MEASUREMENT OF PHYSICAL AND OPTICAL PROPERTIES OF THIN FILMS WITH AN ELLIPSOMETRIC TECHNIQUE

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ABSTRACT

MEASUREMENT OF PHYSICAL AND OPTICAL PROPERTIES OF THIN FILMS WITH AN ELLIPSOMETRIC TECHNIQUE

In this thesis, working mechanism of ellipsometer is studied in details. Thickness and refractive index of polyethyleneglycol(PEG), gold and silicon dioxide films are measured using an elipsometer. PEG is attached to a gold coated surface on a BK7 glass using a chemical synthesis method. Potasiumcloride is used to control the relative humidity of the enviroment for insitu measurments of the humidity dependent thickness of PEG polymer film. The PEG thicknesses, which correspond to certain relative humidity levels, are measured using the ellipsometry. It is observed that the thickness increases with the increasing humidity. Apart from PEG thickness and refractive indices of SiO_2 and gold films are measured.

ÖZET

ELİPSOMETRİK TEKNİK KULLANARAK İNCE FİLMLERİN FİZİKSEL VE OPTİK ÖZELLİKLERİNİN ÖLÇÜMÜ

Bu tezde, elipsometrenin çalşıma tekniği detaylı bir şekilde çalışıldı. Polietilenglikol, altın ve silikon dioksit ince filmlerinin kalınlıkları ve bazı optiksel özellikleri elipsometre ile ölçüldü. Polietilenglikol, kimyasal sentez yoluyla altın kaplı BK7 camının üzerine bağlandı. PEG in neme bağlı kalınlığı ölçülürken etrafın bağıl nem düzeyi potasyumnitrat tuzu ile kontrol edildi. Bu nem değerlerine tekabül eden polietilenglikol kalınlıkları elipsometre ile ölçüldü. Nemdeki artış ile polietilenglikolun kalınlaştığı gözlendi. PEG in dışında, silikon dioksit ve altın filmlerinin kalınlığı ve kırıcılık indisleri ölçüldü.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS/ABBREVIATIONS

PEG	polyethylene glycol
AFM	Atomic force microscope
Au	Gold
BK7	Borosilicate crown glass
$CHCl_3$	Choloroform
MW	Molecular Weight
rpm	rate per minute
SEM	Scanning electron microscope
SiO_2	Silicon dioxide

1. INTRODUCTION

A thin film is a layer which has a thickness varying from sub-nanometers to a few microns. Thin films are widely used in many kinds of experimental works such as optical coatings and electronic semiconductor devices. In design of a device, optical properties of thin films are very essential. There are many ways of designating the optical properties of thin films such as thickness, index of refraction, etc.

Ellipsometry is a device which is used to determine the optical properties of thin films. Complex refractive index, dielectric function and thickness of thin films can be measured by ellipsometry. In comparision to plasmon resonance tecnique, ellipsometry is an easier way of measuring thickness. On the other hand, once the appropriate data about the sample of interest is entered into the software, one can get very precise information about the optical properties of the thin films instantly. That's why ellipsometric measurment is more practical than SEM(Scanning Electron Microscope) and AFM(Atomic Force Microscope) if only physical thickness and refractive index are concerned.

In situ measurments are carried out with ellipsometry. Ellipsometry takes two parameters, either angle of incidence or wavelenght. It calculates the property of interest immediately by first measuring and then comparing the intencities of incoming and reflected light beams. In stead of exact measurment of the light intensity the comparision is enough to analyze the data taken.

Chapters of this thesis are ordered as follows: the second chapter is devoted to the theoretical background of the ellipsometry, which includes light and polarization, index of refraction, reflection and transmission of polarized light, ellipsometric measurments and the ambient-film-substrate system.

In the third chapter, preperation of thin films and optical setup are explained. This is followed by results on the thickness and refractive index.

In the forth chapter, conclusion is given which includesa discussion on the results and experimental method discussed. This is followed by suggestions on future work with an ellipsometric technique.

2. REVIEW

2.1. Light and Polarization

Light is an electromagnetic(EM) wave travelling through a media. In order to understand the ellipsometry only consider the electric field($\vec{E}$) component of an EM wave. The change in $\vec{E}$ of an EM wave(or light) with respect to time is known as polarization. For the sake of generality consider that light is travelling along z axis which means that the $\vec{E}$ have x and y components. If light has random orientation and phase , it is called as unpolarized light. In the ellipsometric measurment one should consider polarized light i.e, light wave with an $\vec{E}$ which has a regular path.If the oscillations of $\vec{E}$ are on a well defined line then the electromagnetic wave is said to be linearly polarized. If the $\vec{E}$ forms a circle by rotating around the direction of

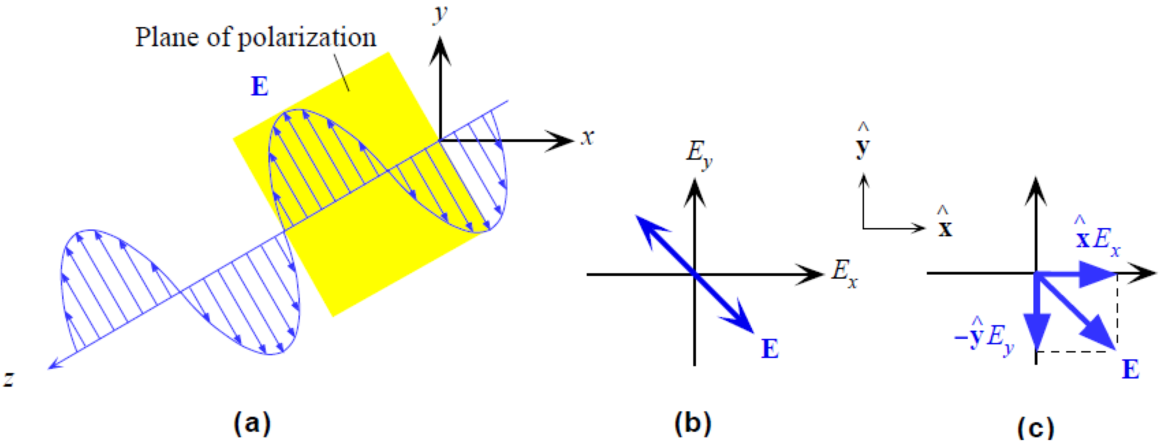


Figure 2.1. (a)A linearly polarized wave has its electric field oscillations defined along a line perpendicular to the direction of propagation, z. The field vector E and z define a plane of polarization.(b) The E-field oscillations are contained in the plane of polarization. (c)A linearly polarized light at any instant can be represented by the superposition of two fields E_x and E_y with the right magnitude and phase.

the propogation, such a wave is called circularly polarized light. As in the circular polarization if light forms an ellipse then it is called the elliptically polarized light. [1]

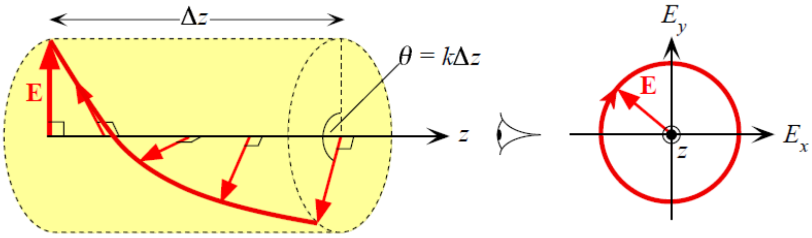


Figure 2.2. A right circularly polarized light. The field vector E is always at right angles to z, rotates clockwise around z with time, and traces out a full circle over one wavelenght of distance propagated.

2.2. Index of Refraction

Refractive index may simply be defined as ratio of speed of light in the vacuum to the speed of light in a medium. For some materials refractive index has a complex representation:

$$N = n + jk \tag{2.1}$$

where n is called as index and k is called as extinction coefficient. Dielectric function is also useful to express optical properties of material.

$$\tilde{\epsilon} = \epsilon_1 + j\epsilon_2 \tag{2.2}$$

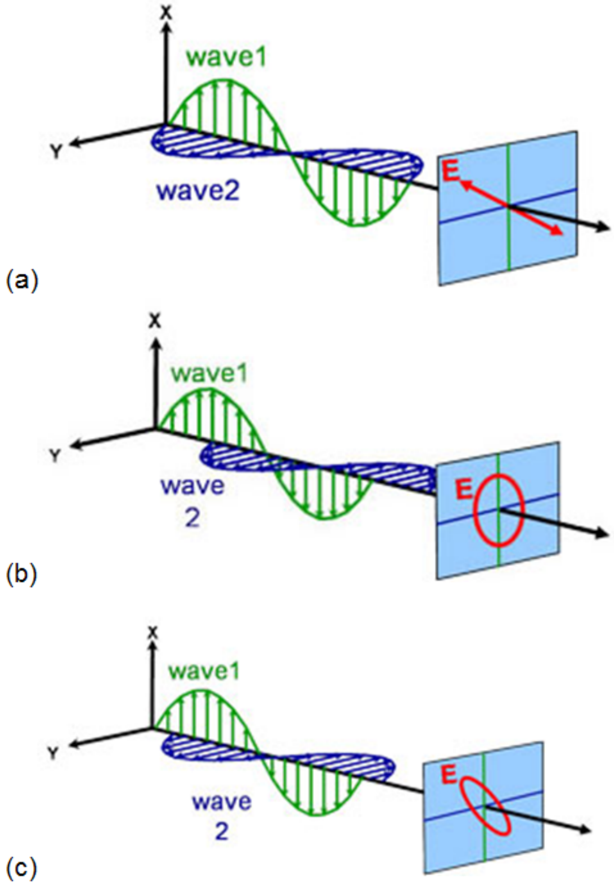


Figure 2.3. (a) Linear polarization.(b) Circular Polarization.(c) Elliptical Polarization.

The relation between index of refraction and dielectric function is

$$\tilde{\epsilon}^2 = N^2 \tag{2.3}$$

A media with high index of refraction decreases the speed of light. Extinction coefficient is used to describe the loss of wave energy which is related to absorbtion coefficient α.

$$\alpha = 4\pi k/\lambda \tag{2.4}$$

Intensity also changes in a different medium with the the following relation [7]

$$I(z) = I(0)e^{-j\alpha z} \tag{2.5}$$

2.3. Refletion and Transmission of Polarized Light

The expression for the $\vec{E}$ component of the light travelling along z direction is defined as.

$$\vec{E} = E_0 e^{j(\omega t + \delta)} e^{-j\omega N z/c} \tag{2.6}$$

where δ is a constant phase angle, c is the free space wave velocity and E_0 is the amplitude and polarization of the wave, c/n is the wave velocity and the decay rate of the amplitude is ωk/c or 2πk/λ, λ is the free space wavelenght.

When light travels from one medium to another, $\vec{E}$ and $\vec{B}$ components are reflected, refracted and transmitted at their interface.

As seen from figure 2.4, $\vec{E}$ component of light travels along two semi-infinite media (0 and 1) with complex indicies of N_0 and N_1. Angle of incidence Φ_0 and reflection Φ_1 have the following relation.

$$N_0 sin\Phi_0 = N_1 sin\Phi_1 \tag{2.7}$$

This is known as the Snell's Law. If both media are transparent, N_0 and N_1 are real numbers and calculations for above picture become simple. However, when either one or both media are absorbing, angles Φ_0 and Φ_1 become complex numbers.

Let (E_{ip}, E_{is}), (E_{rp}, E_{rs}) and (E_{tp}, E_{ts}) represent the complex amplitudes of $\vec{E}$ of the incident, reflected, and transmitted waves respectively. Applying boundary conditions for tangential components of $\vec{E}$ and $\vec{H}$ at the interface give;

$$\frac{E_{rp}}{E_{ip}} = r_p = \frac{N_1 cos\Phi_0 - N_0 cos\Phi_1}{N_1 cos\Phi_0 + N_0 cos\Phi_1} \tag{2.8}$$

$$\frac{E_{rs}}{E_{is}} = r_s = \frac{N_0 cos\Phi_0 - N_1 cos\Phi_1}{N_0 cos\Phi_0 + N_1 cos\Phi_1} \tag{2.9}$$

$$\frac{E_{tp}}{E_{ip}} = t_p = \frac{2N_0 cos\Phi_0}{N_1 cos\Phi_0 + N_0 cos\Phi_1} \tag{2.10}$$

$$\frac{E_{ts}}{E_{is}} = t_s = \frac{2N_0 cos\Phi_0}{N_0 cos\Phi_0 + N_1 cos\Phi_1} \tag{2.11}$$

which are known as Fresnell reflection (r) and transmission (t) components. Using equation 2.7, one can cancel N_0 and N_1:

$$r_p = \frac{tan(\Phi_0 - \Phi_1)}{tan(\Phi_0 + \Phi_1)} \tag{2.12}$$

$$r_s = \frac{-sin(\Phi_0 - \Phi_1)}{sin(\Phi_0 + \Phi_1)} \tag{2.13}$$

$$t_p = \frac{2sin\Phi_1 cos\Phi_0}{sin(\Phi_0 + \Phi_1) + cos(\Phi_0 - \Phi_1)} \tag{2.14}$$

$$t_p = \frac{2sin\Phi_1 cos\Phi_0}{sin(\Phi_0 + \Phi_1)} \tag{2.15}$$

In order to make a sensible analysis, we write the Fresnel coefficients as

$$r_p = |r_p|\, e^{j\delta_{rp}} \tag{2.16}$$

$$r_s = |r_s|\, e^{j\delta_{rs}} \tag{2.17}$$

where $|r_p|$ is the ratio of the amplitude E_{rp} to E_{ip}. δ_{rp} is the phase shift upon reflection

[2].

2.4. Ellipsometric Measurement

Ellipsometric measurement is based on the ratio

$$\rho = \frac{r_p}{r_s} \tag{2.18}$$

which can be written in the form

$$\rho = tan\Psi e^{j\Delta} \tag{2.19}$$

where

$$tan\Psi = \frac{|r_p|}{|r_s|} \tag{2.20}$$

$$\Delta = \delta_{rp} - \delta_{rs} \tag{2.21}$$

subsituting r_p and r_s and using equation 2.7 we can find the relation between two media as

$$\frac{N_1}{N_0} = sin\Phi_0 \left[1 + (\frac{1-\rho}{1+\rho})^2 tan^2\Phi_0 \right]^{1/2} \tag{2.22}$$

. It can be seen from the above equation that N_1 can be determined if N_0 is known and ρ is measured at one angle of incidence [2].

2.4.1. Ambient-Film-Subtrate System

d_1 is the film thickness, Φ_0 is the angle of incidence in the ambient and Φ_1, Φ_2 are the angles of refraction in the film and substrate, respectively. Fresnel reflection and transmission coefficients for 0^{th} media are r_{01}, $t_{01}t_{10}r_{12}e^{-j2\beta}$, $t_{01}t_{10}r_{12}^2e^{-j4\beta}$,

$t_{01}t_{10}r_{10}^2r_{12}^3e^{-j6\beta}$ and for the second media $t_{01}t_{12}e^{-j\beta}$, $t_{01}t_{12}r_{10}r_{12}e^{-j3\beta}$, $t_{01}t_{12}r_{10}^2r_{12}^2e^{-j5\beta}$ where β is the phase delay the beam experiences during propogation from the top surface of the beam to the bottom surface of the film.

$$\beta = 2\pi\left(\frac{d_1}{\lambda}\right)N_1cos\Phi_1 = 2\pi\left(\frac{d_1}{\lambda}\right)\left(N_1^2 - N_0^2sin^2\Phi_0\right)^{1/2} \tag{2.23}$$

Addition of partial waves gives the reflected and transmitted amplitude as

$$R = \frac{r_{01} + r_{12}e^{-j2\beta}}{1 + r_{01}r_{12}e^{-j2\beta}} \tag{2.24}$$

$$T = \frac{t_{01}t_{12}e^{-j\beta}}{1 + r_{01}r_{12}e^{-j2\beta}} \tag{2.25}$$

and indicating the plane of incidences as p or s;

$$R_p = \frac{r_{01p} + r_{12p}e^{-j2\beta}}{1 + r_{01p}r_{12p}e^{-j2\beta}} \tag{2.26}$$

$$R_s = \frac{r_{01s} + r_{12s}e^{-j2\beta}}{1 + r_{01s}r_{12s}e^{-j2\beta}} \tag{2.27}$$

$$T_p = \frac{t_{01p}t_{12p}e^{-j\beta}}{1 + r_{01p}r_{12p}e^{-j2\beta}} \tag{2.28}$$

$$T_s = \frac{t_{01s}t_{12s}e^{-j\beta}}{1 + r_{01s}r_{12s}e^{-j2\beta}} \tag{2.29}$$

Fresnel reflection and transmission coefficients at the 0-1 and 1-2 interfaces are more convinientto give in the form of

$$r_{01p} = \frac{N_1 cos\Phi_0 - N_0 cos\Phi_1}{N_1 cos\Phi_0 + N_0 cos\Phi_1} \tag{2.30}$$

$$r_{12p} = \frac{N_2 cos\Phi_1 - N_1 cos\Phi_2}{N_2 cos\Phi_1 + N_1 cos\Phi_2} \tag{2.31}$$

$$r_{01s} = \frac{N_0 cos\Phi_0 - N_1 cos\Phi_1}{N_0 cos\Phi_0 + N_1 cos\Phi_1} \tag{2.32}$$

$$r_{12s} = \frac{N_1 cos\Phi_1 - N_2 cos\Phi_2}{N_1 cos\Phi_1 + N_2 cos\Phi_2} \tag{2.33}$$

$$t_{01p} = \frac{2N_0 cos\Phi_0}{N_1 cos\Phi_0 + N_0 cos\Phi_1} \tag{2.34}$$

$$t_{12p} = \frac{2N_1 cos\Phi_1}{N_2 cos\Phi_1 + N_1 cos\Phi_2} \tag{2.35}$$

$$t_{12s} = \frac{2N_1 cos\Phi_1}{N_1 cos\Phi_1 + N_2 cos\Phi_2} \tag{2.36}$$

Three angles Φ_0, Φ_1 and Φ_2 have the relation

$$N_0 sin\Phi_0 = N_1 sin\Phi_1 = N_2 sin\Phi_2, \tag{2.37}$$

which are linked by the Snell's Law. To examine the change of amplitude and phase seperately, as a plane wave is obliquely reflected from or transmitted by a film covered substrate, the overall complex amplitude and reflection (R_p, R_s) and transmission

(T_p, T_s) coefficients are written in terms of their absolute values and angles as

$$R_p = |R_p|\, e^{j\Delta_{rp}} \tag{2.38}$$

$$R_s = |R_s|\, e^{j\Delta_{rs}} \tag{2.39}$$

$$T_p = |T_p|\, e^{j\Delta_{tp}} \tag{2.40}$$

$$T_s = |T_s|\, e^{j\Delta_{ts}} \tag{2.41}$$

$|R_p|$ and Δ_{rp} represent the amplitude attenuation and phase shift respectively for p-polarization. From measurments of the incident and reflected polarizations, the ratio

$$\rho_r = \frac{R_p}{R_s} \tag{2.42}$$

of the overall complex amplitude reflection coefficients of the ambient-film-substrate system for the p and s polarizations is determined. If we express ρ_r in terms of the ellipsometric angles Ψ and Δ we find

$$tan\Psi_r = \frac{|R_p|}{|R_s|} \tag{2.43}$$

$$\Delta_r = \Delta_{rp} - \Delta_{rs} \tag{2.44}$$

The relation between ellipsometric angles Ψ, Δ and Fresnel reflection coefficients is given as

$$\tan\Psi e^{j\Delta} = \frac{r_{01p} + r_{12p}e^{-j2\beta}}{1 + r_{01p}r_{12p}e^{j2\beta}} \times \frac{1 + r_{01s}r_{12s}e^{-j2\beta}}{r_{01s} + r_{12s}e^{-j2\beta}} \tag{2.45}$$

From equations 2.23 and 2.37;

$$\tan\Psi e^{j\Delta} = \rho(N_0, N_1, N_2, d_1, \phi_0, \lambda) \tag{2.46}$$

breaking into two real equations gives

$$\Psi = \arctan|\rho(N_0, N_1, N_2, d_1, \phi_0, \lambda)| \tag{2.47}$$

$$\Delta = arg\,[\rho(N_0, N_1, N_2, d_1, \phi_0, \lambda)] \tag{2.48}$$

where $|\rho|$ and $[\rho]$ are the absolute value and angle of the complex function ρ, respectively. Equations 2.47 and 2.48 which are not easy to handle with nine parameters(six from N and three from other values) can be solved by a software program included in the ellipsometry [2].

The thickness and refractive index can be extracted from the experimentally measured Ψ and Δ pairs by fitting to a model. The best fit to experimental data is determined by minimizing the MSE(mean square error) which is equal to;

$$MSE = \frac{1}{2N - M_i}\sum\left[\left(\frac{\Psi_i^{mod} - \Psi_i^{exp}}{\sigma_{\Psi,i}^{exp}}\right)^2 + \left(\frac{\Delta_i^{mod} - \Delta_i^{exp}}{\sigma_{\Delta,i}^{exp}}\right)^2\right] \tag{2.49}$$

where N is the number of (Ψ, Δ) pairs, M is the number of variable parameters, σ are the standard deviations of the experimental data points, and the superscripts mod and experimental values respectively. [3]

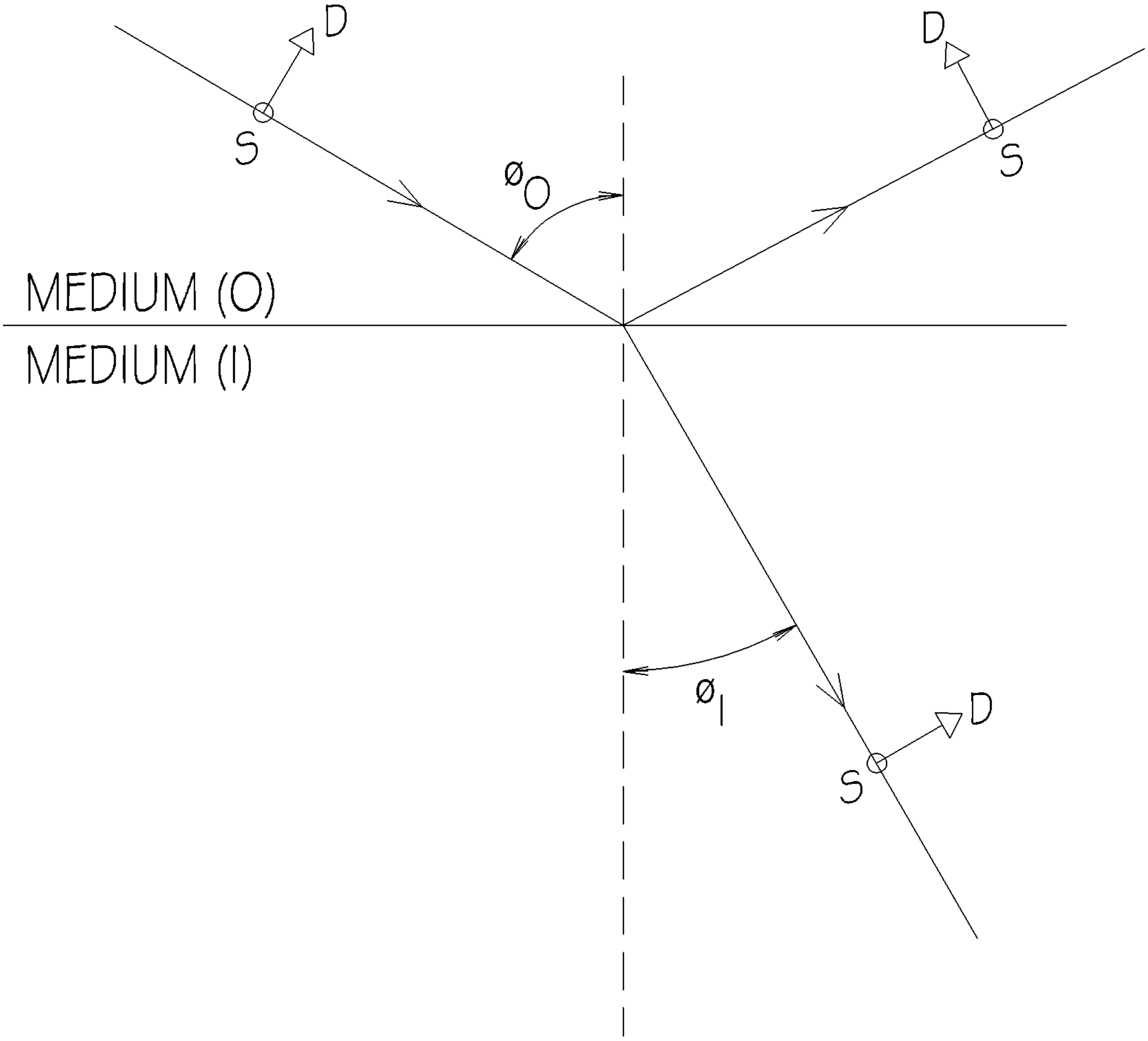


Figure 2.4. Reflection and transmission of a plane wave at the planar interface between two semi-infinite media. p×s gives the direction of propagation.

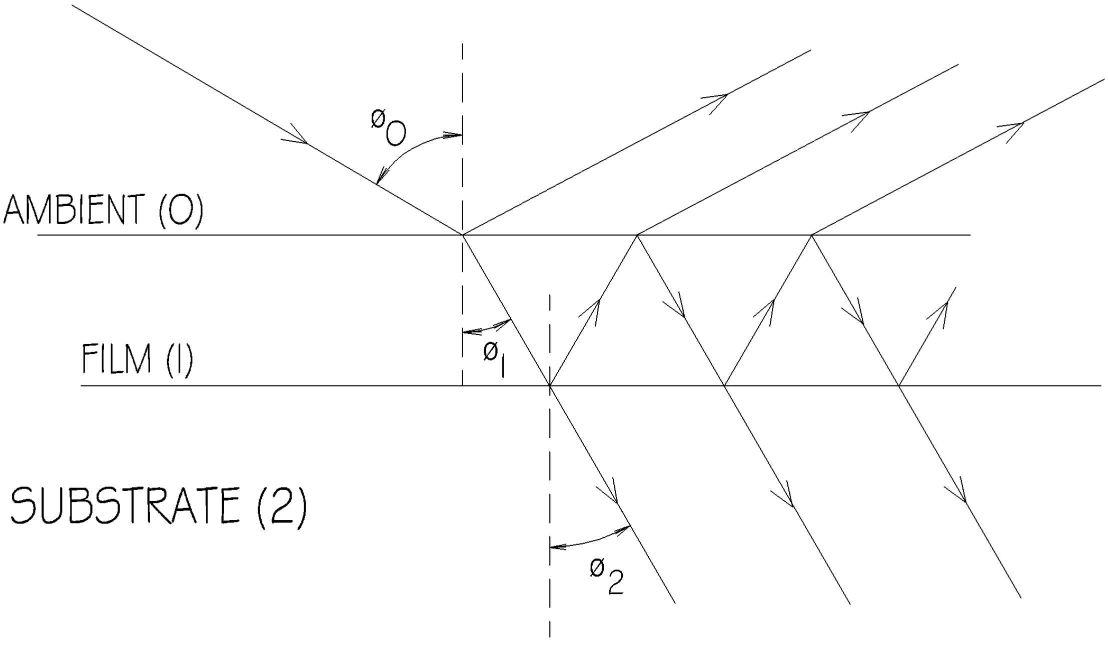


Figure 2.5. Reflection and transmission of a plane wave by an ambient(0)-film(1)-subtrate(2).

3. EXPERIMENT AND RESULTS

3.1. Gold Film Preperation

31 nm thick (measured by ellipsometry) Au layer is evaporated onto BK7 glass by vacuum evaporation technique using an Edwards Coating System (E306A). BK7 glasses are cleaned with acetone and methanol, then they are put into the evaporation machine that includes a holder. Very tiny gold particles cut from a gold plate. Gold is placed into the tunsten boat and is evaporated by the resistive heating [5].

3.2. Peg Film Preperation

1000mg/ml PEG with MW=1000 is dissolved in Choloroform $CHCl_3$ at room temperature. $CHCl_3$ solvent with high volatility is used to decrease the non-homogenety of the PEG film. The gold coated glass surface was blown with nitrogen in order to get rid of small dust particles and placed on a spincoater. The polymer solution was flowed through a GPC filter and dropped on the surface. The substrates were then spin-coated at 500 rpm for 10 seconds and 600 rpm for 30 seconds, respectively. 534 nm films were obtained [4].

3.3. SiO_2 Film

Silicon dioxide film naturally grows on the Si surface due to oxidation as a result of interaction of the Si with atmosphere.

3.4. Optical Setup(Ellipsometry)

Ellipsometry is used for the detrmination of the refractive index and thickness of PEG, SiO_2, Au layers.

Ellipsometry is a device with two arms, one is sending light the other is detecting light with a certain wavelenght; 632.8 nm He-Ne Laser onto the sample of interest.

Angle of incidence can change from 20 to 90 degrees, which can be increased 5 degrees in each step. 90 degree is not used for measurment but for adjustment.

As seen in figure 3.1 laser light source in the first arm follows the optical path and passes through a polarizer prizm. Circularly polarized light is then converted into a linearly polarized form. A constant intensity linearly polarized beam is obtained depending upon the presence of a quarter wave compansator. The usage of this quarter wave compensator is determined by the computer. In the presence of this quarter wave compansator, a circularly polarized beam is obtained. The beam is projected onto the sample of interest. Depending upon the optical properties of the sample, the intensity of the incoming light beam is changed and reflected exactly onto the second arm because angle of incidence and reflectance are adjusted to the same value.

Reflected light passes through rotating analyzer prism and is then sensed by a photodetector. Photodetector converts light energy into the electric current. Before the photodetector, a filter is used to elliminate the light, which has a wavelenght other than the incident wavelenght. A picture of the ellipsometer device we used in our experiments is given in figure 3.2.

3.5. Results

The SiO_2 film used in this work is naturally grown on Si substrate and is measured to have a thickness of 76.63 nm. The value of index of refraction is found to be between 1.458410 and 1.456710.(see figures 3.3 and 3.4). Gold film, coated on BK7 glass is measured to have a thickness of 31.80 nm. Refractive index n has a value of 0.166, where k equals to 3.150(see figures 3.5 and 3.6). Lastly, PEG film on top of BK7+Gold Film system is in situ studied in a relative humidity enviroment to have thicknesses of 534.34 nm, 538.85 nm, 660.70 nm at relative humidities 37% , 50% and 80% respectively(see figures 3.7, 3.8 and 3.9).

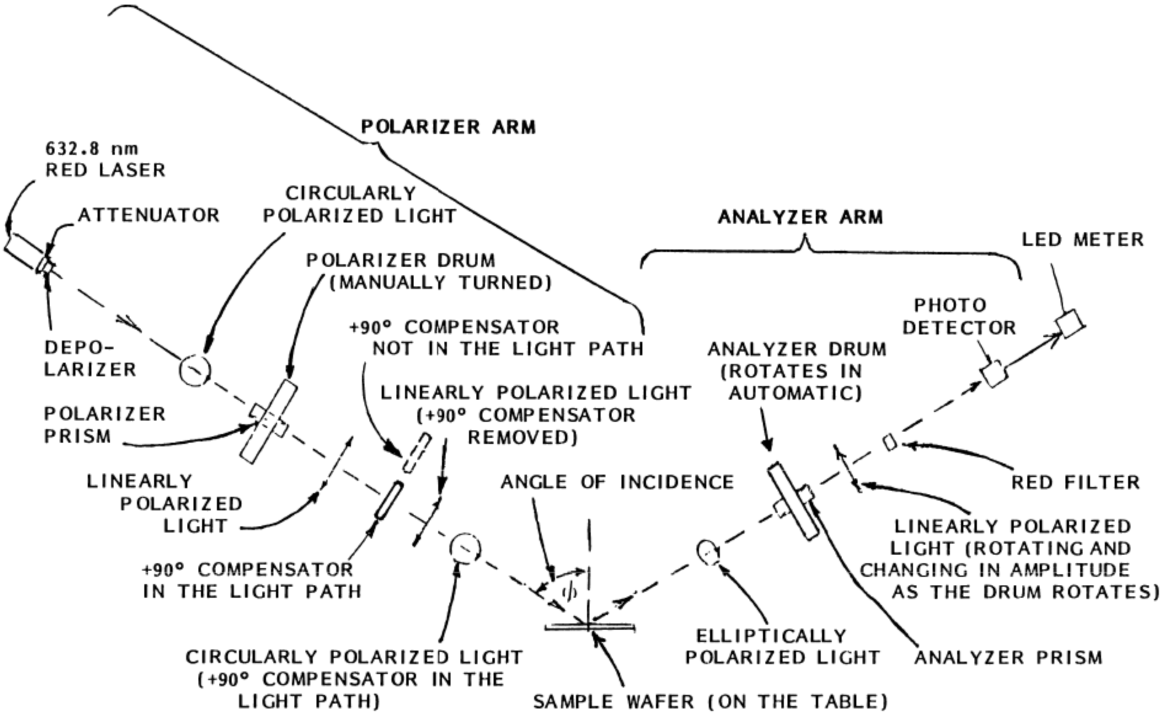
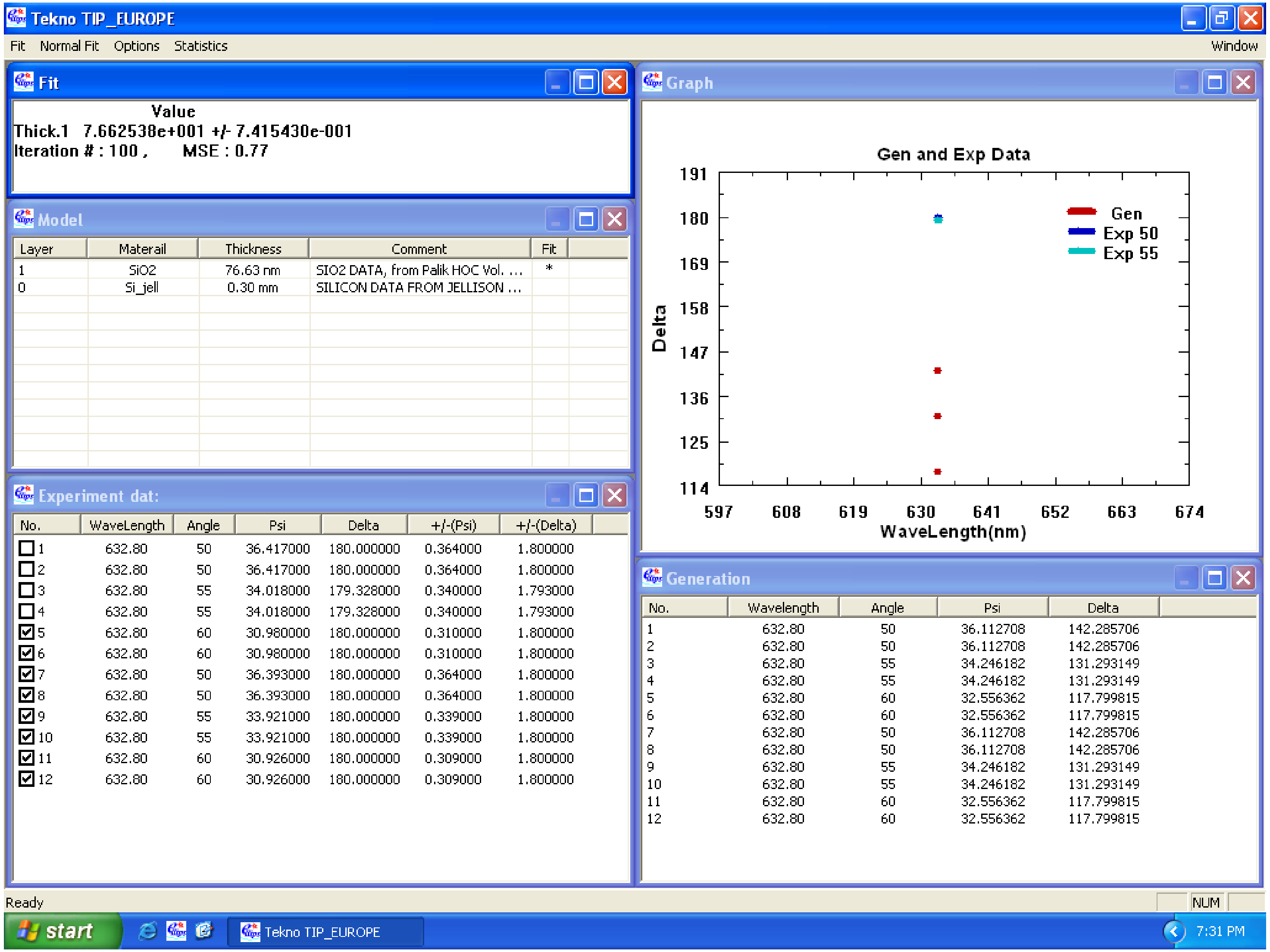


Figure 3.1. Optical setup under the ellipsometry

Figure 3.2. Picture of the ellipsometry used in our experiments



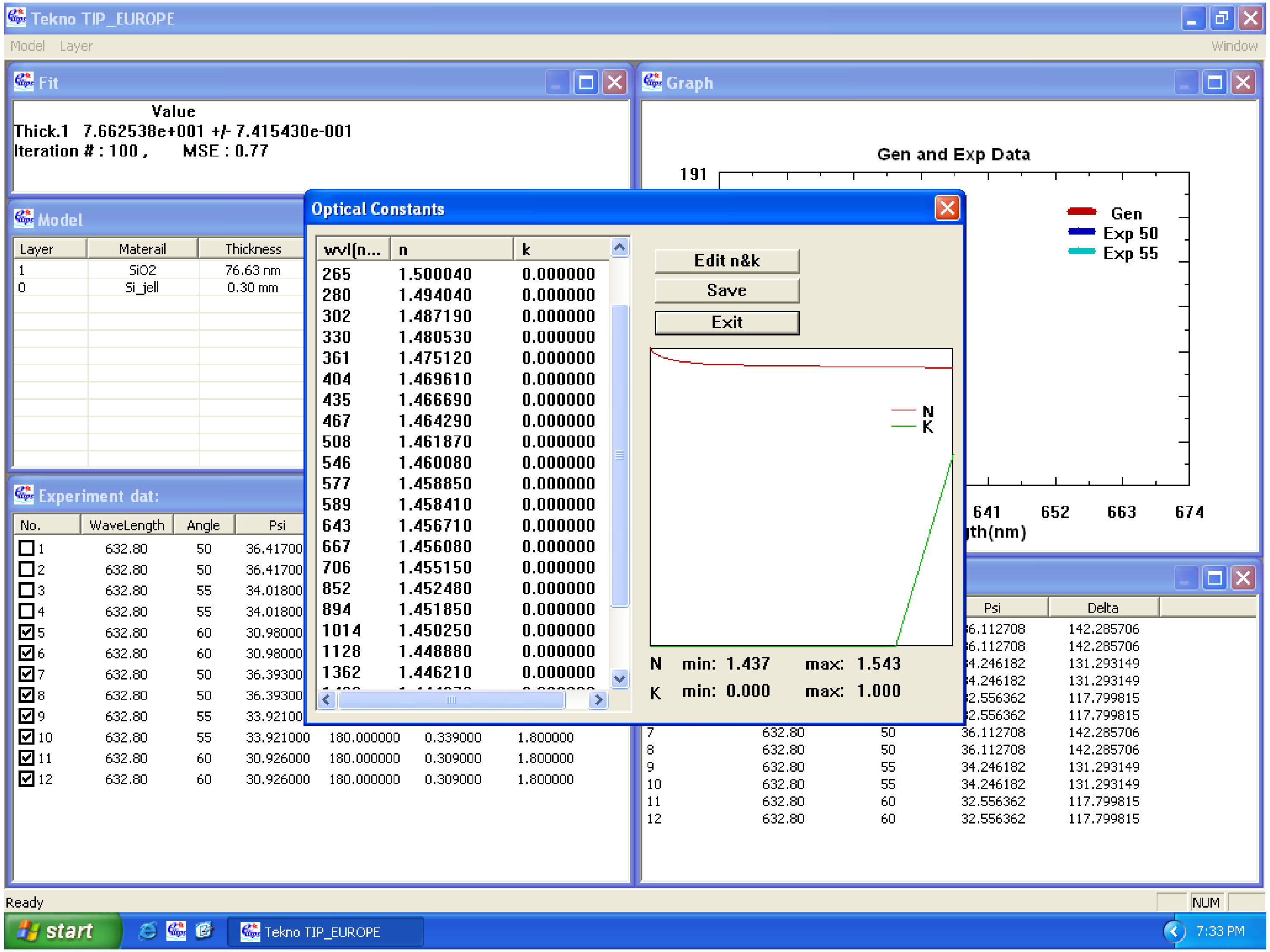
Value
Thick.1 7.662538e+001 +/- 7.415430e-001
Iteration # : 100 , MSE : 0.77

Layer	Materail	Thickness	Comment	Fit
1	SiO2	76.63 nm	SIO2 DATA, from Palik HOC Vol. ...	*
0	Si_jell	0.30 mm	SILICON DATA FROM JELLISON ...	

No.	WaveLength	Angle	Psi	Delta	+/-(Psi)	+/-(Delta)
☐ 1	632.80	50	36.417000	180.000000	0.364000	1.800000
☐ 2	632.80	50	36.417000	180.000000	0.364000	1.800000
☐ 3	632.80	55	34.018000	179.328000	0.340000	1.793000
☐ 4	632.80	55	34.018000	179.328000	0.340000	1.793000
☑ 5	632.80	60	30.980000	180.000000	0.310000	1.800000
☑ 6	632.80	60	30.980000	180.000000	0.310000	1.800000
☑ 7	632.80	50	36.393000	180.000000	0.364000	1.800000
☑ 8	632.80	50	36.393000	180.000000	0.364000	1.800000
☑ 9	632.80	55	33.921000	180.000000	0.339000	1.800000
☑ 10	632.80	55	33.921000	180.000000	0.339000	1.800000
☑ 11	632.80	60	30.926000	180.000000	0.309000	1.800000
☑ 12	632.80	60	30.926000	180.000000	0.309000	1.800000

No.	Wavelength	Angle	Psi	Delta
1	632.80	50	36.112708	142.285706
2	632.80	50	36.112708	142.285706
3	632.80	55	34.246182	131.293149
4	632.80	55	34.246182	131.293149
5	632.80	60	32.556362	117.799815
6	632.80	60	32.556362	117.799815
7	632.80	50	36.112708	142.285706
8	632.80	50	36.112708	142.285706
9	632.80	55	34.246182	131.293149
10	632.80	55	34.246182	131.293149
11	632.80	60	32.556362	117.799815
12	632.80	60	32.556362	117.799815

Figure 3.3. Thickness calculation of SiO_2 film



Value
Thick.1 7.662538e+001 +/- 7.415430e-001
Iteration # : 100 , MSE : 0.77

Layer	Materail	Thickness
1	SiO2	76.63 nm
0	Si_jell	0.30 mm

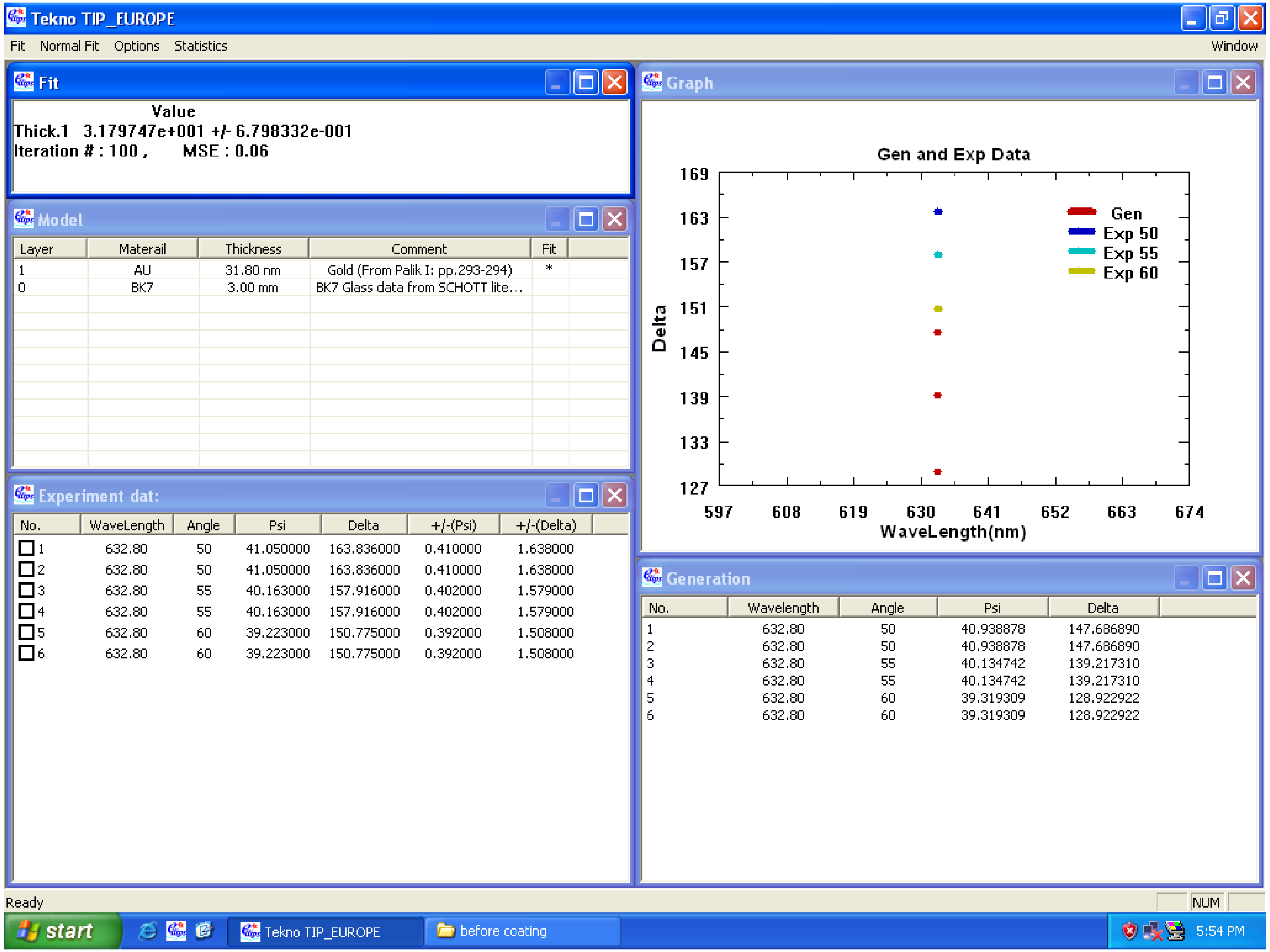
No.	WaveLength	Angle	Psi			
☐ 1	632.80	50	36.41700			
☐ 2	632.80	50	36.41700			
☐ 3	632.80	55	34.01800			
☐ 4	632.80	55	34.01800			
☑ 5	632.80	60	30.98000			
☑ 6	632.80	60	30.98000			
☑ 7	632.80	50	36.39300			
☑ 8	632.80	50	36.39300			
☑ 9	632.80	55	33.92100			
☑ 10	632.80	55	33.921000	180.000000	0.339000	1.800000
☑ 11	632.80	60	30.926000	180.000000	0.309000	1.800000
☑ 12	632.80	60	30.926000	180.000000	0.309000	1.800000

wvl(n...	n	k
265	1.500040	0.000000
280	1.494040	0.000000
302	1.487190	0.000000
330	1.480530	0.000000
361	1.475120	0.000000
404	1.469610	0.000000
435	1.466690	0.000000
467	1.464290	0.000000
508	1.461870	0.000000
546	1.460080	0.000000
577	1.458850	0.000000
589	1.458410	0.000000
643	1.456710	0.000000
667	1.456080	0.000000
706	1.455150	0.000000
852	1.452480	0.000000
894	1.451850	0.000000
1014	1.450250	0.000000
1128	1.448880	0.000000
1362	1.446210	0.000000

N min: 1.437 max: 1.543
K min: 0.000 max: 1.000

			Psi	Delta
			6.112708	142.285706
			6.112708	142.285706
			4.246182	131.293149
			4.246182	131.293149
			2.556362	117.799815
			2.556362	117.799815
7	632.80	50	36.112708	142.285706
8	632.80	50	36.112708	142.285706
9	632.80	55	34.246182	131.293149
10	632.80	55	34.246182	131.293149
11	632.80	60	32.556362	117.799815
12	632.80	60	32.556362	117.799815

Figure 3.4. n calculation of SiO_2 film



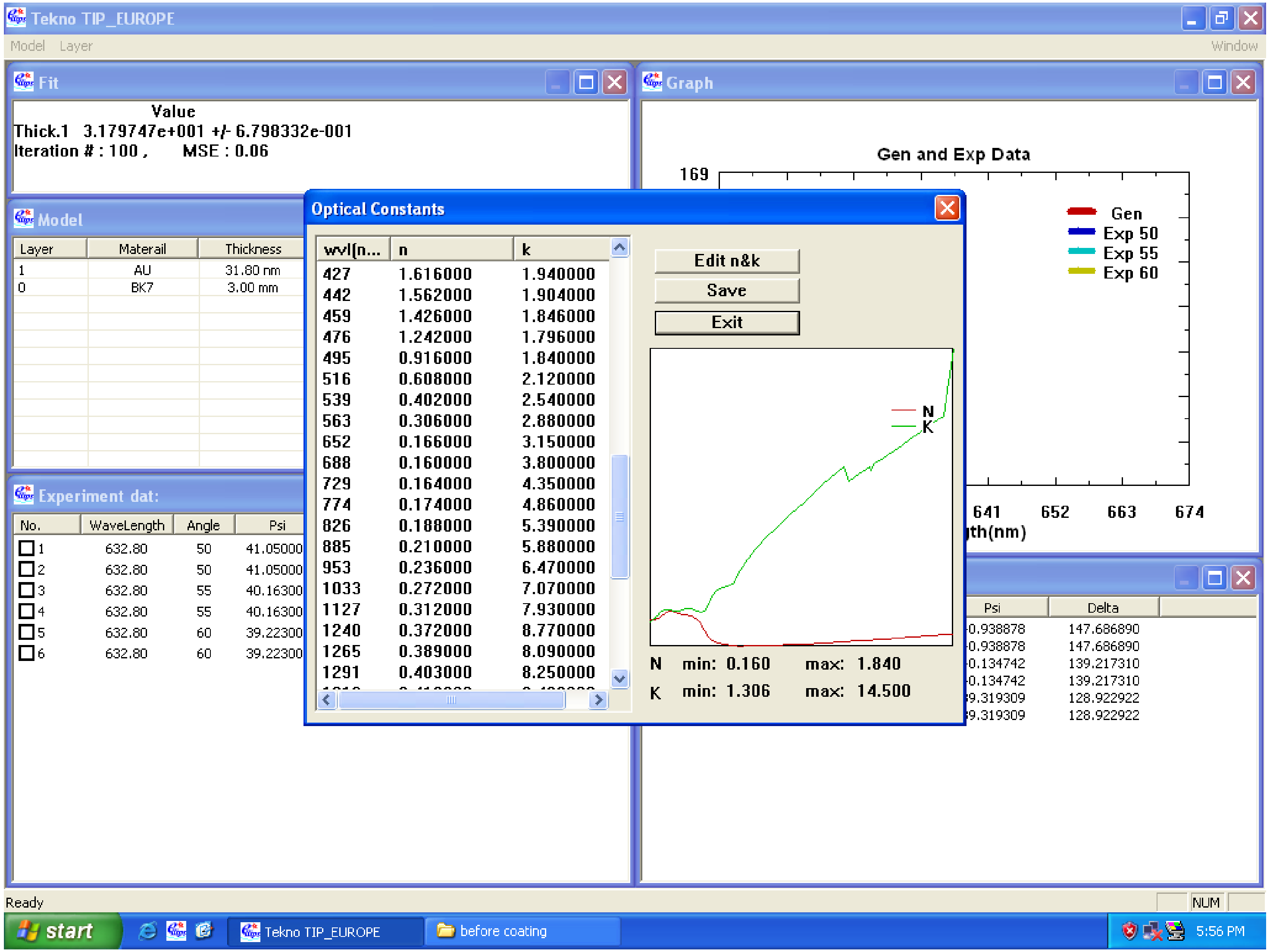
Value
Thick.1 3.179747e+001 +/- 6.798332e-001
Iteration # : 100 , MSE : 0.06

Layer	Materail	Thickness	Comment	Fit
1	AU	31.80 nm	Gold (From Palik I: pp.293-294)	*
0	BK7	3.00 mm	BK7 Glass data from SCHOTT lite…	

No.	WaveLength	Angle	Psi	Delta	+/-(Psi)	+/-(Delta)
☐ 1	632.80	50	41.050000	163.836000	0.410000	1.638000
☐ 2	632.80	50	41.050000	163.836000	0.410000	1.638000
☐ 3	632.80	55	40.163000	157.916000	0.402000	1.579000
☐ 4	632.80	55	40.163000	157.916000	0.402000	1.579000
☐ 5	632.80	60	39.223000	150.775000	0.392000	1.508000
☐ 6	632.80	60	39.223000	150.775000	0.392000	1.508000

No.	Wavelength	Angle	Psi	Delta
1	632.80	50	40.938878	147.686890
2	632.80	50	40.938878	147.686890
3	632.80	55	40.134742	139.217310
4	632.80	55	40.134742	139.217310
5	632.80	60	39.319309	128.922922
6	632.80	60	39.319309	128.922922

Figure 3.5. Thickness calculation of Au film



Value
Thick.1 3.179747e+001 +/- 6.798332e-001
Iteration # : 100 , MSE : 0.06

Layer	Materail	Thickness
1	AU	31.80 nm
0	BK7	3.00 mm

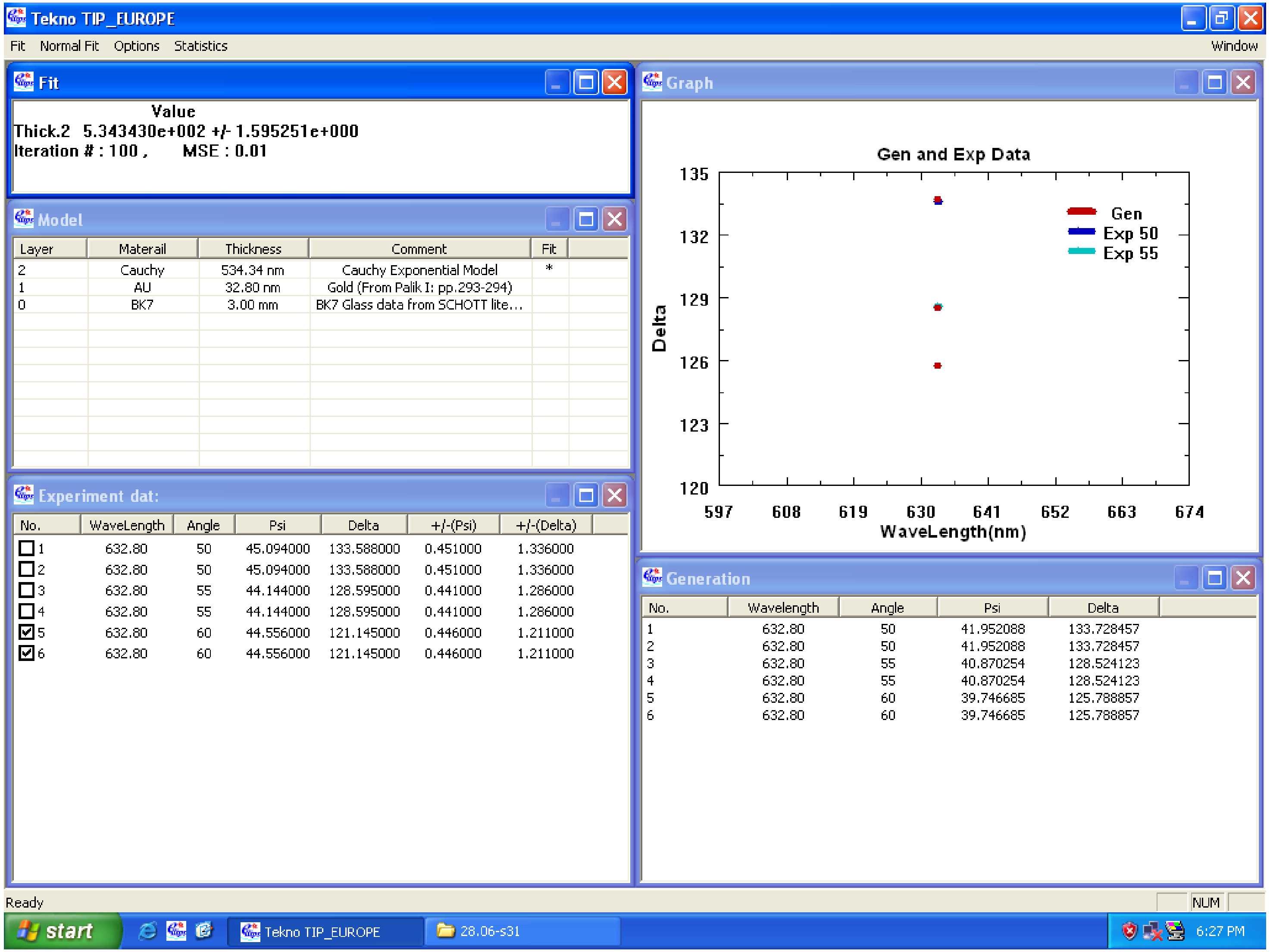
No.	WaveLength	Angle	Psi
☐ 1	632.80	50	41.05000
☐ 2	632.80	50	41.05000
☐ 3	632.80	55	40.16300
☐ 4	632.80	55	40.16300
☐ 5	632.80	60	39.22300
☐ 6	632.80	60	39.22300

Psi	Delta
0.938878	147.686890
0.938878	147.686890
0.134742	139.217310
0.134742	139.217310
9.319309	128.922922
9.319309	128.922922

wvl(n...	n	k
427	1.616000	1.940000
442	1.562000	1.904000
459	1.426000	1.846000
476	1.242000	1.796000
495	0.916000	1.840000
516	0.608000	2.120000
539	0.402000	2.540000
563	0.306000	2.880000
652	0.166000	3.150000
688	0.160000	3.800000
729	0.164000	4.350000
774	0.174000	4.860000
826	0.188000	5.390000
885	0.210000	5.880000
953	0.236000	6.470000
1033	0.272000	7.070000
1127	0.312000	7.930000
1240	0.372000	8.770000
1265	0.389000	8.090000
1291	0.403000	8.250000

N min: 0.160 max: 1.840
K min: 1.306 max: 14.500

Figure 3.6. n and k calculation of Au film



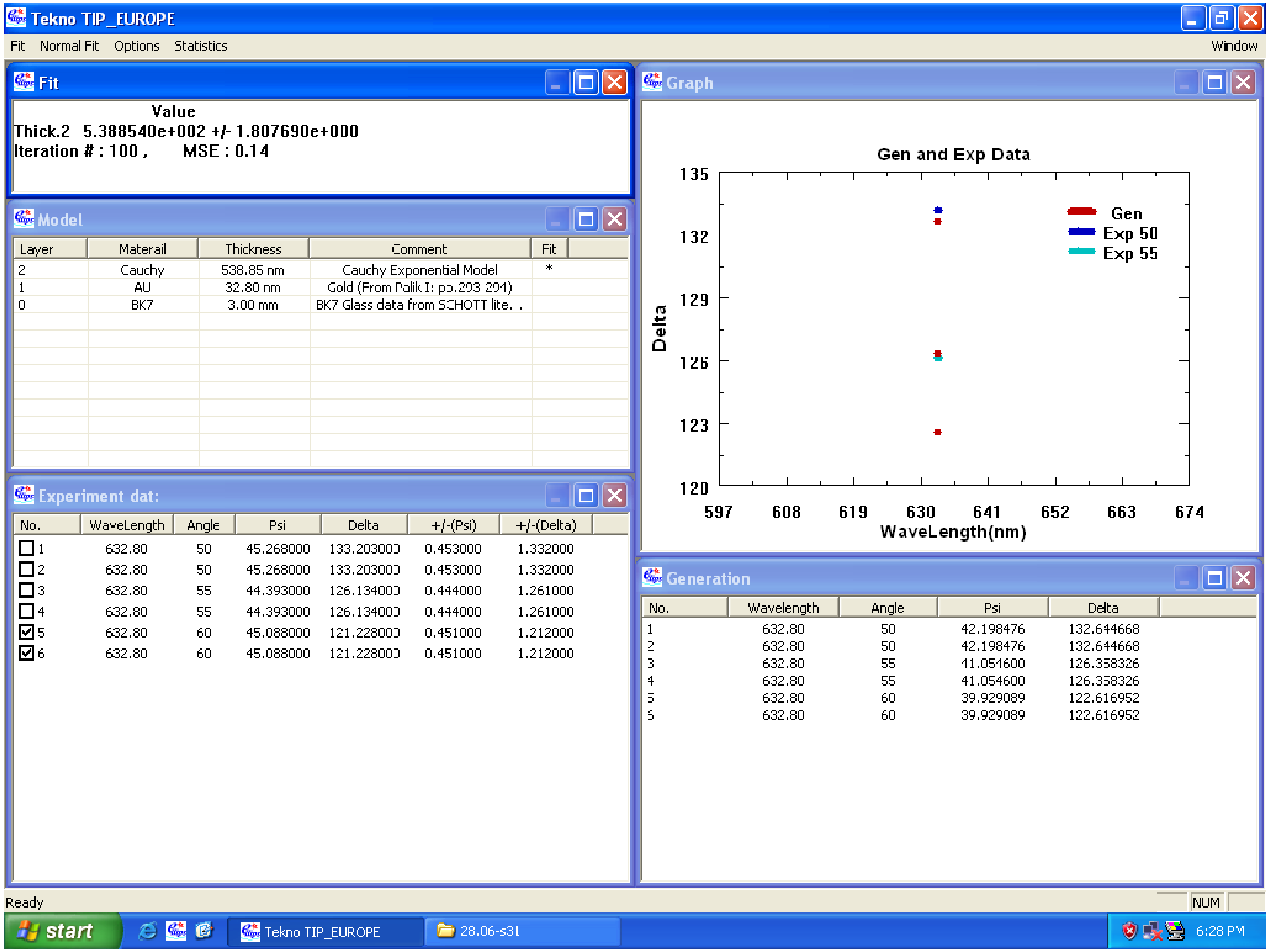
Value
Thick.2 5.343430e+002 +/- 1.595251e+000
Iteration # : 100 , MSE : 0.01

Layer	Materail	Thickness	Comment	Fit
2	Cauchy	534.34 nm	Cauchy Exponential Model	*
1	AU	32.80 nm	Gold (From Palik I: pp.293-294)	
0	BK7	3.00 mm	BK7 Glass data from SCHOTT lite...	

No.	WaveLength	Angle	Psi	Delta	+/-(Psi)	+/-(Delta)
☐ 1	632.80	50	45.094000	133.588000	0.451000	1.336000
☐ 2	632.80	50	45.094000	133.588000	0.451000	1.336000
☐ 3	632.80	55	44.144000	128.595000	0.441000	1.286000
☐ 4	632.80	55	44.144000	128.595000	0.441000	1.286000
☑ 5	632.80	60	44.556000	121.145000	0.446000	1.211000
☑ 6	632.80	60	44.556000	121.145000	0.446000	1.211000

No.	Wavelength	Angle	Psi	Delta
1	632.80	50	41.952088	133.728457
2	632.80	50	41.952088	133.728457
3	632.80	55	40.870254	128.524123
4	632.80	55	40.870254	128.524123
5	632.80	60	39.746685	125.788857
6	632.80	60	39.746685	125.788857

Figure 3.7. Thickness calculation of PEG film at 37% humidity



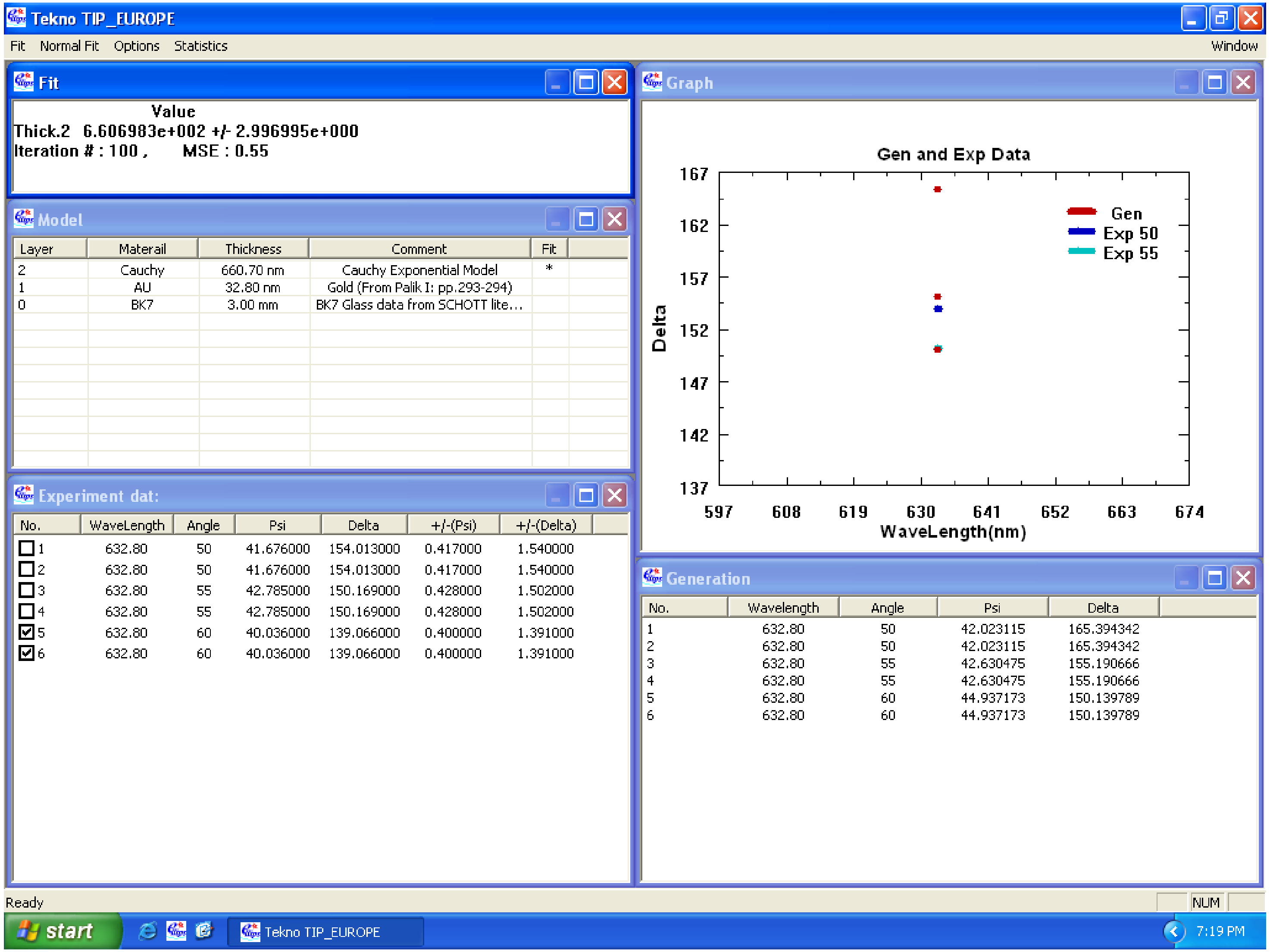
Value
Thick.2 5.388540e+002 +/- 1.807690e+000
Iteration # : 100 , MSE : 0.14

Layer	Materail	Thickness	Comment	Fit
2	Cauchy	538.85 nm	Cauchy Exponential Model	*
1	AU	32.80 nm	Gold (From Palik I: pp.293-294)	
0	BK7	3.00 mm	BK7 Glass data from SCHOTT lite...	

No.	WaveLength	Angle	Psi	Delta	+/-(Psi)	+/-(Delta)
☐ 1	632.80	50	45.268000	133.203000	0.453000	1.332000
☐ 2	632.80	50	45.268000	133.203000	0.453000	1.332000
☐ 3	632.80	55	44.393000	126.134000	0.444000	1.261000
☐ 4	632.80	55	44.393000	126.134000	0.444000	1.261000
☑ 5	632.80	60	45.088000	121.228000	0.451000	1.212000
☑ 6	632.80	60	45.088000	121.228000	0.451000	1.212000

No.	Wavelength	Angle	Psi	Delta
1	632.80	50	42.198476	132.644668
2	632.80	50	42.198476	132.644668
3	632.80	55	41.054600	126.358326
4	632.80	55	41.054600	126.358326
5	632.80	60	39.929089	122.616952
6	632.80	60	39.929089	122.616952

Figure 3.8. Thickness calculation of PEG film at 50% humidity



```
            Value
Thick.2   6.606983e+002 +/- 2.996995e+000
Iteration # : 100 ,      MSE : 0.55
```

Layer	Materail	Thickness	Comment	Fit
2	Cauchy	660.70 nm	Cauchy Exponential Model	*
1	AU	32.80 nm	Gold (From Palik I: pp.293-294)	
0	BK7	3.00 mm	BK7 Glass data from SCHOTT lite...	

No.	WaveLength	Angle	Psi	Delta	+/-(Psi)	+/-(Delta)
☐ 1	632.80	50	41.676000	154.013000	0.417000	1.540000
☐ 2	632.80	50	41.676000	154.013000	0.417000	1.540000
☐ 3	632.80	55	42.785000	150.169000	0.428000	1.502000
☐ 4	632.80	55	42.785000	150.169000	0.428000	1.502000
☑ 5	632.80	60	40.036000	139.066000	0.400000	1.391000
☑ 6	632.80	60	40.036000	139.066000	0.400000	1.391000

No.	Wavelength	Angle	Psi	Delta
1	632.80	50	42.023115	165.394342
2	632.80	50	42.023115	165.394342
3	632.80	55	42.630475	155.190666
4	632.80	55	42.630475	155.190666
5	632.80	60	44.937173	150.139789
6	632.80	60	44.937173	150.139789

Figure 3.9. Thickness calculation of PEG film at 80% humidity

4. CONCLUSION

In this study, physical and optical properties of thin films are measured. Thickness of PEG film is measured at three different relative humidity levels. In many experimental work, film thickness is an important quantitiy. For some experiments, determination of thickness is the aim of the experiment while an intermediate step for some others. Ellipsometry provides quick, non-damaging, sensitive measurements.

Ellipsometry provides a straightforward and practical advantage for in situ measurments of n and d, which can be very useful for a future work.In this work, thickness of a PEG film is in situ measured at only three different values. However, this range can be extended further and as a future work, different kinds of polymer films can be set into a special chamber the humidity level may be extended from 10% to 100% to compare films and their values with each other. This technique can be interrogated in conjuction with other optical measurments such as optical sensors where changes of refractive index and thickness are desirable.

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