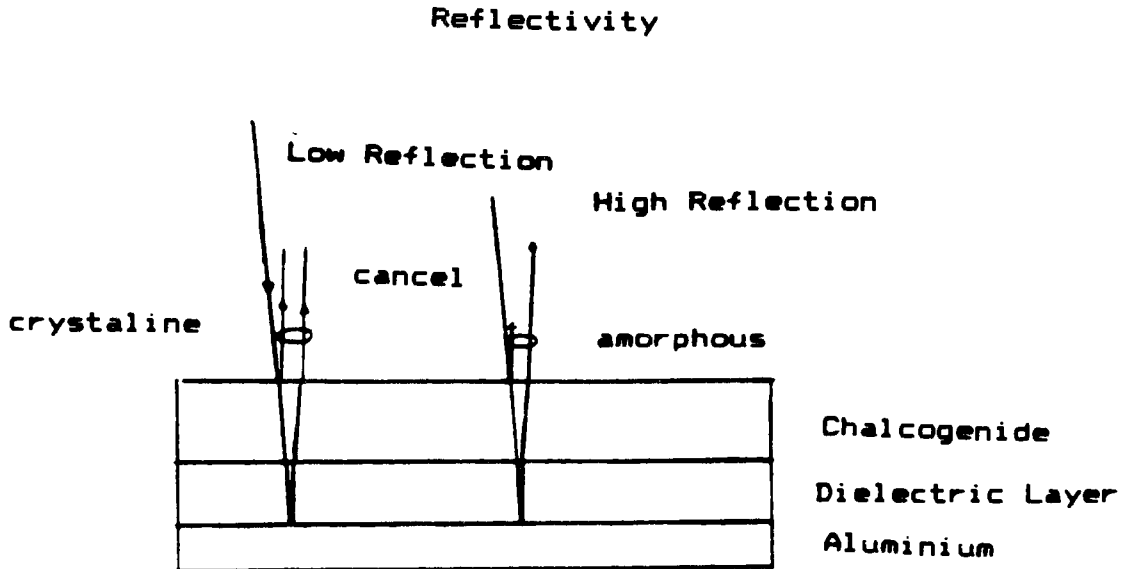
amorphous state. These changes in refractive indices changes the amount of energy that is reflected back to the sensor. The sensor will generate the "on" signal when the energy reflected back is above a certain level. Otherwise an "off" signal is recorded

Theoretical

Figure One illustrates the interference that is created due to the two out of phase reflections that occurs off of the two reflective layers of the disk. Note that the first reflection off of the chalcogenide layer causes a 180 phase shift. The second reflection that occurs (off of the aluminium reflection layer) interferes with the energy of the first reflection. The destructive interference occurs because the thickness of the glass dielectric is a multiple of one half the reading laser's wavelength. However, because the amplitudes of the reflected beams are not equivalent, some radiation makes it back to the reading sensor.

The same physical interference occurs when the laser scans across an amorphized spot. But because the index of refraction of the amorphized spot is less than the polycrystalline spot, a substantially greater amount of energy is reflected back to the sensor. This change is due to the destructive interference that occurs at the dielectric layer. The energy is of enough magnitude to create an "on" signal.

Figure 1

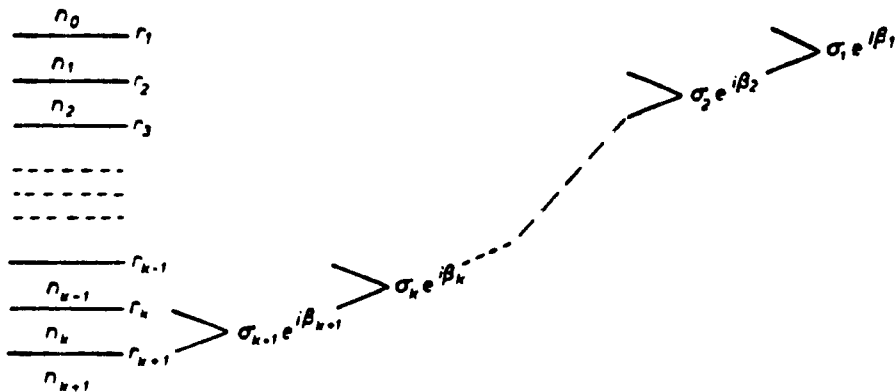


The method in which to compute the amplitude of the reflected energy must be able to incorporate all the internal reflections and refractions that are occurring when the disk is being scanned. Several computational techniques for doing such a summation are noted in O.C. Heavens's book on thin film technology [16].

Since a single film bounded by two surfaces possesses an effective reflection coefficient and accompanying phase change, then such a film may be replaced by a single surface with these properties [17]. The method chosen to do this internal summation, Rouard's method, is to start by defining the bottom layer and work up to the surface of the tri-layer

configuration by adding the next surface interaction to the existing definition [18]. Figure Two illustrates the surface interactions and summations for the k layers of thin films. Sigma is the amplitude of reflection and beta is the phase change.

Figure 2
Energy Interactions [19]



The expression for the reflectivity of the system is more easily extracted if Rouard's method is used as compared to the other researched techniques. Starting with Fresnel coefficients r_1, r_2, r_3 (for radiation going from n_0 to n_2), first generate the amplitude, ρ , and then the phase change off the film, Δ . What is generated is the effective Fresnel coefficient for n_2 .

Fresnel Coefficient

$$\rho_1 e^{i\delta_1} = \frac{r_1 + \rho_2 e^{i\delta_2} e^{-2i\delta_1}}{1 + r_1 \rho_2 e^{i\delta_2} e^{-2i\delta_1}}$$

[20]

Then in order to get the Fresnel coefficient for n_1 , simply insert ρ_1 into the corresponding expression for the whole system which is now regarded as a film thickness d_1 lying on surface whose Fresnel coefficient is ρ_2 .

If the system has absorbing layers in its structure the indices of refraction must be replaced by the material's complex index. It must be noted that the chalcogenide is a highly absorbing anisotropic medium, therefore such a replacement is necessary. If the incident radiation is normal to the surface the procedure is as follows.

If the k and the $(k-1)$ layers are absorbing, with complex indices $N_k = n_k - ik_k$ and $N_{k-1} = n_{k-1} - ik_{k-1}$ then the Fresnel coefficient for the light traveling from $(k-1)$ to k is

$$r_k = g_k + ih_k \equiv \frac{n_{k-1} - n_k}{n_{k-1} + n_k}$$

where

$$g_k = \frac{n_{k-1}^2 - n_k^2 + k_{k-1}^2 - k_k^2}{(n_{k-1} + n_k)^2 + (k_{k-1} + k_k)^2}$$

$$h_k = \frac{2(n_{k-1}k_k - n_k k_{k-1})}{(n_{k-1} + n_k)^2 + (k_{k-1} + k_k)^2}$$

[21]

These values are then inserted into the equation ρ_k , together with the complex value of δ_k . Note the exponential is then written

$$\begin{aligned}\exp(-2i\delta_k) &= \exp\left(-\frac{4\pi}{\lambda}k_1d_k\right)\exp\left(-\frac{4\pi}{\lambda}in_1d_k\right) \\ &= e^{-\alpha_k}(\cos \theta_k - i \sin \theta_k)\end{aligned}$$

We obtain

$$\rho_k^2 = \frac{\{g_k + e^{-\alpha_k}(g_{k+1} \cos \theta_k + h_{k+1} \sin \theta_k)\}^2 + \{h_k + e^{-\alpha_k}(h_{k+1} \cos \theta_k - g_{k+1} \sin \theta_k)\}^2}{\{1 + e^{-\alpha_k}[(g_k g_{k+1} - h_k h_{k+1}) \cos \theta_k + (h_k g_{k+1} + h_{k+1} g_k) \sin \theta_k]\}^2 + \{e^{-\alpha_k}[(h_k g_{k+1} + h_{k+1} g_k) \cos \theta_k - (g_k g_{k+1} - h_k h_{k+1}) \sin \theta_k]\}^2}$$

and writing $\Delta = \epsilon + \eta$ where

$$\tan \xi_k = \frac{e^{-\alpha_k}[(h_k g_{k+1} + h_{k+1} g_k) \cos \theta_k - (g_k g_{k+1} - h_k h_{k+1}) \sin \theta_k]}{1 + e^{-\alpha_k}[(g_k g_{k+1} - h_k h_{k+1}) \cos \theta_k - (h_k g_{k+1} + h_{k+1} g_k) \sin \theta_k]}$$

and

$$\tan \tau_{ik} = \frac{h_k + e^{-\alpha_k}(h_{k+1} \cos \theta_k - g_{k+1} \sin \theta_k)}{g_k + e^{-\alpha_k}(g_{k+1} \cos \theta_k + h_{k+1} \sin \theta_k)}$$

[22]

These values of ρ and Δ are then inserted in equation and the process is then repeated successively as before.

A mathematical model describing this optical memory disk is in demand. The model encompasses the properties of the disk that define the disk's output. Parameters such as the indices of refraction of the chalcogenide and the dielectric layer will have to be incorporated into the model's program.

The model utilizes the complex index of refraction of the chalcogenide. After inserting the basic material constants and layer thicknesses, it will then manipulate the layer thicknesses, particularly that of the dielectric in order to maximize the contrast ratio of the reflectivities. (The contrast ratio is simply the reflectivity of the amorphous material divided by the reflectivity of the polycrystalline material.)

Approach

In order to use the modeling program for the reversible tri-layer disk, the optical constants of the disk's materials had to be determined. The disk's tri-layer configuration consisted of an aluminium bottom reflection layer, a silicon dioxide dielectric layer, and a tellurium based chalcogenide top layer. The reflectivity of the aluminium reflection layer was assumed to be one in order to simplify the model. The index of refraction of the dielectric layer was simply found by using a CRC handbook for optical constants [23].

The optical constants of the chalcogenide layer was to be determined by using ellipsometric techniques. Ellipsometry has the advantages over conventional techniques for measuring optical constants of applicability to strongly absorbing media and of simplicity of measurement and sample preparation [24]. The chalcogenide material is a highly absorbing material, thus a complex index of refraction must be measured for the material. These complex indices are easily measured using ellipsometry.

As the optical constants were being generated, a technique for finding the reflectivities of the two forms of the chalcogenide was being researched. The method chosen to accomplish this is called Rouard's treatment [25]. The method generates the amplitude for reflection and the

resultant phase change. The technique was then implemented into a computer program that when given the optical constants for the disk's materials, a reflectivity for that material is generated. Then by using the reflectivities computed for each of the chalcogenide's two different physical phase changes, a contrast ratio of the reflectivities is generated.

Test Materials

Samples of chalcogenide material in both phases were used to do the ellipsometric measurements. Energy Conversion Devices, in Troy, Michigan, coated the material in its amorphous phase and its polycrystalline phase in two coating thicknesses. Received, were samples coated 100 angstroms and 500 angstroms. These samples were deposited on glass microscope slides and were received on January 11, 1984.

Ellipsometry

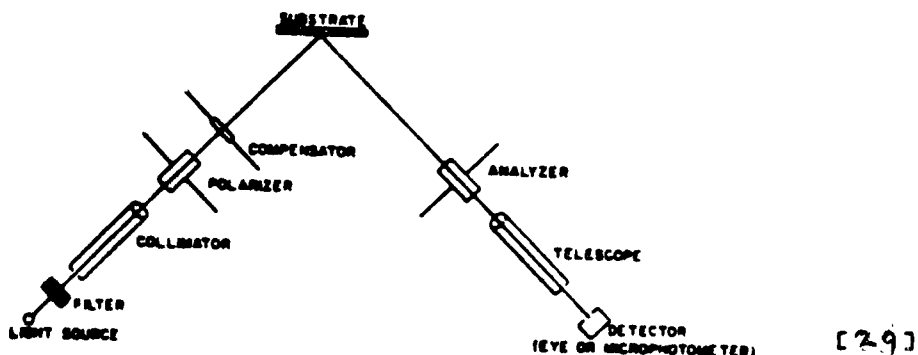
Ellipsometry may be defined as reflection polarimetry [26]. It is the measurement of the effect of reflection on the state of polarization and phase of radiation. Such measurements may be interpreted to yield the optical constants of a reflecting material or if a reflecting material is coated with a thin film, the thickness and the optical constants of the film.

The general principal of ellipsometry is based on the reflection of monochromatic, collimated, polarized radiation [27]. This state of polarization can be defined by the phase and amplitude relationship between the two component plane waves. One wave is in the plane of incidence and the other wave is perpendicular to the plane of incidence. If the two waves are in phase then a plane polarized wave is generated. Other phase changes, in general, generates elliptical polarizations. Upon reflection the wave pairs often undergo a relative change in phase and in the ratio of their amplitudes. This effect of reflection is characterized by, Δ , the change in phase and Ψ , the arctangent of the factor by which the amplitude ratios change [28]. By utilizing these characterization and the ellipsometry equations located in the appendix section, two optical constants of the material may be generated.

The operational procedure for using the ellipsometer is as follows. Turn on the unit and allow the machine to warm up. Set up the compensator or the quarter wave plate to generate circularly polarized radiation. Set the angle of incidence to 70 degrees. Place the sample on the sample platen and maximize by raising or lowering the sample platen. Minimize the output by visual means or by nulling a microphotometer's output. This nulling procedure is done by coordinating two independent polarizers located after the source and before the sensor. These two polarizing

configurations are called the polarizer and the analyzer. (See Figure Three.)

Figure Three



The angles that are generated by this minimizing procedure are the polarizing angle, P , and the analyzer angle, A . These two angles are related to Δ and Ψ by the following relationships:

$$\Delta = 90 - 2P$$

$$\Psi = -A.$$

[30]

A computer program was written that implements the referenced equations for generating the optical constants using ellipsometry. (See Appendix A.) Given the polarizing angle, the analyzer angle, and the angle of incidence, the program will generate the complex index of refraction. (See Appendix B.) The program utilizes a numerical root finding

method in order to solve the fourth order polynomial that is generated. This function is formed by solving the two standard ellipsometry equations for its two unknowns. The unknowns are the index of refraction, n , and the extinction coefficient, k . These two units make up the complex index of refraction, N .

$$N = n - ik.$$

Before any data was taken at Rochester Institute of Technology, some first order measurements were made at Energy Conversion Devices in Troy, Michigan. Two of the chalcogenide samples were tested. They were coated 500 angstroms thick in both its amorphous state and its polycrystalline state. A Gaertner ellipsometer was used to make the measurements. The polarizing angle and the analyzer angle were then processed by using a pre-programmed routine written for the Gaertner ellipsometer. The routine was dependent on a known parameter of the disk. Either the layer thickness, the index of refraction, or the extinction coefficient needed to be known. Given an approximated parameter the program will compute the other two parameters as a function of the estimated value. By knowing what one of these values should be, the first approximated value can be re-estimated so the program generates the known value.

Because the data generated at Rochester Institute of

Technology differed from that generated at Energy Conversion Devices, reasons for the error were explored. The first potential source of error was the ellipsometer source itself. The index of refraction changes as the wavelength of radiation changes. Because of this it was crucial to find the dominant wavelength of the source. Therefore a spectral profile was made of the source using an E.G.&G. spectroradiometer, courtesy of Munsell Color Laboratory at Rochester Institute of Technology. The generated profile suggested that the source was fluorescent in nature.

The polarizers within the compensator, the polarizer dial, and the analyzer dial was also analyzed. Several tests were done to see if these polarizers were calibrated with respect to each other. The ellipsometer was arranged so that the source was pointing directly at the sensor. This was done by changing the angle of incidence and the angle of acceptance 180° apart. Theoretically, if the compensator was set to 45° and circularly polarized radiation was being output, then that radiation could be minimized by setting the polarizer to 45° and the analyzer to 135° . In order to test the compensator, the polarizer and the analyzer were pre-set to 45° and 135° respectively. In this case, the radiation should be nulled if the compensator was set at 45° . Because it did not null at any of the predicted angles, the dial on the compensator was adjusted so that the compensator did null at 45° .

Model Building

Several modeling techniques were researched for applicability to the anisotropic medium that is being used for the reversible tri-layer optical memory disk. Each method was judged by its ease of use and practicality for the desired computer model. (See Appendix D for details on the three methods researched.)

The chosen method, Rouard's method, was implemented into a BASIC computer program. (See Appendix C.) Given the complex indices of refraction for the two thin films used in the disk's tri-layer structure and the layer thicknesses of the films, the amplitude of reflection and its corresponding phase change is generated for each material. Then, by computing the reflectivity for the two different physical phase states of the chalcogenide, a contrast ratio is generated.

The model also gives the option to view the contrast ratio trend if a particular parameter is varied. If, for instance, a manufacturer wanted to create a disk given a specific chalcogenide layer thickness. The effect of different dielectric thicknesses on the contrast ratio could be predicted by setting the dielectric layer thickness range

within the program. The same could be done if it was desirable to vary the chalcogenide layer thickness.

Several trends were observed using some theoretical parameters. These parameters were created based on the past data that had been generated at Energy Conversion Devices in Troy, Michigan.

Apparatus

The ellipsometry measurements made at Energy Conversion Devices proved to be far more dependable than the measurements made at Rochester Institute of Technology. The ellipsometer used at E.C.D. was a Gaertner Scientific ellipsometer. It was equipped with a collimated helium-neon laser. Its detector system utilized a microphotometer. In order to generate circularly polarized radiation, a quarter wave plate was used.

The ellipsometer used at Rochester Institute of Technology was an Applied Materials ellipsometer. Its source was tested. The spectral profile generated suggested that the source was fluorescent in nature. Its detector system was also a microphotometer. A compensator was utilized to set up the circularly polarized radiation.

The computer that was being used to do all the programming was a Commodore 64 personal computer. It utilizes an eight bit microprocessor. A utility cartridge was used in

order to simplify many of the computer's basic commands. The cartridge, Simon's Basic, gives the Commodore 64 one hundred and fourteen extra commands. All written programs were stored on a magnetic floppy disk.

Ellipsometry

An estimated index of refraction for the chalcogenide material in its polycrystalline form is $n=5$. The material in its amorphous state has an approximate index of refraction of $n=4$. The values generate for the complex index of refraction is expected to differ, but the real component of the complex index, n , is still expected to remain around the corresponding refractive indices. Also note that there should exist a difference of one between the refractive indices of the polycrystalline material and the amorphous material.

The first set of data collected was at Energy Conversion Devices in Troy, Michigan. Using their Gaertner ellipsometer, and two samples of the chalcogenide material coated 500 angstroms thick, some first order values for the complex index of refraction were computed. There was one amorphous sample tested and one polycrystalline sample tested. The values generated for different materials are illustrated in table two.

As stated in the Experimental section, the values for the complex index of refraction were generated using a canned computer program written by Gaertner for a Hewlett Packard computer. The program assumes that one of the defining parameters, layer thickness, index of refraction, or

extinction coefficient, is known. Because none of these parameters were exactly known some assumptions had to be made. The assumption that the layer thickness was coated 500 angstroms was made in order to complete the first order measurement of the complex index of refraction. Because an approximated layer thickness had to be used, there was little belief that the generated values would be accurate.

Table Two
E.C.D. Data

	POLARIZER ANGLE	ANALYZER ANGLE	DELTA	PSI	INDEX REFRACTION	EXTICNTION COEFFICIENT
POLYCRYSTALINE	64.3	24.3	141.1	24.4	4.72	0.514
AMORPHOUS	67.0	16.6	136.0	16.6	0.0	0.0

It was believed that there existed another technique that could extract the optical constants from the generated phase change and amplitude ratio without using an approximated layer thickness. With this in mind, more ellipsometry measurements were made at Rochester Institute of Technology. The Applied Materials ellipsometer was utilized

to make these measurements. The polarizing angles and the analyzer angles were then processed using the ellipsometry program written at R.I.T. This program was based on the standard ellipsometry equations and is fully explained in the Experimental section of this report. The first set of data generated using the ellipsometer is shown in Table Three. Note that the data represents the first attempt at using Rochester Institute of Technology's Applied Material ellipsometer.

Table Three
R.I.T. Ellipsometry Data

	POLARIZER ANGLE	ANALYZER ANGLE	DELTA	PSI	INDEX REFRACTION	EXTICTION COEFFICIENT
POLYCRYSTALINE (E.C.D.)	64.3	24.3	141.1	24.4	3.96	3.030
AMORPHOUS (E.C.D.)	67.0	16.6	136.0	16.6	3.41	1.690
POLYCRYSTALINE (500 A)	79.4	22.8	111.0	22.8	2.53	2.220
AMORPHOUS (500 A)	81.6	17.6	106.9	17.6	2.66	1.627
POLYCRYSTALINE (100 A)	75.3	11.8	119.4	11.8	3.07	1.071
AMORPHOUS (100 A)	55.9	2.05	158.1	2.05	2.91	0.069

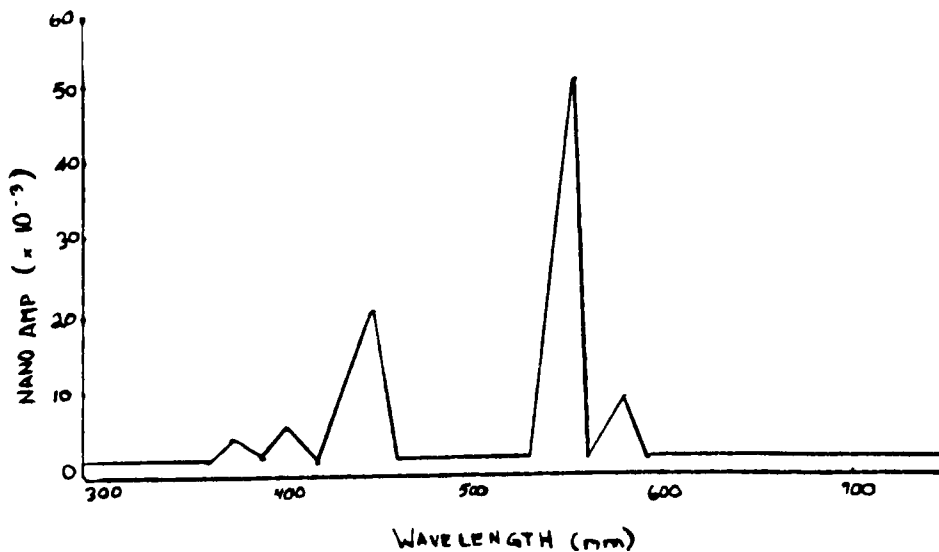
Note the discrepancy between the data generated at E.C.D. and those to values presented in Table Three. Their existed several potential reasons for error in the measurement technique and the data processing. The first tested potential error was that of the source. A material's

optical constants are very dependent on the wavelength of radiation used to analyze that material. As the wavelength increases the index of refraction decreases.

A spectral profile of the ellipsometer source was then generated using an E.G.&G. spectroradiometer. The resultant profile indicates that the source in the ellipsometer is not monochromatic. The profile resembles that of a fluorescent source. (See Graph 1.) Because, in principal, ellipsometry is based on a collimated, monochromatic source, it would be inferred that the source is not applicable to the ellipsometry. A filter would be a logical solution to this problem. However, it must be noted that there was no filter for this source.

Graph 1

Spectral Profile of Ellipsometer Source



Another potential problem with the ellipsometry technique used at R.I.T. was that there was no practical means with which to focus the reflected energy up to the detector to maximize the output. This was remedied by loosening the sample platen with an allen wrench. The data generated after this modification is located in Table Four.

Table Four

R.I.T. Ellipsometry Data: After Platen Modification

	POLARIZER ANGLE	ANALYZER ANGLE	DELTA	PSI	INDEX REFRACTION	EXTINCTION COEFFICIENT
POLYCRYSTALINE (500 A)	78.6	22.7	112.8	22.7	2.60	2.254
AMORPHOUS (500 A)	174.2	153.0	-78.4	153.0	1.90	2.328
POLYCRYSTALINE (1100 A)	163.0	154.0	-56.0	154.0	2.92	2.939
AMORPHOUS (1100 A)	45.0	3.00	180.0	3.00	5.3E-4	1.2E-6

The resultant data deviated and illustrated more error after the platen modification. It was then assumed that the ellipsometer in some way had been modified or drifted off calibration. Steps were then taken to check the calibration of the polarizers in the ellipsometer. The results of this check suggested that the ellipsometer's polarizers were indeed off calibration. If the compensator is set to 45° the resultant energy should be nulled with a polarizing angle of

45° and an analyzer angle of 135°. The minimization did not occur at the predicted polarizer and analyzer angles. The compensator polarizer was then tested by pre-setting the polarizing angle and the analyzing angle to 45° and 135° respectively. Again the null did not occur at the predicted 45° angle. These results are illustrated in Table Five.

Table Five

Ellipsometer Calibration Results

POLARIZER ANGLE	ANALYZER ANGLE	COMPENSATOR ANGLE	INCIDENT ANGLE
54.89	144.58	45.0	70.0
145.06	234.56	45.0	70.0
45.0	135.0	35.7	70.0
45.0	135.0	125.6	70.0
45.0	135.0	216.5	70.0
45.0	135.0	305.6	70.0

Note that the null did occur when the polarizing and analyzer angles were set at 45° and 135° respectively and the compensator was set at 35.7°. It was then proven that the polarizers could be put back in calibration by calibrating

the polarizers with respect to one another. This was done by setting the polarizing angle to 45° , the analyzer angle to 135° , and then nulling the output by adjusting the compensator. When the null was found, the dial on the compensator was then re-adjusted so that it read 45° .

Further testing of the ellipsometer consisted of setting the angle of incidence at the Brewster angle for a piece of glass. At this angle no energy was detected by the sensor due the fact that all the radiation was planar polarized. This result suggests that ellipsometer's polarizers were indeed calibrated. Further measurements were made using this calibrated ellipsometer. These results are located in Table Six.

Table Six

Ellipsometry Data:After Polarizer Calibration

	POLARIZER ANGLE	ANALYZER ANGLE	DELTA	PSI	INDEX REFRACTION	EXTICTION COEFFICIENT
POLYCRYSTALINE (500 A)	70.2	22.2	129.6	22.8	3.39	2.546
AMORPHOUS (500 A)	75.8	21.7	118.4	21.7	2.88	2.242
POLYCRYSTALINE (100 A)	67.4	14.9	135.2	14.9	3.57	1.354
AMORPHOUS (100 A)	61.0	5.50	148.0	5.50	3.16	0.298

Note that the complex indices of refraction were not the values expected. A fuller understanding of the instrument needed to be gained before resuming the extraction of the optical constants from the chalcogenide material. Derivations of the standard ellipsometry equations were undertaken, but due to the time restrictions of this project, they could not be completed. However, the data generated does still indicate the trends of the indices of refraction and the extinction coefficients as the chalcogenide layer thickness is varied and the physical phase states change.

Computer Model

The computer model is based on Rouard's method for summing the reflections and the refractions in a multi-layer film configuration. The technique was simplified by translating the method into a BASIC computer program. It must be noted that the computer is only in its rough stages. However, the model does generate enough information to make some conclusions on the critical parameters of the optical memory disk. The data generated is located in Table Seven.

The data was generated keeping the complex indices of refraction of the materials constant as a function of the layer thickness. This is a poor assumption due to the fact that the chalcogenide material is anisotropic. An anisotropic medium is a medium in which the velocity of light

is varies as a function path length. Because of this varying velocity , the optical constants would vary as a function of the location of the optical axis. The dielectric layer is isotropic, therefore no such variance exists.

Table Seven
First Order Contrast Ratios

CONTRAST RATIO	DIELECTRIC LAYER THICKNESS (ANGSTROMS)	CHALCOGENIDE LAYER THICKNESS (ANGSTROMS)	WAVELENGTH OF LASER (ANGSTROMS)
1.119	244	100	4880
1.119	122	100	4880
0.287	244	500	4880
1.457	244	75.0	4880
1.499	244	70.0	4880
1.513	244	67.0	4880
1.519	244	65.0	4880
1.488	244	50.0	4880
1.360	244	42.0	4880
1.302	244	37.0	4880
1.179	244	25.0	4880

The index of refraction for the dielectric layer was set to 1.54, with zero for an extinction coefficient. The index of refraction for the chalcogenide in its amorphous state was assumed to be 4.0 with an extinction coefficient of 0.40. The index of refraction for the chalcogenide in its polycrystalline state was assumed to be 5.0 with its

extinction coefficient of 0.51.

The most significant result extracted from the current data is that, assuming that the dielectric layer remains a multiple of one half the reading laser's wavelength thick, the dielectric layer thickness has little if any effect on the resultant contrast ratio. This would be expected because the dielectric layer has an insignificant extinction coefficient. The purpose of this layer is to change the phase of the reflected radiation so that it will destructively interfere with the amplitude of the first reflected beam. If however a different material was used for the dielectric layer, it is believed that the contrast ratio would be changed.

It makes intuitive sense that since the chalcogenide material is anisotropic, the layer thickness of this material is the most critical to the present disk's layer configuration. Note that there does exist a maximum contrast ratio at a chalcogenide layer thickness of 60 angstroms.

Extracting optical constants from an anisotropic medium is not a trivial task. The problems encountered prompted a re-evaluation of the hardware and software of the ellipsometric techniques used. It is believed that the Applied Materials ellipsometer located at Rochester Institute of Technology is not applicable for extracting these optical constants. The reason for this is because the ellipsometer source does not yet have a means to project monochromatic, collimated radiation down to the sample. If a different source or filter was used and the proper calibration techniques utilized then the ellipsometer would be adequate.

The assumption that the ellipsometer's polarizers are all calibrated with respect to each other can now be made. After careful analysis, it was discovered that the dial on the ellipsometer were loose, causing the polarizing angles to drift. The problem was found to be in the compensator and was immediately remedied. A standard method in which an operator can calibrate the ellipsometer should be researched. This would then eliminate the potential error of the polarizers being off calibration.

Before any tool or technique is implemented into a research project, that instrument or method should be fully understood. An attempt was made in order to gain this type of understanding of the ellipsometer. However due to the time constraints of doing an undergraduate thesis, this

ambitious task was not completed

The theoretical mathematical model defining output of a reversible tri-layer optical memory disk can be generated using a method for summing the reflections and refractions occurring internally in the disk. This summation process can be done by using any one of three methods explored in this thesis project. A geometric series defining these reflections can be generated. Given the boundary conditions of the disk, a matrix method may be used. And a method can be used that is based on systematically substituting a given layer with the reflection coefficient and phase change of a film bounded by two surfaces.

The last method, Rouard's method, proved to be the more understandable method and most applicable method for this model. The reasons for this choice is that the method can handle absorbing mediums very well. This method can also be easily understood and implented into a computer program.

The contrast ratio of the reversible tri-layer optical memory disk can now be generated using the written computer model. It computes the contrast ratios of the system given the complex indices of refraction and the layer thicknesses of the material. It is observed that the contrast ratio is not significantly effected by the manipulation of the dielectric layer thickness. In the disk's current material and layer configuration, it is noted that dielectric layer is silicon dioxide which has an extinction coefficient of zero.

If another material was used as the dielectric layer, the contrast ratio could then be easily manipulated by changing the dielectric layer thickness. Such materials as aluminium oxide and tin oxide should be substituted, and researched.

The driving force for the contrast ratio of the reversible tri-layer optical memory disk is currently the chalcogenide layer thickness. Because the chalcogenide layer is anisotropic, the optical constants of the material changes as the layer thickness changes. This makes mathematically predicting the output of the disk as a function of the chalcogenide layer thickness very difficult. The model would have to implement a routine that could deal with the changing optical constants as a function of the changing layer thickness.

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Complex Index of Refraction Program

```

10 REM#####
20 REM
30 REM  COMPLEX9
40 REM
50 REM THIS PROGRAM WILL COMPUTE THE
60 REM COMPLEX INDEX OF REFRACTION
70 REM
80 REM#####
90 PRINT"(CLR)"
100 PRINT"ELLIPSONOMETRY PROGRAM"
110 PRINT"WRITTEN BY ARIEL SHAW"
120 PAUSE2
130 REM#####
140 REM
150 REM DATA INPUT AND COMPUTATION
160 REM      BLOCK
170 REM
180 REM#####
190 :
200 :   PROC DATA
210 :
220 PRINT"(CLR)"
230 PRINT"ENTER THE TYPE OF MATERIAL; (A)MORPHOUS OR (C)RYSTALINE"
240 INPUT T$
250 IF T$="A" THEN T$="AMORPHOUS"
260 IF T$="C" THEN T$="POLYCRYSTALINE"
270 PRINT"ENTER ALL ANGLES IN DEGREES"
280 PRINT"-----":PRINT:PRINT:PRINT
290 INPUT"ENTER THE POLARIZING ANGLE P ";P
300 PRINT
310 INPUT"ENTER THE ANALYZER ANGLE  A";AN
320 PRINT
330 Q=(90-(2*P))+180
340 PSI=AN
350 INPUT"ENTER THE ANGLE OF INCIDENCE";AP
360 PRINT:PRINT:PRINT
370 REM#####
380 REM
390 REM  THE EQUATIONS USED
400 REM  ARE THE STANDARD
410 REM  ELLIPSONOMETRY EQUATION
420 REM  FROM ARCHER'S MANUAL
430 REM  FOR ELLIPSONOMETRY
440 REM
450 REM#####
460 DEL=Q*PI/180:A1=AN*PI/180:PHI=AP*PI/180
470 PRINT"DEL = ";DEL
480 PRINT"PSI = ";A1

```

Complex Index of Refraction Program

```

490 PRINT"PHI = ";PHI
500 T=SIN(PHI)*TAN(PHI)
510 Y=2*A1
520 A=COS(Y) ↑ 2 - ((SIN(Y) ↑ 2)*SIN(DEL) ↑ 2)
530 B=(1+(SIN(Y)*COS(DEL))) ↑ 2
540 E1=((T ↑ 2*A)/B)+SIN(PHI) ↑ 2
550 C=SIN(4*A1)*SIN(DEL)
560 E2=(T ↑ 2*C)/B
570 PRINT:PRINT:PRINT
580 PRINT"E1=";E1;"E2=";E2
590 PRINT:PRINT:PRINT
600 PRINT"(M ↑ 2)-(K ↑ 2) = E1"
610 PRINT"2NK = E2"
620 PAUSE2
630 C=(E2/2) ↑ 2
640 M=E1
650 REM#####
660 REM   BISECTION ROOT FINDING
670 REM   METHOD
680 REM#####
690 PRINT"(CLR)"
700 INPUT"TOLERANCE LIMIT";L
710 PRINT:INPUT"ENTER RANGE OF THE ROOT";W1,W2
720 X1=W1:X2=W2
730 :
740 :   PROC START
750 :
760 X3=(X1+X2)/2
770 EXEC FORMULAS
780 U=SGN(F1):V=SGN(F2):W=SGN(F3)
790 IF W<>U THEN X2=X3
800 IF W=U THEN X1=X3
810 IF L<=ABS(X1-X2)/2 THEN CALL START
820 PRINT:PRINT:PRINT
830 PRINT"THE ROOT IS "X3:PRINT:PRINT
840 PRINT"DO YOU WISH TO CONTINUE (Y/N)"
850 INPUT C$:IF C$="Y" THEN CALL COMPUTE
860 IF C$="N" THEN END
870 :
880 :   PROC COMPUTE
890 :
900 PRINT"(CLR)"
910 M=ABS(E2)/2/X3
920 PRINT:PRINT:PRINT"THE COMPLEX INDEX OF REFRACTION IS:"PRINT
930 PRINT"Y= "M" - I*X3:PRINT:PRINT
940 PRINT"DO YOU WANT A HARD COPY (Y/N)"
950 INPUT H$:IF H$="Y" THEN CALL PRINT
960 IF H$="N" THEN CALL ANGLE

```

Complex Index of Refraction Program

```

970 :
980 :   PROC ANGLE
990 :
1000 PRINT:PRINT
1010 PRINT"WISH TO TRY ANOTHER SET OF ANGLES (Y/N)"
1020 INPUT D$:IF D$="Y" THEN CALL DATA
1030 IF D$="N" THEN END
1040 REM#####
1050 REM
1060 :   PROC PRINT
1070 REM
1080 REM#####
1090 OPEN4,4:CMD4
1100 PRINT"ELLIPSONOMETRY PROGRAM"
1110 PRINT:PRINT"WRITTEN BY ARIEL SHAW"
1120 PRINT:PRINTT$ " SAMPLE":PRINT:PRINT
1130 PRINT:PRINT:PRINT"THE COMPLEX INDEX OF REFRACTION IS : "
1140 PRINT"-----"
1150 PRINT:PRINT:PRINT"Y= "N" -I*I3
1160 PRINT:PRINT:PRINT"THE ANGLES ARE:"
1170 PRINT"-----"
1180 PRINT:PRINT"POLARIZER = "P
1190 PRINT:PRINT"ANALYZER = "AN
1200 PRINT:PRINT"ANGLE OF INCIDENCE = "AP
1210 PRINT:PRINT"PSI = "AN
1220 PRINT:PRINT"IN RADIANS PSI = "A1
1230 PRINT:PRINT"DELTA = "Q
1240 PRINT:PRINT"IN RADIANS DELTA = "DEL
1250 PRINT:PRINT"-----"
1260 PRINT"-----"
1270 PRINT:PRINT"TOLERANCE ON ROOT IS "L
1280 PRINT:PRINT"ROOT WAS FOUND BETWEEN "M1" AND "M2
1290 PRINT:PRINT"THE ROOT WAS "X3
1300 PRINT#4,:CLOSE4
1310 PRINT"(CLR)"
1320 PRINT"WISH TO TRY ANOTHER SET OF ANGLES (Y/N)"
1330 INPUT D$:IF D$="Y" THEN CALL
1340 IF D$="N" THEN END
1350 :
1360 :   PROC FORMULAS
1370 :
1380 F1=X1 ↑ 4+M8X1 ↑ 2-C
1390 F2=X2 ↑ 4+M8X2 ↑ 2-C
1400 F3=X3 ↑ 4+M8X3 ↑ 2-C
1410 END PROC

```

Ellipsometry Equations

$$t = \sin(\dot{\Theta}) \tan(\dot{\Theta})$$

$$n^2 - k^2 = [t(\cos^2(2\psi) - \sin^2(2\psi) \sin^2(2\Delta)) / (1 + \sin(2\psi) \cos(\Delta))] + \sin(\dot{\Theta})$$

$$2nk = t^2 [\sin(4\psi) \sin(\Delta) / (1 + \sin(2\psi) \cos(\Delta))]^2$$

Mathematical Model For A Reversible Tri-Layer Optical Memory Disk Program.

```

10 REM*****
20 REM
30 REM  MODEL10 FOR A REVERSIBLE
40 REM    TRI-LAYER OPTICAL
50 REM    MEMORY DISK
60 REM
70 REM  WRITTEN BY ARIEL SHAW
80 REM
90 REM*****
100 :
110 REM  DATA INPUT FOR THE FIRST
120 REM    DIELECTRIC LAYER
130 PRINT*(CLR)*
140 PRINT AT(9,9)"MATHEMATICAL MODEL FOR"
150 PRINT AT(9,10)"A REVERSIBLE TRI-LAYER"
160 PRINT AT(9,11)"OPTICAL MEMORY DISK"
170 PRINT AT(9,13)"WRITTEN BY ARIEL SHAW"
180 PAUSE3
190 REM*****
200 REM
210 REM  DATA INPUT BLOCK
220 REM
230 REM*****
240 :
250 :    PROC DATA
260 :
270 PRINT*(CLR)*
280 PRINT*ENTER THE FOLLOWING VALUES IN ANGSTROMS*
290 PRINT AT(5,9)"READING LASER'S WAVELENGTH";
300 INPUT LAMDA
310 PRINT AT(5,11)"DIELECTRIC LAYER THICKNESS";
320 INPUT DSI
330 PRINT AT(5,13)"CHALCOGENIDE LAYER THICKNESS";
340 INPUT DTE
350 PRINT*(CLR)*
360 PRINT*ENTER THE OPTICAL CONSTANTS OF THE      DIELECTRIC LAYER*
370 PRINT AT(9,9)"COMPLEX INDEX OF REFRACTION"
380 PRINT AT(9,10)"FOR THE DIELECTRIC LAYER"
390 PRINT AT(9,12)"INDEX OF REFRACTION";
400 INPUT NSI
410 PRINT AT(9,14)"EXTINCTION COEFFICIENT";
420 INPUT KSI
430 PRINT*(CLR)*
440 PRINT*ENTER THE OPTICAL CONSTANTS FOR THE      CHALCOGENIDE (CRYSTALINE)*
450 PRINT AT(9,9)"COMPLEX INDEX OF REFRACTION"
460 PRINT AT(9,10)"FOR THE CHALCOGENIDE"
470 PRINT AT(9,12)"INDEX OF REFRACTION";
480 INPUT NTE

```


Model Program

```

490 PRINT AT(9,14)"EXTINCTION COEFFICIENT";
500 INPUT KTE
510 PRINT"(CLR)"
520 PRINT"ENTER THE OPTICAL CONSTANTS FOR THE          CHALCOGENIDE (AMORPHOUS)"
530 PRINT AT(9,9)"COMPLEX INDEX OF REFRACTION"
540 PRINT AT(9,10)"FOR THE CHALCOGENIDE"
550 PRINT AT(9,12)"INDEX OF REFRACTION";
560 INPUT NA
570 PRINT AT(9,14)"EXTINCTION COEFFICIENT";
580 INPUT KA
590 PAUSE3
600 REM"*****"
610 :      PROC COMPUTATION
620 REM
630 REM      DECISSION BLOCK
640 REM      FOR TREND VIEWING
650 REM      OPTION
660 REM
670 REM"*****"
680 :
690 :
700 REM  NOTE THAT RAL=GAL+HAL=1
710 :
720 GAL=1
730 HAL=1
740 MO=1;KO=0
750 PRINT"(CLR)"
760 PRINT AT(2,9)"WISH TO ANALYZE A TREND (Y,N)";
770 INPUT A$
780 IF A$="N" THEN CALL SINGLE
790 IF A$="Y" THEN CALL TREND
800 :      PROC TREND
810 PRINT"(CLR)":PRINT AT(5,9)"(D)IELECTRIC OR (C)HALCOGENIDE";
820 INPUT J$
830 IF J$="D" THEN CALL DIE
840 IF J$="C" THEN CALL CALC
850 :      PROC DIE
860 PRINT"(CLR)":PRINT AT(9,9)"DIELECTRIC THICKNESS TREND"
870 PRINT AT(9,11)"RANGE OF THICKNESSES"
880 PRINT AT(9,12)"IN NANOMETERS";
890 INPUT X1,X2
900 DSI=0
910 FOR DSI=X1 TO X2 STEP 1000
920 CALL SINGLE
930 :      PROC CALC
940 PRINT"(CLR)":PRINT AT(9,9)"CHALCOGENIDE THICKNESS TREND"
950 PRINT AT(9,11)"RANGE OF THICKNESSES"
960 PRINT AT(9,12)"IN NANOMETERS";

```

Model Program

```

970 INPUT Y1,Y2
980 DTE=0
990 FOR DTE=Y1 TO Y2 STEP 1000
1000 CALL SINGLE
1010 :
1020 :   PROC SINGLE
1030 :
1040 REM#####
1050 REM
1060 REM   COMPUTING THE FRESNEL
1070 REM   COEFFICIENT AND PHASE
1080 REM   SID2 LAYER
1090 REM   WITH RESPECT TO
1100 REM   CRYSTALLINE CHALCOGENIDE
1110 REM   USING ROUARD'S METHOD
1120 REM
1130 REM#####
1140 ASI=-4# PI#KSI#DSI/LAMDA
1150 THETASI=-4# PI#NSI#DSI/LAMDA
1160 ATE=-4# PI#KTE#DTE/LAMDA
1170 TTE=-4# PI#NTE#DTE/LAMDA
1180 TNA=-4# PI#NA#DTE/LAMDA
1190 ANA=-4# PI#KA#DTE/LAMDA
1200 :
1210 REM   COMPUTING GSI AND HSI
1220 :
1230 GSI=NTE↑2-(NSI↑2)+(KTE↑2)-(KSI↑2)
1240 HSI=2#(NTE#KSI-(NSI#KTE))
1250 DENSI=((NTE+NSI)↑2)+((KTE+KSI)↑2)
1260 GSI=GSI/DENSI
1270 HSI=HSI/DENSI
1280 RISI=6SI+(EXP(-ASI)#(6AL#COS(THETASI)+HAL#SIN(THETASI)))↑2
1290 R2SI=(HSI+(EXP(-ASI)#(HAL#COS(THETASI)-6AL#SIN(THETASI)))↑2)
1300 RDSI=(1+(EXP(-ASI)#((GSI#6AL)-(HSI#HAL))#COS(THETASI)))
1310 RBSI=(HSI#6AL#HAL#6SI)#SIN(THETASI)
1320 RSI=(RDSI+RBSI)↑2
1330 RASI=EXP(-ASI)#((HSI#6AL)+(HAL#6SI))#COS(THETASI)
1340 RCSI=(6AL#6SI-(HSI#HAL))#SIN(THETASI)
1350 DNSI=RSI+((RASI-RCSI)↑2)
1360 ROSI=RISI+R2SI/DNSI
1370 :
1380 REM   DELTA=NU+EPSILON
1390 :
1400 ESI=EXP(-ASI)#((HSI#6AL)+(HAL#6SI))#COS(THETASI)
1410 E1SI=((6SI#6AL)-(HSI#HAL))#SIN(THETASI)
1420 EPSI=ESI-E1SI/(SQR(RSI))
1430 REM   WATCH FOR THE TANGENT
1440 USI=HSI#(EXP(-ASI)#(HAL#COS(THETASI))-(6AL#COS(THETASI)))

```

Model Program

```

1450 U1SI=6SI*(EXP(-ASI)*(HAL*DCOS(THETASI))+(GAL*DCOS(THETASI)))
1460 M1SI=U1SI/U1SI
1470 PRINT*(CLR)*
1480 PRINT*THE OPTICAL PROPERTIES OF THE DIELECTRIC LAYER*
1490 PRINT*WITH RESPECT TO CRYSTALLINE*
1500 PRINT AT(9,9)*AMPLITUDE OF REFLECTION IS *
1510 PRINT AT(9,10)R1SI
1520 PRINT AT(9,12)*PHASE CHANGE IS *
1530 PRINT AT(9,13)M1SI
1540 PAUSE3
1550 :
1560 REM   COMPUTING GSI AND HSI
1570 :
1580 REM*****
1590 REM
1600 REM   COMPUTING THE FRESNEL
1610 REM   COEFFICIENT AND PHASE
1620 REM   SiO2 LAYER
1630 REM   WITH RESPECT TO
1640 REM   AMORPHOUS CHALCOGENIDE
1650 REM   USING ROUARD'S METHOD
1660 REM
1670 REM*****
1680 G1=NA↑2-MSI↑2+KA↑2-KSI↑2
1690 H1=2*(NA*KSI-(NSI*KA))
1700 D1SI=((NA+NSI)↑2)+((KA+KSI)↑2)
1710 G1=G1/D1SI
1720 H1=H1/D1SI
1730 R3SI=(G1+(EXP(-ASI)*(HAL*DCOS(THETASI)+HAL*DSIN(THETASI)))↑2)
1740 R4SI=(H1+(EXP(-ASI)*(HAL*DCOS(THETASI)-HAL*DSIN(THETASI)))↑2)
1750 R5SI=(1+(EXP(-ASI)*((G1*GAL)-(H1*HAL))*DCOS(THETASI)))
1760 R6SI=(H1*GAL*HAL*G1)*DSIN(THETASI)
1770 R1=(R5SI+R6SI)↑2
1780 R7SI=EXP(-ASI)*((H1*GAL)+(HAL*G1))*DCOS(THETASI)
1790 R8SI=(GAL*G1-(H1*HAL))*DSIN(THETASI)
1800 D1=RI+((R7SI-R8SI)↑2)
1810 R9SI=R3SI+R4SI/D1
1820 :
1830 REM   DELTA=NU+EPSILON
1840 :
1850 E1=EXP(-ASI)*((H1*GAL)+(HAL*G1))*DCOS(THETASI)
1860 E2I=((G1*GAL)-(H1*HAL))*DSIN(THETASI)
1870 EPI=E1-E2I/(SQR(R1))
1880 REM   WATCH FOR THE TANGENT
1890 U1=H1*(EXP(-ASI)*(HAL*DCOS(THETASI))-(GAL*DCOS(THETASI)))
1900 U2I=G1*(EXP(-ASI)*(HAL*DCOS(THETASI))+(GAL*DCOS(THETASI)))
1910 M1=U1/U2I
1920 PRINT*(CLR)*

```

Model Program

```

1930 PRINT"THE OPTICAL PROPERTIES OF THE DIELECTRIC LAYER"
1940 PRINT"WITH RESPECT TO AMORPHOUS"
1950 PRINT AT(9,9)"AMPLITUDE OF REFLECTION IS "
1960 PRINT AT(9,10)R9SI
1970 PRINT AT(9,12)"PHASE CHANGE IS "
1980 PRINT AT(9,13)NI
1990 PAUSE3
2000 :
2010 REM    COMPUTING GTE AND HTE
2020 :
2030 REM*****
2040 REM
2050 REM    COMPUTING THE FRESNEL
2060 REM    COEFFICIENT AND PHASE
2070 REM    FOR THE CHALCOGENIDE
2080 REM    IN CRYSTALLINE FORM
2090 REM    USING ROUARD'S METHOD
2100 REM
2110 REM*****
2120 GTE=NO↑2-(NTE↑2)+(K0↑2)-(KTE↑2)
2130 HTE=2*(NO*KTE-(NTE*K0))
2140 DENTE=((NO+NTE)↑2)+((K0+KTE)↑2)
2150 GTE=GTE/DENTE
2160 HTE=HTE/DENTE
2170 O7TE=(GTE+(EXP(-ATE)*(GSI*ICOS(TTE))+(HSI*ISIN(TTE)))↑2)
2180 O2TE=(HTE+(EXP(-ATE)*(HSI*ICOS(TTE)-(GSI*ISIN(TTE))))↑2)
2190 RDTE=(1+(EXP(-ATE)*(GTE*GSI-(HSI*HTE)))*COS(TTE))
2200 RBTE=(HTE*GSI*HSI*GTE)*SIN(TTE)
2210 RTE=(RDTE+RBTE)↑2
2220 RATE=EXP(-ATE)*((HTE*GSI+(HSI*GTE))*COS(TTE))
2230 RCTE=(GSI*GTE-(HTE*HSI))*SIN(TTE)
2240 DCTE=RTE+((RATE-RCTE)↑2)
2250 ROTE=O7TE+O2TE/DCTE
2260 :
2270 REM    DELTA=NU+EPSILON
2280 :
2290 ETE=EXP(-ATE)*((HTE*GSI)+(HSI*GTE))*COS(TTE)
2300 E1TE=((GTE*GSI)-(HTE*HSI))*SIN(TTE)
2310 EPTE=ETE-E1TE/(SQR(RTE))
2320 REM    WATCH FOR THE TANGENT
2330 UTE=HTE*(EXP(-ATE)*(HSI*ICOS(TTE)-(GSI*ICOS(TTE)))
2340 U1TE=GTE*(EXP(-ATE)*(HSI*ICOS(TTE)+(GSI*ICOS(TTE)))
2350 NUTE=UTE/U1TE
2360 PRINT"(CLR)"
2370 PRINT"THE OPTICAL PROPERTIES OF THE          CHALCOGENIDE LAYER"
2380 PRINT"POLYCRYSTALLINE"
2390 PRINT AT(9,9)"AMPLITUDE OF REFLECTION IS "
2400 PRINT AT(9,10)ROTE

```

Model Program

```

2410 PRINT AT(9,12)*PHASE CHANGE IS *
2420 PRINT AT(9,13)MUTE
2430 PAUSE3
2440 :
2450 REM COMPUTE GA AND HA
2460 :
2470 REM*****
2480 REM
2490 REM COMPUTING FRESNEL
2500 REM COEFFICIENT AND PHASE
2510 REM FOR THE CHALCOGENIDE
2520 REM IN AMORPHOUS FORM
2530 REM USING ROUARD'S METHOD
2540 REM
2550 REM*****
2560 GA=NO↑2-(NA↑2)+(KO↑2)-(KA↑2)
2570 HA=2*(NO*KA-(NA*KO))
2580 DNTA=((NO+NA)↑2)+((KO+KA)↑2)
2590 GA=GA/DNTA
2600 HA=HA/DNTA
2610 V7TA=(GA+(EXP(-ANA)*(GI*ICOS(TNA)+(HI*ISIN(TNA))))↑2)
2620 V2TA=(HA+(EXP(-ANA)*(HI*ICOS(TNA)-(GI*ISIN(TNA))))↑2)
2630 VDTA=(1+(EXP(-ANA)*(GA*GI-(HA*HI))*COS(TNA)))
2640 VBTA=(HA*GI*HI*GA)*SIN(TNA)
2650 VTA=(VDTA+VBTA)↑2
2660 VVTA=EXP(-ANA)*((HA*GI+(HI*GA))*COS(TNA))
2670 VCTA=(GI*GA-(HA*HI))*SIN(TNA)
2680 BNTA=VTA+((VVTA-VCTA)↑2)
2690 VA=V7TA+V2TA/BNTA
2700 :
2710 REM DELTA=NU+EPSILON
2720 :
2730 YTA=EXP(-ANA)*((HA*GI)+(HI*GA))*COS(TNA)
2740 YITA=((GA*GI)-(HA*HI))*SIN(TNA)
2750 YPTA=YTA-YITA/(SQR(VTA))
2760 REM WATCH FOR THE TANGENT
2770 ZTA=HA*(EXP(-ANA)*(HI*ICOS(TNA)-(GI*ICOS(TNA))))
2780 ZITA=GA*(EXP(-ANA)*(HI*ICOS(TNA)))+(GI*ICOS(TNA))
2790 NZTA=ZTA/ZITA
2800 PRINT*(CLR)*
2810 PRINT*THE OPTICAL PROPERTIES OF THE CHALCOGENIDE LAYER*
2820 PRINT*AMORPHOUS*
2830 PRINT AT(9,9)*AMPLITUDE OF REFLECTION IS *
2840 PRINT AT(9,10)VA
2850 PRINT AT(9,12)*PHASE CHANGE IS *
2860 PRINT AT(9,13)NZTA
2870 PAUSE3

```

Model Program

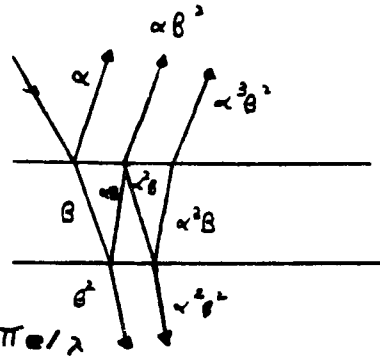
```
2880 REM#####
2890 REM
2900 REM      COMPUTING CONTRAST
2910 REM      RATIO
2920 REM
2930 REM#####
2940 PRINT"(CLR)"
2950 PRINT AT(9,9)"THE CONTRAST RATIO IS"
2960 PRINT AT(9,11)VA/ROTE
2970 IF A6="Y" THEN NEXT
2980 PAUSE3
2990 :
3000 PRINT"(CLR)"
3010 PRINT AT(9,9)"DO YOU WISH TO"
3020 PRINT AT(9,10)"HAVE A PRINTOUT (Y/N)";
3030 INPUT P$
3040 IF P$="N" THEN END
3050 IF P$="Y" THEN CALL PRINT
3060 :
3070 :   PROC PRINT
3080 :
3090 REM#####
3100 REM
3110 REM      PRINT BLOCK
3120 REM
3130 REM#####
3140 OPEN4,4:CMD4
3150 PRINT"DIELECTRIC LAYER THICKNESS ";DSI;" ANGSTROMS"
3160 PRINT:PRINT"CHALCOGENIDE LAYER THICKNESS ";DTE;" ANGSTROMS "
3170 PRINT:PRINT"THE COMPLEX INDICES OF REFRACTION FOR THE TRI-LAYER STRUCTURE"
3180 PRINT:PRINT"FOR DIELECTRIC LAYER"
3190 PRINT"N= ";NSI"-I ";KSI
3200 PRINT:PRINT"FOR THE CHALCOGENIDE"
3210 PRINT"IN AMORPHOUS STATE"
3220 PRINT"N= ";NTE"-I "KTE
3230 PRINT:PRINT"IN POLYCRYSTALLINE STATE"
3240 PRINT"N= ";NA"-I "KA
3250 PRINT:PRINT"~~~~~"
3260 PRINT:PRINT"THE CONTRAST RATIO IS:"
3270 PRINT:PRINT"C.R.= "VA/ROTE
3280 PRINT#4,:CLOSE4
3290 PRINT"(CLR)"
3300 PRINT AT(9,9)"DO YOU WISH TO TRY AGAIN"
3310 PRINT AT(9,10)"(Y/N)";
3320 INPUT T$
3330 IF T$="Y" THEN CALL DATA
3340 IF T$="N" THEN END
```

Summation Methods

Method One: Direct Summation.

α = reflection coefficient

β = transmission coefficient



let $f = \alpha^2$ and $a_1 = \beta^2$ and $\delta = -2\pi e/\lambda$

The intensity simplifies to $I = a_1 [(1-f)^2 + 4f \sin^2(\delta/2)]^{-1}$

Method Two: Matrix Method.

For incoherent radiation

$$\begin{array}{c} \leftarrow I_i^- \\ \rightarrow I_i^+ \end{array} \left| \begin{array}{c} \rightarrow I_{i+1}^- \\ \leftarrow I_{i+1}^+ \end{array} \right. \quad \begin{array}{c} \left| I_{i+1}^+ \right| \\ \left| I_{i+1}^- \right| \end{array} = \begin{array}{c} \left| \frac{r^2}{1-r^2} \quad \frac{1}{1-r} \right| \left| \begin{array}{c} I_i^- \\ I_i^+ \end{array} \right| \end{array}$$

Between 2 surfaces

$$\begin{array}{c} \left| \begin{array}{c} \rightarrow I_i^+ \\ \leftarrow I_i^- \end{array} \right| \left| \begin{array}{c} \rightarrow I_{i+1}^+ \\ \leftarrow I_{i+1}^- \end{array} \right| \end{array} \quad \begin{array}{c} \left| I_{i+1}^+ \right| \\ \left| I_{i+1}^- \right| \end{array} = \begin{array}{c} \left| \begin{array}{cc} r & 0 \\ 0 & R \end{array} \right| \left| \begin{array}{c} I_i^+ \\ I_i^- \end{array} \right| \end{array}$$

For Entire System

$$\begin{array}{c} \left| \begin{array}{c} I_{n+1}^+ \\ I_{n+1}^- \end{array} \right| = \begin{array}{c} \left| \begin{array}{cc} a & b \\ c & d \end{array} \right| \left| \begin{array}{c} I_1^+ \\ I_1^- \end{array} \right| \end{array} \quad \begin{array}{c} T = \frac{1}{d} \\ R = \frac{-c}{d} \end{array}$$

Ariel Shaw began his photographic career at the early age 10 at his Elementary school. When he reached high school, Ariel became comfortable enough with the medium that he was able to skip the required preliminary photography courses offered. At this time, his ability to do the maths and sciences also matured. Eventually his photographic and technical skills directed him to the Imaging and Photographic Science Program at Rochester Institute of Technology, where he has already received an Associates Degree in Imaging and Photographic Sciences. He will receive his Bachelors of Science Degree in May, 1984.