Thin Film Measurement

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Abstract: The most efficient way to measure thickness of a semi-conductor sample and it's insulation layer, is to use Fizeau technique and Ellipsometry; Michelson provide more accurate value, but is more complicated.

Introduction:

As semi-conductor technologies getting more and more advance everyday, the thickness the integrated circuit masking are getting thinner and thinner. And the thickness of the thin film is crucial. Therefore, an accurate measurement is required. Consider the thickness of the masking is in atom-size scale, normal mechanical measurement will never be able to provide a value. Consequently, optical measurements are being use.

In this experiment, one had tested several method of thin film thickness measuring. These methods included using Michelson Technique, Fizeau Technique, and Ellipsometry technique.

Methods and Theories:

Three different techniques had been used in this laboratory, Michelson, Fizeau, and Ellipsometry. For Michelson and Fizeau, Light interference was being used; for Ellipsometry, Polarization was being used.

In 1887, Albert Michelson and Edward Morley had built an interferometer in order to detect the earth's motion through the ether optically (Pedrotti, 3). However, it turns out that this device can be very useful in measurement of atom scale objects.

The setup in this laboratory, the Michelson interferometer was setup as follow (fig 1):

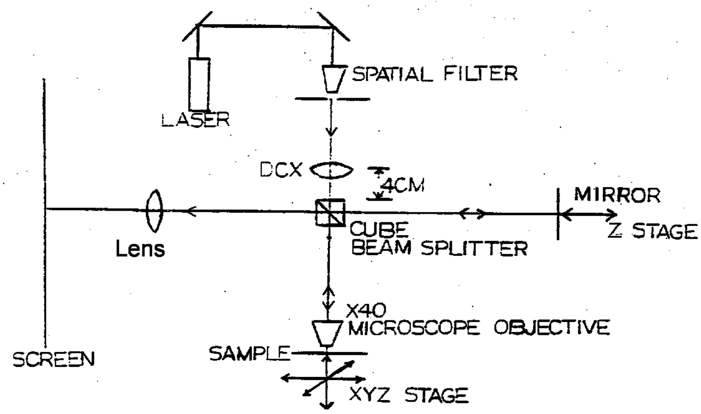

Fig 1: Lab Setup for Michelson interferometer (Lab, 2)

[Modified with extra lens before screen]

If the microscope objective and if the samples is replaced by a mirror, then an interference pattern will appear on the screen (Fig. 2) once the path difference between the two reflected beam equal zero (Pedrotti 227). However, due to the fact that the sample consists of masking that have a very small, but finite thickness. There should be a small path difference between the mask and the base of the sample. As a result, the interference pattern will have a step when the edge of the mask is being project to the screen.

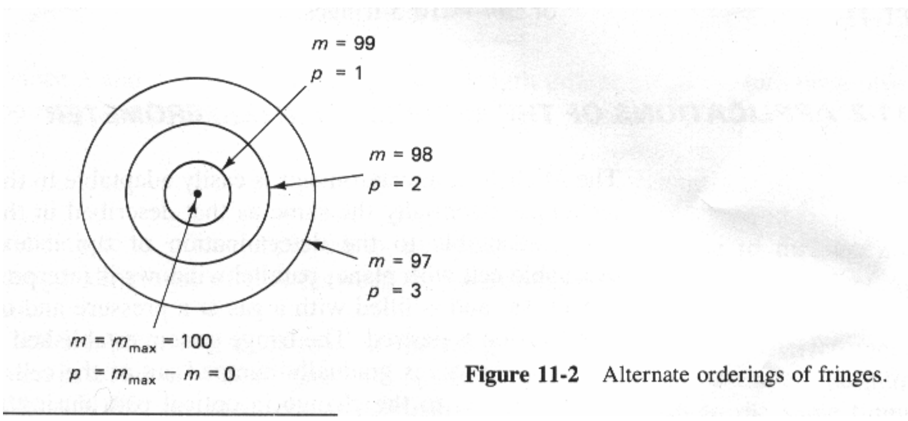

Figure 11-2 Alternate orderings of fringes.

Fig 2: Interference pattern expected to see on the screen. (Pedrotti, 227)

The finite thickness of the thin film will create a path difference to the light. And therefore one can first the base to be zero path length, then measure how much does it require to move backward to get zero path length for the film. Then the change will be proportional to the thickness. The thickness and the change in position is proportional the magnification and the refractive index of oxide on the sample, which is equal to 1.46.

$$thickness = \frac{change\_in\_micrometer\_position}{magnification \times \eta_{oxide}}$$

Equation 1: Equation used in Michelson technique (Lab, 2)

Fizeau fringes were usually appeared in air wedge. It appears due to the reflection of two or more surfaces interfere with each other. However, whenever there is a small step on the masking, it will display on the screen as well. With this technique, the thickness of the mask, or depth of a defect can be measure. The technique was widely used in the industries to measure the thickness of substrate.

The basic idea of setup of the Fizeau technique is shown in fig 3. Since the thickness of the mask had introduced a small path difference, a small bump will appear along with the interference pattern. The expected pattern should be similar to fig 4.

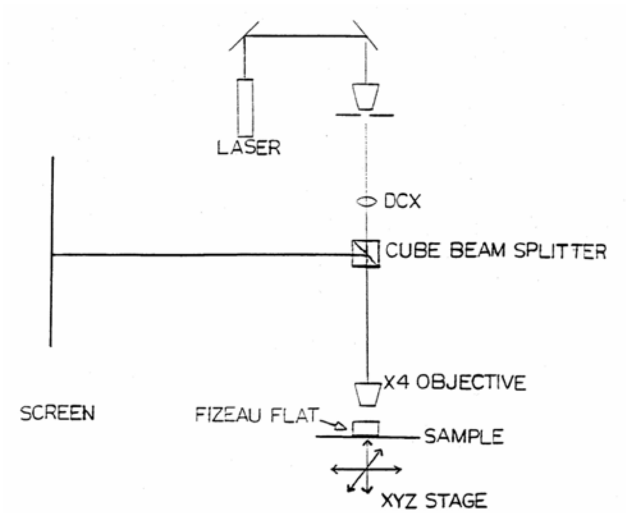

Fig 3, Setup for Fizeau technique of thickness measuring (Lab, 3)

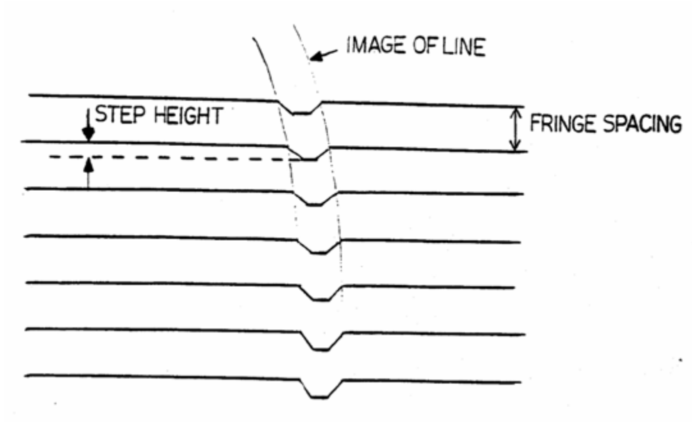

Fig 4: Expected pattern in Fizeau measurement technique (Lab, 4)

$$Film\_Thickness = 3164 \times \frac{Step\_height}{Fringe\_spacing}$$

Equation 2: Equation to be used in Fizeau interference measurement technique (Lab, 4)

Metal oxide is usually grown on top of the circuits in order to provide insulation. The thickness of the oxide is very essential; however, one would also like to ignore the integrated circuit structure itself. This could be done by using an ellipsometer (Lab, 5).

The setup of the Ellipsometry is shown in figure 5. A mercury green line of 546.07nm was being use as the light source. After the polarized light passed through the compensator (birefringent plate), light will be converted to elliptically polarized. However, after the light reflected off the sample oxide layer, it will become linear polarized again. Moreover, the polarization axis can be determine by rotating the analyser (another linear polarizer), maximum intensity will occur when the analyser transmission axis is parallel to the polarization of the light (Lab 6-7)

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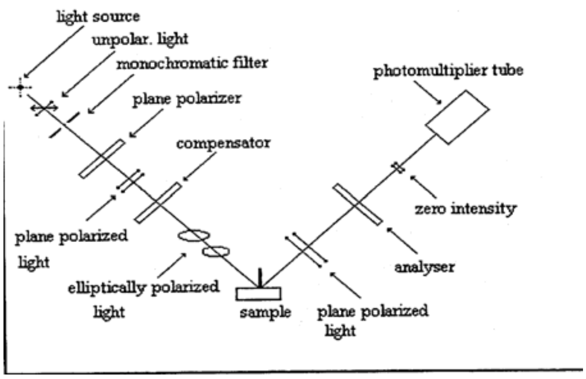

Fig 5: Setup of the ellipsometer (Lab, 7)

The calculation of δ (defined below) can be complicated, and therefore, a table of value was being used (refer to appendix A), given that Δ, ϕ, angle of incidence, refractive indices of the substrate and wavelength is known. (Lab, 7-10)

$$\delta = (\frac{360}{\lambda})d(n_1^2 - \sin^2\phi)^{1/2}$$
$$\Rightarrow d = \delta(\frac{\lambda}{360})(n_1^2 - \sin^2\phi)^{-1/2}$$

Equation 3: Definition of δ (Lab, 9)

$$\Delta = \frac{\pi}{2} - 2P$$
$$\Psi = -A_p = A_S$$

Equations 4: Definitions of Delta and Psi (Lab 7)

Experimental Results:

In terms of Michelson technique, the experiment was not successful. An interference pattern was observed, however, one was not able to measure the change in path length due to the limitation of the equipment. Detail will be explained in discussions part.

On the other hand, by using the Fizeau technique, a result as expected in theory was observed. A picture of the pattern was taken in the lab (Fig. 6), the step height was found to be 28 pixels, and the fringe spacing was found to be 45 pixels.

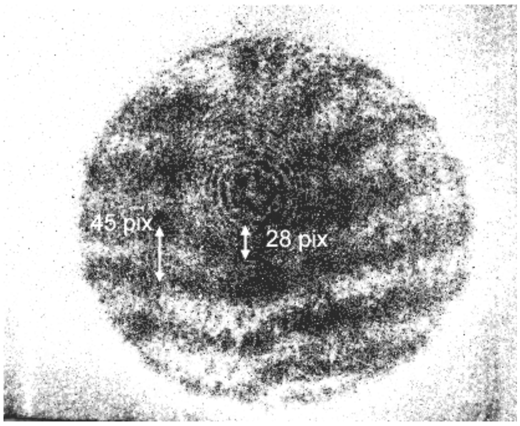

Fig 6: Interference pattern observed using Fizeau technique.

With equation 2 above, the film thickness was found to be 196.8nm.

In term of Ellipsometry, the data were collected and tabulated as follow:

	Sample #1	Sample #3	Sample X
Index of refraction	1.47	1.8	1.6
Compensator Angle	315 °	315°	315°
Polarizer Angle	0°	0°	0°
Analyser Angle	132±2°	330±2°	318±2°
Angle of incidence	69°	69°	69°
Small Delta (From table)	107-140°	130-140°	113-140°
Thickness(from Equation 3)	142.9-187.0nm	128.1-138.0nm	131.9-163.4nm

Table 1: Experimental result for Ellipsometry

With equations 4 above, the Capital Delta is found to be $1/2\pi$, Ψ= 132° and 350° for sample 1 and 3 respectively. According to the table of small delta and equation 3, one can easily found the thickness of the oxide. The values are shown in table 1.

Discussions:

The failure of the Michelson technique in this laboratory is due to the limitation of the equipment. In this experiment, the path length was changed by a micrometer; however, the smallest scale on the micrometer is 1/100mm. On the other hand, the thickness is in the order of hundreds of angstrom. As one can see, the measurement is much smaller than the scale the equipment can be measure. As a result, measurement cannot be made (3W04). However, if limitation of equipment were allowed, a precise measurement could be made.

Comparing between the Michelson and Fizeau techniques, the advantage of Michelson its it provide a more accurate measurement, since there are no measurement of the pattern were involve. While the Fizeau technique is rather hard to justify where the maximum and minimum of are each fringes located.

However, on the other hand, the Fizeau technique is much easier to setup. Because the sample in Michelson was magnified 40 times, a small movement or misalignment will destroy the interference pattern. Moreover, the Fizeau does not require adjustment to achieve zero path length. Where in Michelson case requires a long time to find effective zero paths difference (since the objective will introduce an extra distance due to higher refractive index).

For Ellipsometry, it is used for measuring the thickness of the oxide layer on top of the circuit. Due to the complicity of the equations, a table was used. Since it is impossible to include all the value in a table, accuracy had decreased. After one simplified the equations, it will end up with an equation with different unknown in the exponential function (Appendix B). The only way to solve it is by trial and error, by comparing the value in the exponential, and that can be easily done with computer. With computer, using Newton method (Mathews & Fink, 70-80), an accurate answer can be found.

With the use of table or computer, thickness of the oxide can be calculated very easily with Ellipsometry.

Conclusions:

In conclusion, the Michelson method is the most complicated to setup, however, it provide more accurate value of calculations. The most efficient way to gather information of a semi-conductor is to use Fizeau technique to measure the thickness circuit and use Ellipsometry to measure the thickness of the oxide.

Work Cited

3W04, Dr. D. Cassidy, Course notes.

Lab Manual, Engineering Physics 4U04

Pedrotti, F and Pedrotti, L. Introduction to Optics, Prentice-Hall Inc. New Jersey, 1993

Mathews, J and Fink, K. Numerical Methods using MATLAB. Prentice-Hall Inc. Upper Saddle River, 1992

Appendix A: Table of Small Delta

Δ and ψ as Functions of n_1 and δ (small delta) for Transparent Films on Silicon. n(Si) = 4.050 − 0.028i, ϕ = 70.00° and λ = 5461 Å

INDEX OF REFRACTION—	1.10		1.20		1.30		1.40		1.50		1.60		1.70
SMALL DELTA	DELTA	PSI	DELTA	PSI	DELTA	PSI	DELTA	PSI	DELTA	PSI	DELTA	PSI	DELTA
0.	179.050	11.760	179.050	11.760	179.050	11.760	179.050	11.760	179.050	11.760	179.050	11.760	179.050
0.05	178.906	11.761	178.859	11.761	178.842	11.761	178.838	11.761	178.841	11.761	178.847	11.761	178.856
0.25	178.334	11.763	178.099	11.764	178.012	11.764	177.992	11.764	178.006	11.764	178.039	11.763	178.041
0.50	177.619	11.767	177.149	11.769	176.975	11.770	176.934	11.770	176.963	11.770	177.028	11.769	177.114
2.50	171.938	11.859	169.621	11.904	168.762	11.919	168.558	11.917	168.692	11.906	169.607	11.892	169.424
5.00	165.059	12.116	160.592	12.284	158.932	12.336	158.515	12.329	158.738	12.291	159.312	12.239	160.065
7.50	158.587	12.521	152.242	12.873	149.869	12.981	149.222	12.965	149.465	12.887	150.208	12.778	151.242
10.00	152.640	13.053	144.722	13.635	141.727	13.812	140.833	13.787	141.024	13.659	141.856	13.481	143.024
12.50	147.282	13.694	138.070	14.533	134.532	14.786	133.374	14.750	133.449	14.568	134.243	14.315	135.485
15.00	142.528	14.421	132.250	15.533	128.226	15.864	126.791	15.818	126.700	15.581	127.403	15.249	128.617
17.50	138.360	15.216	127.189	16.604	122.717	17.013	120.991	16.957	120.697	16.667	121.259	16.257	122.380
20.00	134.745	16.062	122.803	17.722	117.904	18.207	115.877	18.143	115.352	17.082	115.733	17.317	116.716
22.50	131.641	16.943	119.011	18.868	113.693	19.426	111.354	19.356	110.578	18.968	110.751	18.412	111.562
25.00	129.006	17.849	115.741	20.029	110.006	20.656	107.344	20.582	106.301	20.151	106.245	19.529	106.857
27.50	126.800	18.769	112.933	21.194	106.778	21.888	103.781	21.811	102.455	21.341	102.153	20.659	102.548
30.00	124.991	19.696	110.543	22.356	103.957	23.115	100.612	23.037	98.990	22.534	98.427	21.796	98.588
32.50	123.551	20.625	108.532	23.510	101.501	24.333	97.796	24.258	95.863	23.725	95.026	22.937	94.937
35.00	122.457	21.551	106.875	24.656	99.389	25.543	95.302	25.474	93.042	24.915	91.914	24.081	91.562
37.50	121.693	22.471	105.554	25.794	97.591	26.746	93.105	26.686	90.501	26.106	89.066	25.230	88.455
40.00	121.247	23.383	104.549	26.924	96.096	27.946	91.189	27.899	88.219	27.302	86.459	26.388	85.534
42.50	121.112	24.287	103.864	28.052	94.895	29.149	89.543	29.121	86.183	28.510	84.076	27.561	82.857
45.00	121.283	25.182	103.494	29.180	93.986	30.364	88.158	30.359	84.380	29.739	81.902	28.757	80.528
47.50	121.761	26.068	103.443	30.316	93.371	31.599	87.033	31.627	82.805	31.000	79.926	29.986	77.590
50.00	122.547	26.946	103.723	31.467	93.058	32.866	86.170	32.938	81.451	32.310	78.136	31.264	75.811
52.50	123.646	27.815	104.347	32.640	93.058	34.181	85.575	34.308	80.317	33.684	76.523	32.606	73.773
55.00	125.064	28.677	105.335	33.846	93.392	35.559	85.256	35.760	79.402	35.145	75.078	34.033	71.859
57.50	126.811	29.530	106.712	35.092	94.082	37.020	85.228	37.318	78.707	36.720	73.788	35.571	70.050
60.00	128.896	30.375	108.510	36.390	95.162	38.587	85.509	39.013	78.231	38.441	72.640	37.249	68.320
62.50	131.326	31.208	110.768	37.747	96.674	40.283	86.126	40.879	77.978	40.348	71.613	39.166	66.635
65.00	134.112	32.026	113.531	39.171	98.673	42.137	87.111	42.961	77.946	42.489	70.679	41.185	64.946
67.50	137.260	32.824	116.853	40.666	101.233	44.176	88.510	45.308	78.135	44.921	69.793	43.540	63.186
70.00	140.773	33.594	120.797	42.228	104.450	46.426	90.389	47.975	78.538	47.713	68.890	46.231	61.258
72.50	144.648	34.326	125.431	43.845	108.458	48.906	92.846	51.024	79.144	50.942	67.864	49.325	59.017
75.00	148.879	35.007	130.829	45.490	113.443	51.617	96.035	54.512	79.933	54.694	66.545	52.890	56.246
77.50	153.445	35.623	137.059	47.117	119.662	54.527	100.222	58.481	80.868	59.053	64.642	56.979	52.613
80.00	158.320	36.157	144.168	48.658	127.464	57.545	105.896	62.931	81.884	64.087	61.627	61.603	47.098
82.50	163.461	36.594	152.161	50.020	137.280	60.489	114.041	67.761	82.847	69.826	56.454	65.668	40.463
85.00	168.816	36.916	160.961	51.099	149.515	63.060	126.768	72.655	83.395	76.224	46.899	71.847	30.169
85.50	169.907	36.966	162.804	51.272	152.268	63.495	130.196	73.584	83.370	77.572	44.111	72.835	27.647
86.00	171.004	37.011	164.671	51.428	155.119	63.894	134.019	74.476	83.256	78.939	40.922	73.785	24.961
86.50	172.105	37.050	166.559	51.567	158.064	64.255	138.286	75.318	83.010	80.323	37.279	74.683	22.113
87.00	173.211	37.084	168.467	51.688	161.097	64.575	143.043	76.096	82.564	81.721	33.132	75.513	19.107
87.50	174.320	37.113	170.391	51.791	164.208	64.850	148.324	76.794	81.789	83.131	28.441	76.258	15.954
88.00	175.432	37.137	172.328	51.876	167.399	65.076	154.143	77.394	80.425	84.549	23.191	76.898	12.676
88.50	176.547	37.155	174.278	51.941	170.626	65.253	160.477	77.877	77.846	85.968	17.405	77.411	9.275
89.00	177.663	37.167	176.235	51.987	173.907	65.378	167.254	78.226	72.094	87.371	11.157	77.778	5.796
89.50	178.781	37.174	178.198	52.013	177.216	65.448	174.350	78.426	53.394	88.684	4.582	77.984	2.261
90.00	179.899	37.176	180.163	52.019	180.538	65.465	181.694	78.468	333.327	89.129	357.862	78.017	358.704
90.50	181.017	37.172	182.128	52.006	183.857	65.426	188.793	78.351	293.243	88.000	351.207	77.878	355.158
91.00	182.135	37.162	184.090	51.972	187.157	65.333	195.759	78.080	283.990	86.619	344.812	77.572	351.658
91.50	183.251	37.147	186.045	51.920	190.422	65.187	202.340	77.665	280.361	85.204	338.833	77.113	348.233
92.00	184.365	37.127	187.990	51.847	193.638	64.990	208.438	77.125	278.554	83.784	333.369	76.521	344.917
92.50	185.477	37.101	189.924	51.756	196.793	64.743	214.006	76.477	277.554	82.370	328.460	75.814	341.715
93.00	186.585	37.070	191.843	51.646	199.874	64.450	219.038	75.739	276.977	80.965	324.104	75.015	338.661
93.50	187.689	37.033	193.744	51.518	202.872	64.113	223.560	74.928	276.650	79.574	320.270	74.141	335.762
94.00	188.789	36.991	195.625	51.373	205.781	63.735	227.613	74.061	276.481	78.199	316.910	73.209	333.024
94.50	189.884	36.944	197.485	51.210	208.593	63.321	231.245	73.150	276.419	76.841	313.972	72.234	330.450
95.00	190.974	36.892	199.320	51.032	211.306	62.873	234.503	72.207	276.430	75.504	311.402	71.228	328.039
97.50	196.318	36.558	208.070	49.927	223.337	60.256	246.659	67.292	277.058	69.170	302.560	66.029	318.236
100.00	201.445	36.111	216.005	48.546	232.975	57.293	254.506	62.486	278.036	63.504	297.744	61.004	311.439
102.50	206.302	35.566	223.054	46.993	240.634	54.275	260.009	58.076	279.046	58.541	294.904	56.441	306.659
105.00	210.849	34.941	229.225	45.359	246.741	51.374	264.084	54.150	279.966	54.248	293.093	52.415	303.167
107.50	215.057	34.251	234.568	43.710	251.637	48.677	267.193	50.702	280.735	50.554	291.820	48.508	300.484
110.00	218.910	33.512	239.151	42.091	255.573	46.212	269.688	47.688	281.317	47.373	290.815	45.864	298.294
112.50	222.398	32.735	243.047	40.528	258.730	43.976	271.415	45.049	281.695	44.620	289.916	43.215	296.394
115.00	225.520	31.930	246.326	39.034	261.237	41.948	272.769	42.726	281.857	42.220	289.024	40.894	294.647
117.50	228.280	31.105	249.048	37.609	263.190	40.104	273.714	40.663	281.798	40.104	288.077	38.842	292.959
120.00	230.685	30.266	251.268	36.252	264.660	38.415	274.293	38.811	281.516	38.216	287.033	37.007	291.266
122.50	232.741	29.415	253.030	34.953	265.702	36.854	274.539	37.127	281.013	36.509	285.864	35.345	289.523
125.00	234.460	28.556	254.373	33.705	266.356	35.396	274.477	35.577	280.288	34.945	284.552	33.820	287.697
127.50	235.850	27.688	255.327	32.497	266.654	34.020	274.125	34.130	279.344	33.491	283.082	32.402	285.763
130.00	236.919	26.812	255.917	31.320	266.621	32.705	273.497	32.763	278.180	32.122	281.442	31.066	283.701
132.50	237.673	25.929	256.163	30.165	266.273	31.436	272.601	31.453	276.795	30.816	279.623	29.793	281.495
135.00	238.117	25.037	256.078	29.025	265.624	30.199	271.443	30.185	275.187	29.555	277.616	28.565	279.129
137.50	238.252	24.136	255.673	27.892	264.679	28.982	270.024	28.945	273.351	28.326	275.409	27.370	276.588
140.00	238.078	23.227	254.949	26.759	263.442	27.774	268.340	27.720	271.278	27.116	272.991	26.197	273.856
142.50	237.590	22.310	253.908	25.623	261.907	26.570	266.385	26.504	268.958	25.918	270.345	25.039	270.915
145.00	236.780	21.385	252.541	24.481	260.066	25.362	264.146	25.288	266.374	24.725	267.454	23.888	267.745
147.50	235.636	20.456	250.835	23.330	257.905	24.148	261.605	24.069	263.506	23.532	264.295	22.742	264.322
150.00	234.139	19.525	248.772	22.171	255.400	22.925	258.733	22.845	260.327	22.339	260.840	21.600	260.617
152.50	232.266	18.596	246.321	21.005	252.520	21.695	255.510	21.615	256.802	21.144	257.053	20.462	256.595
155.00	229.989	17.676	243.445	19.838	249.225	20.461	251.880	20.384	252.889	19.953	252.893	19.333	252.216
157.50	227.273	16.773	240.086	18.677	245.460	19.229	247.792	19.158	248.532	18.771	248.307	18.217	247.431
160.00	224.079	15.896	236.212	17.532	241.159	18.011	243.178	17.947	243.667	17.608	243.233	17.126	242.186
162.50	220.364	15.058	231.720	16.419	236.239	16.822	237.958	16.766	238.216	16.479	237.603	16.073	236.418
165.00	216.087	14.273	226.538	15.358	230.607	15.682	232.035	15.636	232.092	15.403	231.399	15.076	230.067
167.50	211.217	13.561	220.581	14.372	224.160	14.618	225.312	14.583	225.206	14.405	224.568	14.158	223.071
170.00	205.542	12.939	213.782	13.494	216.811	13.665	217.700	13.639	217.483	13.516	216.634	13.345	215.405
172.50	199.687	12.430	206.114	12.759	208.512	12.861	209.155	12.846	208.893	12.771	208.125	12.669	207.062
175.00	193.123	12.053	197.632	12.203	199.306	12.250	199.721	12.243	199.489	12.209	198.904	12.162	198.113
177.50	186.183	11.826	188.512	11.862	189.375	11.874	189.577	11.872	189.442	11.864	189.122	11.852	188.701
180.00	179.050	11.760	179.050	11.760	179.050	11.760	179.050	11.760	179.050	11.760	179.050	11.760	179.050

Appendix B: Sample calculations and derivations

Sample calculation and table lookup for Sample 3 in Ellipsometry method:

For As = 330°, Compensator = -π/4

According to table below, P=P+π/2=π/2, and A=2π-As=30°

ZONES	COMPENSATOR	P	A
1	- π/4	P	Ap
		P+π	Ap
		P	AP+π
		P+π	AP+π
2	+ π/4	π/2-P	As
		3π/2-P	As
		π/2-P	As+π
		3π/2-P	As+π
3	-π/4	P + π/2	π-As
		P + 3π/2	π-As
		P + π/2	2π-As
		P + 3π/2	2π-As
4	+π/4	π-P	π-Ap
		2π-P	π-Ap
		π-P	2π-Ap
		2π-P	2π-Ap

Table b: Relationship between Compensator, P and A (Lab, 8)

Applied P and A to Equation 4,

$$\Delta = \frac{\pi}{2} - 2P = \frac{-\pi}{2}$$

$$\Psi = -A_p = A_S = 30°$$

Look up in Appendix A, one would found the value for small delta from above values is approximately equal to 130°

Then apply small delta to equation 3 to find the thickness, d.

Derivation of formula to solve for thickness in Ellipsometry:

From the Fresnel reflection coefficients, one has:

$$\tan\Psi e^{i\Delta} = \frac{r_{p01} + r_{p12}e^{-2i\delta}}{1 + r_{p01}r_{p12}e^{-2i\delta}} \times \frac{1 + r_{s01}r_{s12}e^{-2i\delta}}{r_{s01} + r_{s12}e^{-2i\delta}} \quad \text{(Lab, 9)}$$

Expand the above, one will get

$$\tan\Psi e^{i\Delta} = \frac{r_{p01} + r_{p12}e^{-2i\delta} + r_{s01}r_{s12}r_{p01}e^{-2i\delta} + r_{s01}r_{s12}r_{p12}e^{-4i\delta}}{r_{s01} + r_{s12}e^{-2i\delta} + r_{s01}r_{p12}r_{p01}e^{-2i\delta} + r_{p01}r_{s12}r_{p12}e^{-4i\delta}}$$

Where r's are given by Fresnel Reflection equations:

$$\begin{aligned} r_{pab} &= (n_a \cos\phi_2 - n_b \cos\phi_1)/(n_a \cos\phi_2 + n_b \cos\phi_1) \\ r_{sab} &= (n_a \cos\phi_1 - n_b \cos\phi_2)/(n_a \cos\phi_1 + n_b \cos\phi_2) \end{aligned} \quad \text{(Lab, 9)}$$

Once all the measured values had been substitute in the equations above, only unknown left over is small delta, and one can use trial and error method to find the value, with use of computer and Newton Root Finding Method.

Derivation of formula in Michelson experiment:

At zero path length difference, Effective Path length between mirror and cube (PLM) and effective Path length different between sample and Cube (PLS) are equal.

Therefore:

$$PLA = PLM + (\frac{n_{oxide}}{n_{air}})d$$

$$\Rightarrow PLA - PLM = (\frac{n_{oxide}}{n_{air}})d = \frac{D_{micrometer}}{Magnification}$$

$$\Theta \; n_{air} \cong 1$$

$$\Rightarrow thickness = \frac{change\_in\_Position}{Magnification \times n_{oxide}}$$

The magnification factor is introduce due to the microscope objective is enlarging the effective thickness of the sample.