Eindhoven University of Technology

MASTER

Imaging ellipsometry
development and application

Rozendaal, D.X.E.

Award date:
2014

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
Imaging Ellipsometry: Development and Application

EPG 13-15
D.X.E. Rozendaal
0548059
Abstract

In the new generation Extreme UltraViolet (EUV) lithography machines light with a wavelength of 13.5 nm is used for imaging. This very high energy light is absorbed by lenses, so mirrors are used instead. The mirrors can lose reflectivity due to different contaminating processes present in the machine. Two of these processes are the cracking of residual hydrocarbons and chemisorbed water by the EUV photons. The breaking of molecular bonds can create a non-volatile deposit of carbon and oxidize the surface.

Ellipsometry is a powerful noninvasive optical technique for measuring the thickness and optical constants of thin films. Ellipsometry measures the polarization change after reflection on the surface of a sample. The polarization change can be related to subnanometer thicknesses and makes it possible to measure layer growth in real-time.

This research describes the development and calibration of an imaging ellipsometer. The main advantage for this setup lies in the in-situ spatially resolved measurements, not possible with traditional ellipsometers. This could provide new insights onto the contamination processes. Finally the setup will be used for measuring real-time electron beam induced carbon deposition and oxidation of metallic samples.
TABLE OF CONTENTS

1 INTRODUCTION ............................................................................................................................ 5
   1.1 EUV LITHOGRAPHY .................................................................................................................. 5
   1.2 CARBON DEPOSITION ............................................................................................................. 6

2 THEORY ........................................................................................................................................ 9
   2.1 POLARIZED LIGHT ..................................................................................................................... 10
   2.2 STOKES VECTOR ....................................................................................................................... 12
   2.3 MUELLER MATRIX .................................................................................................................... 14
      2.3.1 MUELLER MATRIX MODEL .............................................................................................. 14
   2.4 IDEAL ELLIPSMETER CONFIGURATIONS .............................................................................. 14
      2.4.1 STANDARD MUELLER MATRICES .................................................................................... 15
      2.4.2 ROTATING ANALYSER ELLIPSMETER ............................................................................ 16
      2.4.3 ROTATING ANALYSER ELLIPSMETER WITH COMPENSATOR ........................................... 17
      2.4.4 ROTATING COMPENSATOR ELLIPSMETER ..................................................................... 17

3 IMAGING ELLIPSMETRY ............................................................................................................. 27
   3.1 ELLIPSMETER CONFIGURATIONS ....................................................................................... 28
   3.2 DESIGN GOALS ...................................................................................................................... 28
   3.3 RCE IMAGING ELLIPSMETER ................................................................................................ 29
   3.4 CALIBRATION ........................................................................................................................... 30

4 SETUP ........................................................................................................................................ 31
   4.1 LIGHT SOURCE AND POWER SUPPLY .................................................................................... 32
      4.1.1 LIGHT SOURCE .................................................................................................................. 32
      4.1.2 POWER SUPPLY ............................................................................................................ 32
   4.2 GENERAL OPTICS .................................................................................................................... 35
   4.3 MECHANICS ............................................................................................................................ 35

5 CALIBRATION OF OPTICAL COMPONENTS ........................................................................... 41
   5.1 LIGHT SOURCE ....................................................................................................................... 41
   5.2 POLARIZERS ............................................................................................................................ 42
5.3 COMPENSATOR
5.3.1 EDMUND OPTICS WAVE PLATE
5.3.2 EDMUND OPTICS WOOLAM COMPARISON
5.3.3 THORLABS WAVE PLATE
5.4 WINDOWS

6 CALIBRATION MEASUREMENTS
6.1 TABLE TOP MEASUREMENTS
6.1.1 MLM SAMPLE WITH EDMUND OPTICS
6.1.2 MLM SAMPLE WITH THORLABS
6.1.3 MLM SAMPLE TEST
6.2 CALIBRATION SAMPLE
6.3 VACUUM CHAMBER MEASUREMENTS

7 RESULTS AND DISCUSSION

8 CONCLUSION
8.1 SETUP
8.2 MEASUREMENTS

REFERENCE DOCUMENTS
APPENDIX A SUPPLEMENTARY DATA
APPENDIX B HARDWARE
APPENDIX C MATLAB FOR ELLIPSOMETRY
1 INTRODUCTION

Ellipsometry was invented in the late 1800s, by being a slow and cumbersome technique it did not receive a lot of interest. Until the semi-conductor industry was starting to develop from the late 1960s, it provided much interest in characterizing thin layers on silicon. Not much later the microcomputer meant new possibilities in automation for more accurate and faster measurement and made ellipsometry in a widely used practice.

Ellipsometry is a powerful noninvasive optical technique for measuring the thickness and optical constants of thin films and is very sensitive for thin layers. Lateral resolution is normally in the order of 50 μm, but height resolution can be around 0.2 nm. This very high resolution is achieved by measuring the polarization change of the reflected light. Upon reflection on the surface of a sample the phase between the electric field components of the light is slightly shifted depending on the optical constants and thickness of the layers. Ellipsometry is very useful for characterizing growth processes of thin films or measuring the optical constants of materials. More advanced application lie in the investigation of electronic band structures.

Recently ellipsometry is gradually fine-tuned for higher accuracy, operation speed, or developed for specific applications, one of these more recent developments is imaging ellipsometry.

Imaging ellipsometry is an evolution of normal ellipsometry in order to measure layer growth in more detail in real-time. The main difference is the ability of an imaging ellipsometer to measure thickness spatially resolved in one measurement. In classic ellipsometry an average measurement over the macroscopic spot of the light source is taken or the sample or probes are scanned over the surface. With the first there is no spatial information and with the latter the measure time is very long. Imaging ellipsometry overcomes both.

This research will pursue the in-situ detection of sub nanometer carbon and oxide layers with imaging ellipsometry. The research is conducted at ASML in the Extreme UltraViolet (EUV) Research department. First the basics of EUV lithography and the mechanisms for carbon growth and oxidation will be discussed. Thereafter the theory, development and calibration of the imaging ellipsometer will be discussed in detail. In the last part of this report measurements will be taken on samples. Thin layers of carbon will be deposited with an electron beam, the imaging ellipsometer will real-time measure the growth and an optical model will be applied to calculate layer thickness.

1.1 EUV LITHOGRAPHY

The previous generation of lithography machines operates with a 193 nm light source for illuminating a wafer and lenses are uses for controlling the light. The new EUV generation was developed in pursue of smaller feature sizes on computers chips the light source is of a shorter wavelength than the previous generation. The EUV light has a wavelength of 13.5 nm, this high energy light is absorbed by regular optics or even air. In order to control the light mirrors are used instead of lenses and the whole optical path is in a large vacuum chamber.

After more than 10 years of research and development the first EUV lithography machines are shipping since 2012 an example is shown in Figure 1.1.
1.2 CARBON DEPOSITION

EUV light is absorbed very easily, this makes the machine very sensitive for contamination on the mirrors. Research shows that for example 1 nm of carbon contamination leads to a reflectance loss of 1.4% [1]. The optical system consists of over 10 mirrors, loss in reflectance adds up rapidly, contamination leads to image errors and lower throughput. There are several sources of contamination present, only hydrocarbon and to a lesser extent water will be discussed. The EUV lithography machine uses a vacuum chamber where residual hydrocarbons will be present due to resist outgassing. These contaminants can be cracked by the EUV photons, due to the high energy of 92 eV. The EUV photons can crack molecular bonds directly and the adsorption of photons on the mirrors surface results in the emission of secondary electrons which can also break bonds. These effects lead to the decomposition of the hydrocarbons, C,H, molecules, in an amorphous hydrocarbon layer, a:CH. This can result in the growth of carbon overlayers by crosslinking between the layers. Another process cracks adsorbed water molecules on the mirrors surface, forming reactive oxygen radicals which can oxidize the top layer of the mirror. Ellipsometry can be used to measure the formation of overlayers and study these processes on a sub nanometer level and differentiate between them.

The formation of an overlayer of just a few nanometers reduces the reflectance of the mirror significantly, a large contamination is easily visible by the naked eye, as illustrated by Figure 1.2.
Measurements done previously shows the influence of carbon on the reflectivity of a mirror, see [1]. EUV induced carbon has less influence on the reflectivity than evaporated carbon, due to a higher hydrogen ration the carbon is less dense.

In order to controllably research carbon deposition the EUV lithography machine conditions are created in a lab environment. A carbohydrate source is used in conjunction with an electron beam. The high energy electrons scatter on the surface and the electrons crack the hydrocarbons and make a carbon deposit in a very similar manner as the EUV photons. The oxidation of the surface is also taken into account, because previous researched showed chemisorbed water is often present.

In more detail, high energy electrons are accelerated towards the surface. The electrons scatter on the surface having elastic and un-elastic collisions. This creates an energy distribution of electrons. Some electrons can break the bonds of the precursor gas absorbed onto the surface. This depends on
the energy crossections and number of electrons. The precursor molecules dissociate into volatile and non-volatile parts. In case of dodecane, C\textsubscript{12}H\textsubscript{26}, carbon and hydrocarbon will stay on the surface and hydrogen gas escapes.

The dissociation rate is given by [2]:

\[ k_e = \sigma(E) \Gamma_e \]  

(1.1)

It depends on the electron beam dissociation crossection, \( \sigma(E) \), this depends on the energy and gives the probability for a dissociation event, and the number of electrons \( \Gamma_e \).

The dissociation is depicted simplified in Figure 1.4. In part a) and b) are hydrocarbon precursor gas molecules adsorbed onto the surface. The electrons from the focused electron beam imping onto the surface and dissociated the hydrogen bonds, c). The volatile hydrogen gas is pumped away and the non-volatile carbon sticks to the surface, d)

\[ \text{Figure 1.4} \quad \text{Electron beam induced deposition (EBID).} \]
2 THEORY

This chapter will discuss the basics of ellipsometry. After a general introduction into the polarization of light a mathematical method for describing these polarization states and modification by optical elements will be discussed in paragraph 2.1, 2.2 and 2.3. Next the most common ellipsometer configurations with perfect elements will be discussed in paragraph 2.4, followed by the impact of non-ideal components in paragraph 2.5. In paragraph 2.6 the interaction of light with the sample will be discussed, this theory of the complex refractive index and Fresnel coefficients is used for creating an optical model in order to calculate layer thicknesses. The last paragraph will give a short introduction to Fourier transforms.

In ellipsometry the polarization state of light is measured, the ellipticity of the light is determined. Many different ellipsometer configurations have been developed in the past, each with their own advantages and disadvantages and spanning wavelength ranges from the deep ultraviolet to the far infrared.

When light reflects on a surface of a sample the polarization state is shifted due to interference effects in the top layers and dipole interactions in the material. This is wavelength dependent. Ellipsometry is very sensitive, because of the high sensitivity of the polarization for refractive effects. Ellipsometry is capable of detecting single atomic layers in a non-invasive way. Ellipsometry was first performed by Paul Drude in the late 1800th, although not called ellipsometry at the time it was the first study of the reflection of polarized light on metal films. Drude described ellipsometry with the newly electromagnetic theory of light from Maxwell and was enable to derive very accurate results for the refractive index of different materials.

![Figure 2.1](image.png)

Fig. 2.1 Ellipsometer build by Paul Drude.

After the invention of the null ellipsometer by Paul Drude in 1887 the development was very slow, only in 1945 Rothen [4] introduced the name ellipsometry, until the late 1960s [3]. Around this time the semiconductor industry started to develop and thin films became a topic of interest. And the first microcomputers brought bulk calculations to every lab, making ellipsometry far less time consuming.

Notable contributions for modern ellipsometry were made by Azzam and Bashara, Hauge, Aspnes and many others [5][6][7]. A lot of effort was put in the automation of the ellipsometer and different approaches where developed, for example the rotating analyzer ellipsometer, the rotating polarizer ellipsometer and the phase modulation ellipsometer.

A difficulty with ellipsometry is that the interesting parameters, the optical constants, are not measured directly, but have to be derived by a model. Creating and calculating models became more straightforward with the wide range introduction of computers. This might also have contributed to the fast developments in ellipsometry.
The polarization of light was first observed by Newton and Huygens as early as the 17th century. The polarization can be rotated by interaction with crystals and by reflection on a surface. With reflection on a surface the parallel and perpendicular polarization exhibit a different change in polarization thereby creating an elliptic polarization. This can be described by the Maxwell equations. For describing the polarization only the electric field component is taken into account. The interaction of charge carriers with the magnetic component is neglectable compared to the electric component.

The ellipticity parameter $\rho$ is given by:

$$\rho = \frac{r_p}{r_s} = \tan(\psi)e^{i\Delta} \quad (1.2)$$

This is the ratio of the $r_p$, parallel, and $r_s$, perpendicular, Fresnel coefficients. The measured variables are the elliptic angle $\psi$ and the phase $\Delta$. Interestingly, no absolute intensity is measured, it cancels out. A more extended description of the polarization of light is given in the next paragraphs.

### 2.1 POLARIZED LIGHT

First light will be described as an electro-magnetic wave with the Jones vector, giving a mathematical description for polarization. Next the most general mathematical form of polarized light is introduced with the Stokes vector. Interaction of polarized light with optical components is described with Mueller formalism. This gives the introduction for optical models for different ellipsometer configurations.

Light can be described as an electro-magnetic wave by [8]

$$\mathbf{E} = E_0 \cdot \exp(i(\omega t - Kz + \delta)) \hat{e}_x \quad (1.3)$$

$$\mathbf{B} = B_0 \cdot \exp(i(\omega t - Kz + \delta)) \hat{e}_y \quad (1.4)$$

Propagating in the z direction. $E_0$ and $B_0$ are the field amplitudes, $\omega$ is the angular velocity and $\delta$ is the phase. $K$ is the propagation number and given by

$$K = \frac{2\pi}{\lambda} \quad (1.5)$$

Here is $\lambda$ the wavelength. The relation between the electric field and the magnetic induction is given by

$$E_0 = cB_0 \quad (1.6)$$

With $c$ the speed of light. For describing the polarization state of a light wave in an optical element the Jones vector is used. The Jones vector of a quasi-monochromatic wave propagating in the $z$ direction is

$$\mathbf{E}(z, t) = \begin{bmatrix} E_{x0} \cdot \exp(i(\omega t - Kz + \delta_x)) \\ E_{y0} \cdot \exp(i(\omega t - Kz + \delta_y)) \end{bmatrix} \quad (1.7)$$

In terms of complex powers of $e$

$$\mathbf{E}(z, t) = e^{i(\omega t - Kz)} \begin{bmatrix} E_{x0} \cdot \exp(i\delta_x) \\ E_{y0} \cdot \exp(i\delta_y) \end{bmatrix} \quad (1.8)$$
This can be simplified to

\[ \vec{E}(z,t) = \begin{bmatrix} E_x \\ E_y \end{bmatrix} \] (1.9)

Different polarizations of light depend on the phase difference between the \( x \) and \( y \) component, this is illustrated in Figure 2.2 for some common polarization states. When the \( x \) and \( y \) component are equal in magnitude and in phase the light is linearly polarized, with a phase difference of \( \pi/2 \) the light is right-circularly polarized and with an in-between state the light is elliptically polarized.

Figure 2.2  Polarization states of light, with (a) Linear polarization, (b) Right-circular polarization and (c) Elliptical polarization (Fujiwara [8]).
For the examples of the Figure 2.2 the Jones vectors are given by:

(a) \( \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \)

(b) \( \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} \)

(c) \( \begin{bmatrix} \sin(\psi)e^{i\Delta} \\ \cos(\psi) \end{bmatrix} \)

For reflections on a surface these components are referred to as the p- and s-polarized light waves. The p-polarization oscillates in the same plane before and after reflection (parallel). The s-polarization changes direction (senkrecht – perpendicular).

The ellipticity of the light wave is given by the ratio of the p and s polarization amplitude.

\[
p = \frac{r_p}{r_s} = \tan(\psi)e^{i\Delta}
\]

For reflections on a surface these components are referred to as the p- and s-polarized light waves. The p-polarization oscillates in the same plane before and after reflection (parallel). The s-polarization changes direction (senkrecht – perpendicular).

![Figure 2.3](image)

**2.2 STOKES VECTOR**

The Jones vector perfectly describes the polarization state of light. Although in practice, light is often not completely polarized but a combination of polarized and unpolarized states, partially polarized. In order to describe these states, Stokes formalism was introduced.

The four Stokes parameters are defined in polarization amplitudes by

\[
S_0 = I_x + I_y
\]

\[
S_1 = I_x - I_y
\]

\[
S_2 = I_{45} + I_{-45}
\]

\[
S_3 = I_R + I_L
\]

In terms of electric field amplitudes this translates into

\[
S_0 = \langle E_x^2(t) \rangle + \langle E_y^2(t) \rangle
\]
\[ S_1 = \langle E_x^2(t) \rangle - \langle E_y^2(t) \rangle \]
\[ S_2 = 2 \langle E_x(t) \cdot E_y(t) \cdot \cos(\delta_y(t) - \delta_x(t)) \rangle \]
\[ S_3 = 2 \langle E_x(t) \cdot E_y(t) \cdot \sin(\delta_y(t) - \delta_x(t)) \rangle \]

Expressed in the ellipticity parameters \( \psi \) and \( \Delta \) this becomes

\[ S_0 = 1 \]
\[ S_1 = -\cos(2\psi) \]
\[ S_2 = \sin(2\psi) \cos(\Delta) \]
\[ S_3 = -\sin(2\psi) \sin(\Delta) \]

The interaction of light with optical elements or the sample is described with Mueller matrices. This makes it possible to create an optical model and calculate the intensities found by the detector.

The Stokes vector makes it very convenient to describe different polarization states. Totally polarized light is one specific state of polarization, while completely random polarization is equal to unpolarized light. In ellipsometry systems partially polarized light is often found. Polarizers are seldom perfect and the light depolarizes by scattering on the surface of the sample. For totally polarized light the squares of the components is equal to the square of the total intensity

\[ S_0^2 = S_1^2 + S_2^2 + S_3^2 \]

In case of partially polarized light this is given by

\[ S_0^2 > S_1^2 + S_2^2 + S_3^2 \]

This leads to the degree of polarization, \( p \), defined as

\[ p = \sqrt{S_1^2 + S_2^2 + S_3^2} / S_0 \leq 1 \]

Inserting the Stokes vector gives

\[ p = \sqrt{\cos^2(2\psi) + \sin^2(2\psi)(\cos^2(\Delta) + \sin^2(\Delta))} = 1 \]

This would simplify to one. In experiment however a variation in \( \Delta \) is possible. \( \Delta \) will then be an average of the actual value. This average is expressed as given by Rösseler [9]

\[ \left[ \left( \cos(\Delta) \right)^2 + \left( \sin(\Delta) \right)^2 \right] \leq 1 \]

In practice this will be smaller than one.
### 2.3 MUELLER MATRIX

The Stokes parameters can be represented in a vector notation. The four dimensional vector is given by

$$\vec{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$  \hspace{1cm} (1.19)

The interaction of light is calculated with the Mueller formalism, a 4x4 transformation matrix introduced by Mueller [10]

$$\vec{M} = \begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix}$$  \hspace{1cm} (1.20)

Each optical component can be described with its individual Mueller matrix, and the azimuthal angles with a rotation matrix.

#### 2.3.1 MUELLER MATRIX MODEL

For calculating the intensity through an optical system the input light Stokes vector can be multiplied with the different Mueller matrices. The Mueller matrices of the optical components are adapted for their individual azimuthal orientations with the rotation matrix. For example two polarizers can be modeled as follows

$$\vec{S}_{out} = \vec{M}_p \cdot \vec{R}(-\alpha) \cdot \vec{M}_p \cdot \vec{S}_{in}$$  \hspace{1cm} (1.21)

If the incident light is natural light and the polarizer is rotated over an angle \(\alpha\) then this becomes

$$\vec{S}_{out} = \vec{M}_p \cdot \vec{R}(-\alpha) \cdot \vec{M}_p \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \frac{1}{4} \begin{bmatrix} 1 + \cos(2\alpha) \\ 1 + \cos(2\alpha) \\ 0 \\ 0 \end{bmatrix}$$  \hspace{1cm} (1.22)

And the measured intensity at the detector is

$$S_0 = \frac{1}{4} [1 + \cos(2\alpha)] = \frac{1}{2} \cos^2(\alpha)$$  \hspace{1cm} (1.23)

### 2.4 IDEAL ELLIPSOMETER CONFIGURATIONS

Since the automation of ellipsometers in the beginning of the 1970s many different configurations have been proposed and explored, each with their own advantages and disadvantages or very specific applications. An overview of standard configurations covered here is for example given by Aspnes [13] and Fujiwara [8]. A more advanced configuration used in commercial ellipsometers was perfected by Jellison [14]. Each ellipsometer consists at least of a polarization state generator (PSG) with the light source, the sample and a polarization state detector (PSD) with the detector. Next the optical models for the three configurations important for this research are presented. They differ in
the number of optical components used and which component is rotating in order to create a polarization modulation. All basic configurations use two polarizers, the first polarizers selects one linear polarization direction and the second rotating polarizer makes a projection to calculate the polarization shift by the sample. A second option is the use of a compensator, a quarter or half-wave plate which creates a phase shift of 90° or 180° between polarization vectors. This compensator can be either used for increased accuracy or as the rotating element.

A schematic overview of the basic ellipsometer is given by Figure 2.4, with on the left side the PSG with the light source, a polarizer and optionally a compensator. On the right side is the second polarizer, the analyzer, and the detector.

![Figure 2.4 Schematic overview of an ellipsometer.](image)

### 2.4.1 STANDARD MUELLER MATRICES

The optical elements used in ellipsometry are the polarizer and the compensator. Their Mueller matrices are given by

The polarizer

$$\mathbf{M}_p = \frac{1}{2} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$  \hspace{1cm} (1.24)

The compensator

$$\mathbf{M}_c = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\delta) & \sin(\delta) \\ 0 & 0 & -\sin(\delta) & \cos(\delta) \end{bmatrix}$$  \hspace{1cm} (1.25)
And the sample is given by

\[
\bar{M}_S = \frac{1}{2} \begin{bmatrix}
1 & -\cos(2\psi) & 0 & 0 \\
-\cos(2\psi) & 1 & 0 & 0 \\
0 & 0 & \sin(2\psi) \cos(\Delta) & \sin(2\psi) \sin(\Delta) \\
0 & 0 & -\sin(2\psi) \sin(\Delta) & \sin(2\psi) \cos(\Delta)
\end{bmatrix}
\]  

(1.26)

The general rotation matrix is

\[
\bar{R}(\alpha) = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(2\alpha) & \sin(2\alpha) & 0 \\
0 & -\sin(2\alpha) & \cos(2\alpha) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(1.27)

This gives a set of transformations for calculating models for different ellipsometer configurations.

### 2.4.2 ROTATING ANALYSER ELLIPSOMETER

The most straightforward ellipsometry configuration is the rotating analyzer ellipsometer (RAE). This configuration can also be described in short by PSA\(_{\alpha}\). The sample is placed between the polarizer and the rotating analyzer. In vector notation this is,

\[
\vec{S}_{\text{out}} = \vec{M}_A \cdot \bar{R}(\alpha) \cdot \bar{M}_S \cdot \bar{R}(-P) \cdot \vec{M}_P \cdot \vec{S}_{\text{in}}
\]

(1.28)

The intensity is given by equation (1.29), assuming \(P = 45^\circ\) this simplifies significantly to:

\[
I = I_0 \left( 1 - \cos(2\psi) \cos(2\alpha) + \sin(2\psi) \cos(\Delta) \sin(2\alpha) \right)
\]

(1.29)

\[
= I_0 \left( 1 + S_1 \cos(2\alpha) + S_2 \sin(2\alpha) \right)
\]

This can be related to the Fourier coefficient of the transformed measured intensity.

\[
I(t) = I_0 (1 + \alpha \cos(2\alpha) + \beta \sin(2\alpha))
\]

(1.30)

Solving the Fourier coefficients gives for the ellipsometric parameters

\[
\tan(\psi) = \sqrt{\frac{1 + \alpha}{1 - \alpha}}
\]

(1.31)

\[
\cos(\Delta) = \frac{\beta}{\sqrt{1 - \alpha^2}}
\]

(1.32)

This configuration is very insensitive for delta near 0° and 180°. For solving this inconvenience a compensator was added [8].
2.4.3 ROTATING ANALYSER ELLIPSOMETER WITH COMPENSATOR

The PCSA configuration uses a compensator to shift the phase and makes measurements of $\Delta$ near 0° and 180° possible. The matrix representation is very similar to the PSA configuration.

\[
\bar{S}_{\text{out}} = \bar{M}_A \cdot \bar{R}(A) \cdot \bar{M}_S \cdot \bar{R}(-P) \cdot \bar{M}_p \cdot \bar{S}_{\text{in}}
\]  
(1.33)

This gives intensity:

\[
l = l_0 \left( 1 - \cos(2\psi) \cos(2A) + \sin(2\psi) \cos(\Delta - \delta) \sin(2A) \right)
\]  
(1.34)

\[
l = l_0 \left( 1 + S_1 \cos(2A) + (S_2 \cos(\delta) - S_3 \sin(\delta)) \sin(2A) \right)
\]  

And $\psi$ and $\Delta$ are given by:

\[
tan(\psi) = \frac{1 + a}{\sqrt{1 - a^2}}
\]  
(1.35)

\[
cos(\Delta - \delta) = \frac{\beta}{\sqrt{1 - a^2}}
\]  
(1.36)

These equations are almost equal to the PSA configuration, but $\cos(\Delta)$ is shifted so also for values near 0° and 180° measurements can be performed.

2.4.4 ROTATING COMPENSATOR ELLIPSOMETER

Similarly the compensator can be rotated instead of the analyzer. The PCnSA configuration or rotating compensator ellipsometer (RCE) is enable to measure the four Stokes vectors in one measurement [15].

\[
\bar{S}_{\text{out}} = \bar{M}_A \cdot \bar{R}(A) \cdot \bar{M}_S \cdot \bar{R}(-C) \cdot \bar{M}_C \cdot \bar{R}(-P) \cdot \bar{M}_p \cdot \bar{S}_{\text{in}}
\]  
(1.37)

The intensity on the detector is:

\[
l = l_0 (a_0 + a_1 \cos(2C) + \beta_1 \sin(2C) + \alpha_2 \cos(4C) + \beta_2 \sin(4C))
\]  
(1.38)

The Fourier components are simplified by assuming $A = \pm 45^\circ$ and reduced to:

\[
a_0 = \frac{1}{2} (1 + \cos(\delta))(-\cos(2P) \cos(2\psi) - sgn(A) \sin(2P) \sin(2\psi) \cos(\Delta)) + 1
\]  
(1.39)

\[
a_1 = -sgn(A) \sin(2P) \sin(\delta) \sin(2\psi) \sin(\Delta)
\]

\[
\beta_1 = sgn(A) \cos(2P) \sin(\delta) \sin(2\psi) \sin(\Delta)
\]

\[
a_2 = \frac{1}{2} (1 - \cos(\delta))(-\cos(2P) \cos(2\psi) - sgn(A) \sin(2P) \sin(2\psi) \cos(\Delta))
\]  

\[
\beta_2 = \frac{1}{2} (1 - \cos(\delta))(-\sin(2P) \cos(2\psi) + sgn(A) \cos(2P) \sin(2\psi) \cos(\Delta))
\]
Solving this set of equations for $\psi$ and $\Delta$ leads to the following relations:

$$
\tan(\psi) = -\left[\frac{(\beta_1^2 + \beta_2^2)(1 - \cos(\delta))^2 \sin^2(\delta) + 4 (\beta_2 \cos(2P) - \alpha_2 \sin(2P))^2}{2 (\alpha_2 \cos(2P) - \beta_2 \sin(2P))}\right]^{1/2}
$$

$$
\tan(\Delta) = \left(\frac{1 - \cos(\delta)}{2 \sin(\delta)}\right) \frac{\alpha_1 \sin(2P) - \beta_1 \cos(2P)}{\alpha_2 \sin(2P) + \beta_2 \cos(2P)}
$$

These are independent of the total intensity and the offset $\alpha_0$. If the value of $\tan(2 \psi)$ is negative then the correct value for $\psi$ is obtained by the addition of $\pi/2$.

### 2.5 NON-IDEAL OPTICAL ELEMENTS

In practice the different optical components are not perfect, the polarizers will have a residual random polarization and the compensator is chromatic. The compensator will have a different retardance for different wavelengths. This makes it necessary to calibrate the different optical components before sample measurements. Different procedures are available, only the necessary will be presented. The extinction ratio of the polarizers will be determined and the retardation of the compensator. Also two window correction models will be presented.

#### 2.5.1 POLARIZER

The Mueller matrix of an imperfect polarizer is given by

$$
\bar{M}_p = \frac{1}{2} \begin{bmatrix}
1 + \alpha & 1 - \alpha & 0 & 0 \\
1 - \alpha & 1 + \alpha & 0 & 0 \\
0 & 0 & 2\sqrt{\alpha} & 0 \\
0 & 0 & 0 & 2\sqrt{\alpha}
\end{bmatrix}
$$

With $\alpha$ the attenuation coefficient given by the ratio of the minimum and the maximum transmittance.

The extinction ratio, which is also referred to with contrast ratio is given by

$$
\varepsilon = \frac{T_{\max}}{T_{\min}} = \frac{1}{\alpha}
$$

Calibration of the polarizers for different wavelengths is rather straightforward. Two polarizers are placed in rotating mounts between a light source and the detector in order to find the minimum and maximum transmission. The background signal of the detector is subtracted for higher accuracy.
2.5.2 COMPENSATOR

The compensator is calibrated with different calibrations procedures. In both methods is the compensator placed between polarizers. In the first case is the second polarizer rotated (PCa) and in the second case is the compensator rotated and are the polarizers fixed (PCaA). For a consistency check the compensator is measured on a Woollam spectroscopic ellipsometer as well.

The light source, polarizers and compensator are all fixed on an optical rail. The camera is added and focused on the compensator.

First both polarizers fast axis are aligned, next the compensator is inserted in the optical row and aligned. The alignment is done by maximizing the transmitted intensity. After alignment is the analyzer rotated for multiple rotations. The retardance can be calculated with a formula from Polarized light by Goldstein [16].

The intensity from the optical system is given by

\[ I(\alpha, \delta) = \frac{I_0}{4} (1 + \cos(\delta) \cos(2\alpha)) \]  

Evaluated at \( \alpha = 0 \) and \( \pi/2 \) gives

\[ I(0, \delta) = \frac{I_0}{4} (1 + \cos(\delta)) \]  

\[ I(\pi/2, \delta) = \frac{I_0}{4} (1 - \cos(\delta)) \]

These equations can be solved for \( \delta \)

\[ \cos(\delta) = \frac{I(0, \delta) - I(\pi/2, \delta)}{I(0, \delta) + I(\pi/2, \delta)} \]  

The second method was presented by Lee et al. [17] and uses the Fourier transform of the signal when the compensator is rotated between the polarizers. With the two \( 4 \omega \) coefficients:

\[ |B_2| = (\alpha_2^2 + \beta_2^2)^{1/2} \]  

An expression for \( \delta \) can be derived. If \( P = 0 \) and \( A = \pi/4 \) this simplifies to:

\[ \cos(\delta) = \sqrt{1 - |B_2|} \]

2.5.3 WINDOWS

One other optical component which cannot be neglected is the windows on the vacuum chamber. The ellipsometer will be used for in-situ contamination measurements making windows necessary. Most errors vanish with a two zone measurement with the analyzer at \( \pm 45^\circ \), unfortunately not the errors induced in \( \Delta \) by the windows. The entrance and exit window can be modeled with their Mueller matrix and added to the optical model. The windows can be modeled with the SRWP approximation, the Small Retardation Wave Plate approximation introduced by King 1966 and for example used by Azzam [18] to extend for optical activity and many others have used it since. Here the derivation of McCrackin is used [19], the window is modeled as an compensator placed at a fixed angle. The Mueller matrix is given by
\[ M_W = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -sw \\ 0 & 0 & 1 & cw \\ 0 & sw & -cw & 1 \end{bmatrix} \] (1.49)

With \( sw \) and \( cw \) given by

\[ sw = \delta_w \sin(\theta_w) \] (1.50)
\[ cw = \delta_w \cos(\theta_w) \] (1.51)

Here is \( \delta_w \) the window retardance. The retardance is assumed small, so \( sw \) and \( cw \) are small and can be used to only first order. \( \theta_w \) is the angle from the normal of the sample surface.

For example can two windows be added to the model from (1.43), the model becomes

\[ S_{out} = \vec{M}_A \cdot \vec{R}(A) \cdot \vec{M}_W1 \cdot \vec{M}_S \cdot \vec{M}_{W0} \cdot \vec{R}(-C) \cdot \vec{M}_C \cdot \vec{R}(-C) \cdot \vec{R}(-P) \cdot \vec{M}_p \cdot \vec{S}_{in} \] (1.52)

### 2.6 LIGHT INTERACTION

In general the interaction of light with media depends on the refractive index and is covered with Snell’s law. The interaction will be described in more detail in terms of the parallel and perpendicular electric field components. Electromagnetic waves, light waves, propagate at the speed of light \( c \) in vacuum.

\[ c = 2.99792 \times 10^8 \text{ m/s} \] (1.53)

The wave can be written as:

\[ E = E_0 \exp[i(\omega t - Kx + \delta)] \] (1.54)

With \( E_0 \) the electric field amplitude, \( \omega \) the angular frequency and \( \delta \) the phase. The propagation number \( K \) is defined as,

\[ K = \frac{\omega n}{c} = \frac{2\pi n}{\lambda} \] (1.55)

With \( n \) the refractive index and \( \lambda \) the wavelength.

### 2.6.1 COMPLEX RefRACTIVE INDEX

In opaque media the propagation speed depends on the refractive index of the medium. Vacuum has a refractive index of \( n = 1 \) while for air \( n = 1.0003 \). The refractive index for non-absorbing media is given by quotient of the speed of light and the speed in the medium.

\[ n = \frac{c}{s} \] (1.56)
Absorbing media need a second constant to be described completely, the extinction coefficient $k$. These together are defined as the complex refractive index $N$

$$N = n - i k$$

(1.57)

The propagating wave becomes

$$E = E_0 \exp \left[ i \left( \omega t - \frac{2\pi N}{\lambda} x + \delta \right) \right]$$

(1.58)

2.6.2
dielectric constant

Light propagates in media in terms of dipole radiation, this can be described with the complex refractive index $N$. The complex refractive index comes from the dielectric polarization in a media. The electric field of the light influences the charge carriers in a medium creating dipole moments. The dielectric constant depends on the electric field and the induced dielectric polarization $P$.

$$\varepsilon = 1 + \frac{P}{\varepsilon_0 E}$$

(1.59)

In this expression is $\varepsilon_0$ the permittivity of free-space and $P$ the polarization. The square of the complex refractive index is defined as the dielectric constant.

$$N^2 = \varepsilon$$

(1.60)
With $\varepsilon$ a complex number defined as

$$\varepsilon = \varepsilon_1 - i\varepsilon_2 \quad (1.61)$$

Out of the definition of the complex refractive index follows

$$\varepsilon_1 = n^2 - k^2 \quad (1.62)$$
$$\varepsilon_2 = 2nk \quad (1.63)$$

### 2.6.3 FRESNEL REFLECTION MODEL

Refraction of light can be described with Snell's law

$$n_i \sin(\theta_i) = n_t \sin(\theta_t) \quad (1.64)$$

This works for non-absorbing media, but when the complex refractive index is inserted the angles become complex. This can be resolved by using the Fresnel equations. The reflection of a light wave consists of two components, a $p$- and $s$-polarized light wave. Depending on the oscillation direction of the electric field as illustrated by Figure 2.6.

![Reflection of p- and s-polarized light.](image)

The electric field $E$ and magnetic induction $B$ follow certain boundary conditions when passing a surface. The $E$ and $B$ component parallel to the surface is continuous. In the case of $p$-polarized light are the boundary conditions

$$E_{tp} \cos(\theta_i) - E_{rp} \cos(\theta_r) = E_{tp} \cos(\theta_t) \quad (1.65)$$
$$B_{tp} + B_{rp} = B_{tp} \quad (1.66)$$

Where the subscripts $ip$, $rp$ and $tp$ represent the incident, reflection and transmission amplitude. An overview of the different components is shown in Figure 2.7.
The magnetic induction can be written as an electric field with the relation

\[ E = sB = \frac{c}{n}B \]  
(1.67)

Equation (1.75) transforms into

\[ n_i(E_{ip} + E_{rp}) = n_tE_{tp} \]  
(1.68)

This can be combined to an expression for the p-polarized light amplitude reflection coefficient, by eliminating \( E_{ip} \).

\[ r_p = \frac{E_{rp}}{E_{ip}} = \frac{n_t \cos(\theta_t) - n_i \cos(\theta_t)}{n_t \cos(\theta_t) + n_i \cos(\theta_t)} \]  
(1.69)

Or it can be combined to the amplitude transmission coefficient by eliminating \( E_{rp} \).

\[ t_p = \frac{E_{tp}}{E_{ip}} = \frac{2n_i \cos(\theta_i)}{n_t \cos(\theta_t) - n_i \cos(\theta_t)} \]  
(1.70)

Figure 2.7  Electric field and magnetic induction components for s- and p-polarized light.
Similarly for s-polarized light the boundary conditions are given by

\[ E_{is} + E_{rs} = E_{ts} \]  
\[ -B_{is} \cos(\theta_i) + B_{rs} \cos(\theta_r) = -B_{ts} \cos(\theta_t) \]

Equation (1.81) can be written in terms of the electric field amplitudes

\[ n_i (E_{is} \cos(\theta_i) + E_{rs} \cos(\theta_r)) = -n_t E_{ts} \cos(\theta_t) \]

The amplitude reflection and transmission coefficient are given by

\[ r_s = \frac{E_{rs}}{E_{is}} = \frac{n_i \cos(\theta_i) - n_t \cos(\theta_t)}{n_i \cos(\theta_i) + n_t \cos(\theta_t)} \]  
\[ t_s = \frac{E_{ts}}{E_{is}} = \frac{2n_i \cos(\theta_i)}{n_i \cos(\theta_i) - n_t \cos(\theta_t)} \]

The four equations \( r_p, t_p, r_s, \) and \( t_s \) are the Fresnel equations and can be used with the complex refractive index \( N \).

### 2.6.4 BREWSTER ANGLE

The Brewster angle is the angle at which the reflected p-polarization intensity vanishes at a medium interface.

![Figure 2.8 p-polarized light reflection near the Brewster angle.](image)

Light transports in media in terms of radiation by electric dipoles. The dipoles cannot transmit light in their oscillatory direction leading to a cut-off angle for light reflection of p-polarization.

The Brewster angle is given by
For s-polarized light is the oscillation of the dipole always parallel to the vibrational direction of the light.

For example for an air/c-Si interface this gives the reflected intensities depicted in Figure 2.9, \( R_n \) is the average intensity.

\[
tan(\theta_B) = \frac{n_t}{n_i}
\]  

(1.76)

Figure 2.9  Reflective s- and p-polarized intensities depending on the angle of incidence.

The Brewster angle is important for ellipsometry, near the Brewster angle is the difference between the s- and p-polarization intensity at a maximum. Ellipsometry measures the ratio of the intensities, so the highest sensitivity can be achieved by measuring near the Brewster angle.

2.7 FOURIER TRANSFORM

A Fourier transform is used to determine the frequency components in the signal. These Fourier coefficients are related to the sample parameters. For one measurement at least one optical cycle of 180° should be measured.

Figure 2.10  Measured light intensity over time for one optical cycle.
The discrete Fourier intensities are given by:

\[ A_j = \int_{(j-1)\pi/4\omega}^{j\pi/4\omega} I_e(t) \, dt \]  \hspace{1cm} (1.77)

With \( I_e(t) \) the measured intensity and \( j \) the number of measurements.
3 IMAGING ELLIPSOMETRY

The imaging ellipsometer is a relatively new development in ellipsometry, traditionally only one spot is measured. This can be a large spot or a small focused spot of several tens of micrometers. One solution to also collect spatial information of the sample is the use of a translation stage for the sample. This will only work for ex-situ measurements and is rather time consuming, a high resolution scan of a 1 inch diameter sample takes hours. Real-time monitoring of layer growth is a very interesting topic which has been done since the beginning of modern ellipsometry, but without spatial information. Spatially resolved in-situ ellipsometry would be an interesting technique to monitor growth in more detail. Imaging ellipsometry can also have some disadvantages. More advanced ellipsometers are of the spectroscopic type, they employ a broadband gas discharge lamp with a spectrometer as detector. For imaging ellipsometers a camera is used as detector and the light should be semi-monochromatic. For this a scanning monochromator could be used, but this complicates the design. Apart from this an imaging ellipsometer requires more expensive optics because large aperture polarizers and compensators are required. Besides these disadvantages are the possibilities of imaging ellipsometry enough motivation for many different designs found in literature. In Figure 3.1 is a schematic overview of the RCE configuration used by Jin et al. [22]. On the left side is the PSG and on the right side the PSD. The PSG consists of the light source with collimating optics in order to create a parallel beam. The light is linearly polarized by the polarizer and next an elliptical modulation is made by the rotating compensator. The elliptically polarized light impinges upon the sample and is transmitted onto the PSD. The analyzer creates a projection of the reflected light on the CCD. One optical cycle is equal to a 180° rotation of the compensator. With a direct Fourier transformation of the collected images can the sample parameters be calculated as shown in paragraph 2.4.4.

![Schematic overview of the imaging ellipsometer](image-url)

In Figure 3.1 is a schematic overview of the RCE configuration used by Jin et al. [22]. On the left side is the PSG and on the right side the PSD. The PSG consists of the light source with collimating optics in order to create a parallel beam. The light is linearly polarized by the polarizer and next an elliptical modulation is made by the rotating compensator. The elliptically polarized light impinges upon the sample and is transmitted onto the PSD. The analyzer creates a projection of the reflected light on the CCD. One optical cycle is equal to a 180° rotation of the compensator. With a direct Fourier transformation of the collected images can the sample parameters be calculated as shown in paragraph 2.4.4.

One of the first imaging ellipsometers was presented by Beaglehole in 1988 [21], it was a RCE design with a lamp and band pass filter as light source. It was capable of detecting down to 50 Å. Another configuration was used by Jin [22]. It employed a beam expander with pinhole for parallelism of the light beam and a camera with Scheimpflug correction. The Scheimpflug correction rotates the CCD surface compared to the imaging lens in order to correct for image skew, additionally this solves problems with a low dept-of-field common for macro imaging systems. They used the same optical configuration, but operated it in null-ellipsometry. The intensity on the substrate is minimalized where after the intensity in areas of growth increases. It achieved a lateral resolution of
5 µm. Later on in 2002 this lateral resolution was increased to 0.5 µm by Zhan [23] with a 5 Å sensitivity.

### 3.1 ELLIPSMETER CONFIGURATIONS

Different ellipsometer configurations are able to measure a different number of Mueller matrix components and have different measurement ranges for ψ and Δ. Fujiwara [8] and Hauge [24] made an overview for increasing complexity of the system.

![Figure 3.2](image)

**Figure 3.2** Overview of different ellipsometer configurations and their measured Mueller components.

As illustrated by Figure 3.2 the most straightforward rotating analyzer and polarizer is able to measure nine out of sixteen Mueller elements. With adding a rotating compensator before or after the sample the first three rows or columns can be determined. Only with two rotating compensators can the full Mueller matrix be measured. This configuration is the most advanced and used in the so-called Mueller matrix ellipsometer.

These configurations also differ in their measurement range, the rotating analyzer and polarizer configuration can only measure 0° ≤ Δ ≤ 180°. It cannot determine the sign of Δ and loses sensitivity near 0° and 180°. By adding a compensator the full measurable range of -180° ≤ Δ ≤ 180° is covered and the depolarization can be determined. One disadvantage is a more advanced calibration procedure because the compensator is chromatic. Also the complexity increases with more elements and rotation stages. As for the dual compensator design the complexity increases with the number of measured parameters. This configuration can measure the full range of ψ and Δ, depolarization spectra and window effects in one measurement.

### 3.2 DESIGN GOALS

The purpose of this setup will be the determination of the ellipsometry parameters of 1 inch multilayer mirrors with a metal coating. The oxidation of the surface and the deposition of carbon will be measured. The setup should measure multiple wavelengths in order to collect enough information and make a distinction between the oxidation and the carbon. A full bandwidth source will add too much complexity and measurement time and is ruled out. The setup is due to physical constraints of limited to a minimum working distance around 30 cm. A preferable lateral resolution would be below
100 μm, in order to at least equal the resolution of the Woollam M2000. Another practical limitation lies in the vacuum chamber mounting, the adjustable stages have a weight limit of 2 kg, limiting the weight of the PSG and PSD part. And a lighter construction will have an added benefit in more resistance to vibrations.

### 3.3 RCE IMAGING ELLIPSMETER

Many different ellipsometer configurations are available besides the ones presented so far. In this research is chosen for the RCE (Rotating Compensator Ellipsometer) configuration. This type proves to have an optimal trade-off between complexity and accuracy. And this type operates at high intensities which make the use of a CCD camera with a limited dynamic range better possible. This is less of an issue with spectrometers or photodiodes.

The basic components for an imaging ellipsometer do not differ from a regular ellipsometer.

One other challenge with imaging ellipsometry is beam parallelism. Typically a parallel beam around 20 mm in diameter is used for imaging, compatible with 1 inch optics. If the beam is diverging then angle of incidence errors are induced, this reduces the image resolution. With collimating optics the light can be projected on a pinhole creating a point source. The smaller the pinhole the more parallel the light can be, but the intensity decreases with the decreasing the pinhole diameter. In practice the smallest pinhole giving enough intensity is used. Instead of a pinhole an optical fiber can be used. This creates advantages when mounting the system on a vacuum chamber, the stress on mounting mechanics can be reduced by coupling with a fiber.

The large diameter beam creates extra demands for the used optics. The polarizers and compensator should be very flat and uniform over their full diameter. Polarizers and compensators employ polarizing or dichroic thin films cemented to fused silica windows. The thin films can be non-uniform or there is a misalignment with cementing. Influence of residual ellipticity of the polarizer can be cancelled with a two zone measurement, but this only works for small errors, still requiring high quality optics. Component quality will be explored with the initial calibration.

The design should be multi-wavelength. By using more wavelengths more sample information is collected than previously possible with a monochromatic design. This should make it possible to do more precise measurements. By limiting the complexity no spectroscopic design is made, this would require a gas discharge lamp with limited life-time and scanning monochromator. Besides complexity in control and data processing this adds costs and increases the minimum acquisition time.

In order to reduce errors a two-zone measurement is used. This has been described in detail by Kleim [15], two measurements with the analyzer at ± 45° are averaged vanishing all azimuthal errors in the system. Two-zone averaging also eliminates small residual polarization errors in the compensator and analyzer and for the polarizer as well if it is set at 0° or 90°. In first order approximation only the window induced errors in Δ remain, these can be minimized by aligning the fast axis of both windows at either ± 45°.

There are different options for the light source, for single wavelengths a laser is used. It employs a narrow bandwidth with high intensity. For collecting more information about the sample and for measuring more complex multilayers often a spectroscopic design is used. A xenon or deuterium gas discharge lamp is used for creating a broad spectrum and a spectrometer is used for detection. In case of an imaging ellipsometer it is not possible to use a spectrometer, so a monochromatic, or semi-monochromatic light source should be used. In case of a spectroscopic imaging ellipsometer a broadband light source is used in conjunction with a scanning grating monochromator.

The detector is a CCD camera. The camera should be corrected for its spectral response and the shutter speed can be adjusted continuously during a wavelength scan [25] in order to increase the signal to noise ratio for wavelengths with lower transmission. In practice the frame rate of the camera is often limiting the acquisition speed. Single photodiodes or small linear arrays used with spot ellipsometers can be red very fast, but high bit depth CCDs remain relatively slow.
3.4 CALIBRATION

Most calibrations are with the setup in straight through configuration, like the polarizers extinction ratio and the compensator retardance. For calibrating the ellipsometer $\psi$ and $\Delta$ and Angle of Incidence (AOI) a commercial calibrated ellipsometer is used, the spectroscopic J.A. Woollam Co. M-2000X. This ellipsometer is also used for reference measurements after the first test measurements and the supplied CompleteEASE 4.64 software is used for modeling and simulations. Finally it will be used to measure the retardance of the compensator and determine the fast-axis of the windows and their retardance.
4 SETUP

As shown in the previous chapter there is chosen for the Rotating Compensator Ellipsometer (RCE) configuration. In this chapter all the different parts will be introduced and their specifications will be summarized.

In Figure 4.1 is a schematic overview of the final design. With on the left side the PSG, light source connected to the optical fiber used as collimator. Next are the polarizer, compensator and the window. In the middle is vacuum chamber with the electron gun for carbon deposition and the sample. And on the right side the PSD with the second polarizer and camera.

![Figure 4.1 Schematic overview of the realized setup.](image)

In practice the setup mounted on a vacuum chamber is illustrated by Figure 4.2. In the left part is in the middle the electron gun on top of the vacuum chamber visible, to the right is the PSG with the orange input fiber just visible. On the left is the PSD. In the top right picture is the stepper motor with the analyzer and the camera (in red). In the bottom right picture are the expanding optics visible followed by the polarizer and the compensator to the right of the picture.

![Figure 4.2 Pictures of the setup mounted of a vacuum chamber.](image)
4.1 LIGHT SOURCE AND POWER SUPPLY

The light source is a commercially available 4 wavelength LED source, the power supply is custom build to be triggered by the controller from the motorized rotation stages. This paragraph will give an overview of the important parameters and the power supply design.

4.1.1 LIGHT SOURCE

The light source is a LED4C38 from Thorlabs. The source employs 4 LEDs with 3 dichroic mirrors. These mirrors couple the light to a condenser lens making one collimated beam. Wavelengths of 455 nm, 530 nm, 590 nm and 627 nm were chosen. These wavelengths span a large range in the visible band, wherefore polarizers and compensators are widely available. They also have options in the near ultraviolet, which is interesting in an ellipsometry perspective, but thin-film polarizers with high performance in such a broad wavelength range are not widely available.

The LEDs are of the high power type and can source at least one ampere, for more details see Table 4.1. The lifetime is longer than 100000 hours.

![Figure 4.3 Picture of the Thorlabs LED4C38.](image)

Table 4.1 Properties of the LEDs

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Power (mW)</th>
<th>Source current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>455</td>
<td>40</td>
<td>1000</td>
</tr>
<tr>
<td>530</td>
<td>15</td>
<td>1000</td>
</tr>
<tr>
<td>590</td>
<td>25</td>
<td>1500</td>
</tr>
<tr>
<td>627</td>
<td>40</td>
<td>1400</td>
</tr>
</tbody>
</table>

The light is coupled out with a SM2 compatible aspheric condenser lens. Thorlabs delivers a standardized optical cage system with SM2 (60 mm) and SM1 (30 mm) size which are used for this setup.

4.1.2 POWER SUPPLY

The power supply for the light source is custom build due to the very specific task it is assigned. The system is centrally triggered by the motorized rotation stages controller, every pre-defined number
of degrees it releases a trigger signal. With this trigger signal the camera takes an image and the light source is powered on for at least the exposure time of the camera. The different colors are powered after each other for making one measurement with all wavelengths in one rotation. Besides this is it possible the power each LED continues for alignment purposes or single wavelength measurements. Waiting for trigger signals, powering the LEDs etc. is controlled by a microcontroller. A Microchip PIC16F1508 is used, this is a versatile controller with enough memory, storage and I/O pins for future expansions and convenient in-circuit programming options. The current through the LEDs is switched by low-voltage MOS-FETs which can be directly driven by the microcontroller. A 20 MHz crystal resonator delivers a stable clock signal. The voltage is stabilized and a number of buttons, LED indicators and switched complete the design for user control. The complete electric schematic is given in Appendix B. Two I/O pins are available for future expansion like control by the computer program.

Figure 4.4  Schematic working of the power supply.

The schematic working of the power supply is shown in Figure 4.4, the trigger is received by the controller which switches the current to the four different LEDs with a MOSFET. The series resistors are matched to the different LEDs for equal brightness during measurements.

The practical implementation is shown in Figure 4.5, a metal box with three soldering boards. The top board is for current matching of the different wavelengths. One central series resistor limits the current to approximately 900 mA, the removable series resistors can be used to match the current through the different LEDs for equal intensity on the detector. Attention should be paid to the manual mode. If the current is high the resistors tend to generate a lot of heat and care should be taken to prevent damage to the power supply.
Figure 4.5  Picture of the power supply.

The timing of the trigger is shown in Figure 4.6, the controller responds to a trigger signal of the stepper motor controller in 2.5 μs and blinks one of the LEDs for 10 ms. The camera has a trigger delay of approximately 25 μs with a shutter time of less than 1 ms. Any jitter in the timing will not result in underexposed images.

Figure 4.6  Timing diagram of the trigger.
4.2 GENERAL OPTICS

The light from the source is collimated, but still has a significant divergence. In order to minimize the divergence an extra collimator is used. The light is focused with a 100 mm achromatic lens on the entrance of a 550 μm core diameter multi-mode fiber. After the fiber is the light collimated by a 50 mm achromatic lens creating a parallel beam of about 23 mm diameter with a divergence smaller than 0.3°. The achromatic lenses have no shift in focal length for different wavelengths, making sure there is no difference in divergence between wavelengths. The general optics were manufactured by Thorlabs.

4.3 MECHANICS

The most advanced mechanics are the motorized rotation stages, their properties are summarized in Table 4.2. The rotation stages are manufactured by Standa. All stages are of the 8MR151 type.

<table>
<thead>
<tr>
<th>Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>4.5 arcsec</td>
</tr>
<tr>
<td>Wobble</td>
<td>0.6 arcmin</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>50°/s</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>10 μm</td>
</tr>
<tr>
<td>Controller</td>
<td>8SMC1</td>
</tr>
</tbody>
</table>

The hollow shaft is compatible with 1" optics and makes it possible to easily mount different optics. One other component is two vacuum chamber mounts from Woollam, in order to align the PSG and PSD with the sample. The two mounts can tilt and the PSD can also translate.

4.4 POLARIZERS

Two sets of polarizers have been used. The first set from Thorlabs, LPVISE100-A, was used for the initial testing. These were later on replaced by a set from Newport, 10LP-VIS-B, which had a higher extinction ratio for the shorter wavelengths. Another advantage of these Newport polarizers was the metal ring they are mounted in. This made mounting in the stage very straightforward. The Newport polarizers have a 17.8 mm clear aperture.

Figure 4.7 Picture of the Thorlabs LPVISE100-A.
Comparing Figure 4.8 and Figure 4.10 extinction ratio shows at 455 nm a specified ratio of about 1:300 versus 1:2500. At the other wavelengths, 530 nm, 590 nm and 627 nm is the extinction very high, at least around 1:10000 for both polarizers.
4.5 COMPENSATORS

Two different compensators have been used. One zero-order quarter wave plate from Thorlabs, WPQ0SM-633. And secondly an achromatic quarter wave plate from Edmund Optics, #48-497. The Thorlabs compensator is mounted in a 1 inch metal ring. The retardation specification is given by Figure 4.11.

![Figure 4.11](image)

Figure 4.11 Retardance spectrum of the Thorlabs WPQ0SM-633.

The retardance is specified within λ/300. The reflectance is shown in Figure 4.12 this will show to be of importance in the results chapter.

![Figure 4.12](image)

Figure 4.12 Reflectance spectrum of the Thorlabs WPQ0SM-633.

The retardance of the Edmund Optics compensator is given in Figure 4.13. The retardance is specified within λ/100 accuracy. This compensator was mounted in a 30 mm ring with 23 mm clear aperture.
Figure 4.13  Retardance spectrum of the Edmund Optics #48-497.

Detailed reflectance data was not available for the Edmund compensator, it is specified at less than 1% for the full wavelength range.

4.6 CAMERA

For imaging is a monochrome CCD camera used with a high bit rate for maximum sensitivity. Due to previous experience a camera from Allied Vision Technologies was chosen. The Stingray F-145B with a FireWire 800 connection. In Table 4.3 is an overview of the most important properties.

Table 4.3 Properties of Stingray F-145B

<table>
<thead>
<tr>
<th>Specification</th>
<th>1388 x 1038</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td></td>
</tr>
<tr>
<td>Sensor size</td>
<td>Type 2/3</td>
</tr>
<tr>
<td>Max fps at full</td>
<td>16</td>
</tr>
<tr>
<td>resolution</td>
<td></td>
</tr>
<tr>
<td>A/D</td>
<td>14 bit</td>
</tr>
</tbody>
</table>

The maximum frame rate for lower resolutions is 30 fps. The camera is like the light source power supply triggered by the rotation stages controller. The trigger delay of the camera is minimal 5.40 µs if reading of the previous image is already finished, if not it may increase to 23.20 µs. The trigger can be programmed for rising or falling edge. For alignment purposes is the trigger disabled and the camera can show a live view of the sample.

4.7 ELECTRON GUN

The electron gun used for experiments is the Kimball Physics ELG-2 with an energy range of 100 eV to 2 keV. The electron gun is shown in Figure 4.14, the electron gun is controlled by the EGPS-1022 power supply unit. This power supply not only controls the output energy and current, but also the beam focus and deflection voltages.
4.8 SOFTWARE

The hardware is controlled by a C# program programmed in the integrated development environment Visual Studio Express 2010 from Microsoft Corporation. The program is a stripped version of a general interfacing and measurement program developed previously to automate various setups with easy integration of new devices due to a modular character.

The program is also used for the alignment of the setup and the azimuthal angles of the optics. After setting the different measurement parameters like the number of rotations per measurement and the number of images per angle the measurement can be started. The program will then collect all images for the four different wavelengths at the different angles. At the moment the program is not used for calculating the Fourier components of sample parameters, this could be easily added in the future.

With the measurement interface a single measurement or multi measurements can be started. The data will be written to the disk as single images from each measurement.

The data is analyzed with different Matlab scripts, the data is processed and plotted. The single calibration and test measurements are directly processed, the long real-time measurements are processed in different steps in order to save time. The disk activity heavy initial calculation of Fourier components is done separately from calculating the sample parameters. The saved Fourier components reduced storage requirements 10 times speeding up the later data processing significantly. The most important Matlab scripts are in 8.2Appendix C.
Finally the microcontroller in the light source power supply is programmed with MPLAB X this integrated development environment is supplied by the manufacturer of the microcontroller, Microchip. The firmware is written in a C language spin-off. The programming can conveniently be done in circuit, making applying updates or different parameters very straight forward.
5 CALIBRATION OF OPTICAL COMPONENTS

This chapter will first show the results from the different calibrations of the optical components, next the proof of concept measurements will be shown.

5.1 LIGHT SOURCE

The spectrum of the light source was measured, exiting the fiber, with an Ocean Optics USB2000+ spectrometer. The spectra were measured with and without a bandpass filter.

In Figure 5.1 the different spectra are presented, the four LEDs have very different bandwidth. The 530 nm LED exhibits almost twice the bandwidth of the 590 nm LED. A summary of the results are shown in Table 5.1.

![Figure 5.1: Spectra of the four LEDs.](image)

Table 5.1: Measured properties of the LEDs

<table>
<thead>
<tr>
<th>LED</th>
<th>Fiber</th>
<th>Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FWHM (nm)</td>
<td>Center (nm)</td>
</tr>
<tr>
<td>455 nm</td>
<td>22.4</td>
<td>463.4</td>
</tr>
<tr>
<td>530 nm</td>
<td>29.8</td>
<td>526.1</td>
</tr>
<tr>
<td>590 nm</td>
<td>15.3</td>
<td>589.7</td>
</tr>
<tr>
<td>627 nm</td>
<td>17.6</td>
<td>631.4</td>
</tr>
</tbody>
</table>
5.2 POLARIZERS

Both sets of polarizers were measured in a straight through configuration of the optics. The extinction ratio were mapped and averaged over the surface area. The results are presented in Figure 5.2.

![Extinction Ratio](image)

*Figure 5.2  Extinction ratios of the different polarizer pairs.*

The Newport polarizers have been used, they also have been checked for their uniformity. The measured extinction ratios are in general lower than the specification, but the Newport pair should be very suitable. An extinction ratio minimum of $1 \cdot 10^3$ is expected to be sufficient for the first order approximation by Kleim. The residual ellipticity is expected to cancel out with a two zone measurement.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Extinction ratio</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>455 nm</td>
<td>$1.1 \cdot 10^3$</td>
<td>$1 \cdot 10^2$</td>
</tr>
<tr>
<td>530 nm</td>
<td>$2.2 \cdot 10^3$</td>
<td>$1 \cdot 10^2$</td>
</tr>
<tr>
<td>590 nm</td>
<td>$2.0 \cdot 10^4$</td>
<td>$9 \cdot 10^3$</td>
</tr>
<tr>
<td>627 nm</td>
<td>$2.0 \cdot 10^4$</td>
<td>$9 \cdot 10^3$</td>
</tr>
</tbody>
</table>

The standard deviations for the two longest wavelengths are rather high due to the large uncertainty for the very low light transmission in the crossed position of the polarizers. This problem was reduced as much as possible by increasing the exposure time of the camera, but could not be completely eliminated.
Figure 5.3  Extinction ratio map of the Newport polarizers.

The maps show in general a uniform performance of the polarizers. For 590 nm and 627 nm the intensity measured when the polarizers are in crossed position is very close to the background noise, increasing the errors near the edges where the intensity is lowest.
5.3 COMPENSATOR

The two different quarter wave plate were tested and calibrated. The wave plates are measured in the rotating compensator, PCA, and rotating analyzer, PCA, configuration as described in section 2.5.2.

5.3.1 EDMUND OPTICS WAVE PLATE

The results from the calibration of the Edmund Optics wave plate are shown in Figure 5.4. In red is the specification given by the manufacturer and the red dotted lines show the boundaries. The other colored lines show the calibration, both methods agree very well. The specification of the manufacturer is lower, and for 455 nm the uncertainty intervals also do not overlap.

Achromatic 1/4 Waveplate Edmund Optics NT46-558

![Graph showing measured retardance and specification](Figure 5.4)

*Figure 5.4 Overview of the measured retardance with different methods and the specification.*

Next are the detailed results from the PCA measurement in order to have a look on the uniformity of the compensator. The results for each wavelength are shown in figure Figure 5.5, the measurements are averaged for A = ±45°. The results look quite uniform with about 2° in spread, only some structure towards the edges of the frame is visible. This picture changes when looking at the not averaged results, four groups of spots are visible, and in the center is also a pattern visible.
Figure 5.5  Averaged retardation of the Edmund Optics wave plate in PCA configuration.

Figure 5.6  Not averaged retardation shows repetitive spots (455 nm).
To investigate these features the calibration procedure was slightly changed. The wave plate was fixed and the analyzer was rotated, PCA$_R$ configuration. The results from different angles of the wave plate are shown in Figure 5.8. A clear spot is visible, a speck of dust, it rotates perfectly with the rotation of the wave plate. So does the gradient in the retardation that is visible, this indicates that it is no alignment.

![Figure 5.7 Retardation of the Edmund Optics wave plate in PCA, configuration.](image)

error of the element. In also cannot be due to an influence of the polarizers, the light source or the detector. If this would be the case the gradient would not change in angle with the rotation of the wave plate.

The wavelength dependent results are given in Figure 5.7. The gradient decreases with wavelength, this could be explained by an angle between the two crystal planes of the wave plate. If there is slightly longer path to travel on a part of the wave plate, then the shorter wavelengths will be more influenced. Their path is relatively longer leading to a larger retardance.
These results show that the wave plate is performing beyond the specification, in absolute values this is maybe no large problem, but the large gradient will make it difficult to perform measurements with this wave plate.
Figure 5.9  Retardation of the Edmund Optics wave plate in PCA, configuration in comparison with the measurements from the Woollam ellipsometer.
Due to the gradient in the Edmund Optics wave plate measured with the calibration, it was measured on the Woollam ellipsometer. The imaging ellipsometer is not validated and this could be due to other optical defect and or effect is the system. The Woollam ellipsometer is calibrated commercially and could give some more conclusive insight in the performance of the wave plate. The measurements with the Woollam where performed in transmission mode. The wave plate was placed in a holder and translated with the motorized wafer stage.

In Figure 5.9 are the results from the previous calibration on the left side, on the right side are the results from the Woollam. The results show strong agreement, the measurements in one row have a constant alignment, between rows in manually realigned. Still in one row is an 8 degrees spread visible which is twice larger than the specified spread of 3.6°.

The 627 nm results look different. This is explainable by the very low signal on the detector. The oscillation measured by the detector is zero for 90° retardance, the measured retardance was around 91° and a typical signal is illustrated by Figure 5.10. The noise is half the signal making it difficult to measure the gradient visible at the other wavelengths. This does not mean the wave plate performs well for 627 nm as will be shown in the next paragraph.

Figure 5.10  Intensity measured by the detector. The oscillation is very small compared to the noise.
5.3.3 THORLABS WAVE PLATE

Next is the calibration of the second wave plate. This wave plate was made by Thorlabs and is of the chromatic type. In Figure 5.11 is an overview of the different measurements, the wave plate proves to be within specification. The $\lambda/300$ specification is plotted for the whole range, but the wave plate is optimized for 633 nm. Far from this center wavelength the measurements are outside the dotted region, but here the specification limit less meaningful. Visible from the trend one would expect 455 nm to be higher in retardance, this $1/\lambda$ behavior is also predicted by literature [8].

![Thorlabs WPQ10M-633 nm](image)

*Figure 5.11 Overview of the measured retardance with different methods and the specification.*

Secondly in Figure 5.12 are the results from the rotating compensator method. This wave plate showed less than half the variation in retardance compared to the Edmund Optics wave plate. Some small spots are visible due to dust speckles.
Figure 5.12  Retardation of the Thorlabs wave plate in PC,A configuration.

The Rotating analyzer results are presented in Figure 5.13, again the Thorlabs wave plate shows less variation. The variation is ≤5°, while for the Edmund Optics the variation is ≤10°. In addition is the variation is more symmetrical, note that the dust speckles are now clearly visible.
Figure 5.13  Retardation of the Thorlabs wave plate in PCA, configuration.
5.4 WINDOWS

The windows act as small retardation wave plates. The windows were measured in a similar fashion as the wave plate with the Woollam, in transmission mode. This only gives an indication of their retardance since the mounting on the vacuum chamber will inevitably lead to more stress induced birefringence. The windows their fast axis was determined and their retardance was measured. The results are given in Figure 5.14, both windows exhibit birefringence. The analyzer window appears to be of higher quality. Due to the non-uniformity it is almost impossible to make a robust correction for measured data. The effects can be minimized by rotating their fast axis to ±45° compared to the optical axis.

Figure 5.14  Retardance of the windows.
6 CALIBRATION MEASUREMENTS

The test measurements will be divided in two parts. The first measurements were performed on a table, with the sample in atmospheric conditions. These measurements were for alignment and rudimental testing purposes. The first were performed with an angle of incidence of approximately 45°, after successful results it was rotated to 70°. This angle is close to the final angle when the ellipsometer is mounted on the vacuum chamber. After these measurements the setup was mounted on the vacuum chamber, realigned and a second series of measurements was performed. These measurements focused on the influences of the vacuum chamber windows. The measurements will be concluded with the measurement of real-time carbon deposition and oxidation of the surface.

6.1 TABLE TOP MEASUREMENTS

The first measurements were performed on a table with an angle of incidence of approximately 45°. These initial measurements were performed with the Edmund Optics wave plate as compensator. The sample for measurements was a 5 mm thick multi-layer mirror specimen (MLM) with an slightly contaminated surface. The Woellam with an AOI of 70° shows one spot on the surface with $\psi \approx 24.8^\circ$ and $\Delta \approx 132.4^\circ$, these values will be showed in more detail in Figure 6.11 when the comparison is made.

6.1.1 MLM SAMPLE WITH EDMUND OPTICS

The initial results for 455 nm are shown in Figure 6.1. One would expect very few visible features. In Figure 6.11 are the reference measurement performed with the Woellam ellipsometer, here is mainly one spot in $\Delta$ visible. With an angle of incidence of 45° the measurements are less sensitive and should show nearly no features. In Figure 6.1 on the left side is $\psi$, $\psi$ shows a unexpected pattern of spots on the edge of the sample and a cross in the center. This might be caused by the gradient across the surface of the compensator. On the right side is the $\Delta$ graph, this shows some details near the edges of the sample, but the sample center is rather uniform. The other wavelengths look similar and are shown in Figure 6.2.

Next the influence averaging for the analyzer angle was investigated. Two measurements with the analyzer azimuth set $\pm 45^\circ$ were averaged. The results are shown in Figure 6.3, the graph for $\psi$ is not changing and the graph for $\Delta$ becomes cleaner.
Figure 6.2  Test measurement with Edmund Optics and MLM sample, Aol = 45°. The other wavelengths.

Figure 6.3  Test measurement with Edmund Optics and MLM sample, Aol = 45°, the averaged result.

One other test was performed to confirm that the spots are induced by the wave plate and are not the result from some other component. Or is the result from misalignment of one of the optical components. The wave plate was removed from the mounting ring, rotated 180°, so the optical path through the wave plate was reversed. The imaging results are shown in Figure 6.4, the measurement is clearly mirrored. Especially the tales of the center cross like figure is mirrored, but also the tales of
the larger red spots near the edge of the sample. These results together with the calibration measurements led to the conclusion that the Edmund Optics wave plate was not suitable for measurements and it is returned to the manufacturer.

![Figure 6.4](image_url) The influence of flipping the wave plate in the mounting ring.

### 6.1.2 MLM SAMPLE WITH THORLABS

The Thorlabs wave plate performed better, but was also now without flaws. It also initially showed artefacts, typical results are depicted in Figure 6.5. These results are only for 455 nm, $\psi$ shows the red spot on the right side. The image for $\Delta$ looks as expected.

![Figure 6.5](image_url) Spots in the imaging of the Thorlabs wave plate.

The large difference between this artifact and the ones visible with achromatic wave plate is the wavelength dependence. The artifact decreases in intensity with wavelength and is completely disappeared for 627 nm. These results are in Figure 6.6. This result is probably due to internal reflections in the optical system, the anti-reflective coating of the wave plate is highly optimized for 633 nm, as shown in Figure 4.12. After contact with the supplier for more reflectance data, it was stated that this can be as high as 20% around 500 nm.
The spot loses intensity with longer wavelengths and disappears completely for 627 nm, very close to the design wavelength of 633 nm.

This information suggested it should be possible to reduce this artifact with better alignment. After some careful realignment the results shown in Figure 6.7 were achieved. These pictures showed no artifacts any more, creating the conditions to take the next step towards real measurements.

The final setup will perform measurements with an angle of incidence close to 70° for higher sensitivity.

Rotation of the arms led to the expected results, Figure 6.8 shows the increased sensitivity at 70° Aol. The spot in Δ of about 0.5° with an AOl of 45° increased to 1.0° for an Aol of 70°. One can also notice the increased perspective distortion, due to the high angle of incidence is the picture more compressed in the direction of the optical axis.
Figure 6.7  With good alignment no unwanted artifacts are visible.
Figure 6.8 After alignment of the optical components the setup was rotated to AOI of 70°, the sensitivity increase makes sample surface features better visible.

One more test was conducted before the results were compared to the Woollam. The influence of the bandwidth of the light source was measured. By measuring with and without a filter, the results are shown in Figure 6.9.

Figure 6.9 Influence of a filter after the light source.
There is a shift in the values of $\psi$ and $\Delta$ visible, the details are very similar. For this measurement the degree of polarization was calculated, this is an indication of scattering effects induced by sample roughness but it is also influenced by imperfections in the optics. It is equal for both measurements with a value of 98.5%.

### 6.1.3 MLM SAMPLE TEST

After previous tests the data from the setup was compared to the data of the Woollam. The data of the Woollam in Figure 6.11 showed a discrepancy in the values of $\Delta$ in Figure 6.8. The measurements were performed in the wrong zone. In the alignment phase the intensity is minimized by crossing the polarizers, but it hard to distinguish between s- and p-polarization. The optics were rotated over 90° in order to select the right zone. From now on all measurements will be averaged for $\Delta = \pm45^\circ$ for best result, unless stated otherwise. This averaging eliminates most errors in the first order.

![Figure 6.10 Measurements in the right zone.](Image)

The measurements are agreeing very well in details visible on the surface of the sample. In absolute values there is a difference of around 1% for each $\psi$ and $\Delta$. This might be due to angle of incidence errors.
Figure 6.11 Woollam reference measurements, AOI = 70°.
When comparing the results on a location near the spot, the trend is similar, only 455 nm is further apart. This is shown in Figure 6.12.

![Graph comparing the results from the IE with Woollam reference measurement.](image)

**Figure 6.12** Graph comparing the results from the IE with Woollam reference measurement.

By optimizing the angle of incidence of the Woollam data with the supplied simulation function in the ComplEASE software, better results are achieved. The optimized simulated angle of incidence is 70.7°. Only the 455 nm point does not fit very well, this might be due to the bandwidth of the source, or the quality of the polarizers. Their extinction ratio might be too low for the first order approximation from Kleim et al. [15].

![Graph comparing the results from the IE with Woollam reference measurement.](image)

**Figure 6.13** Graph comparing the results from the IE with Woollam reference measurement.
6.2 CALIBRATION SAMPLE

Next a calibration sample was measured. The calibration sample was a one inch silicon wafer with a checker pattern of silicon oxide. The measurements are shown in Figure 6.15, the results can be compared with the Woollam measurements in Figure 6.16. The measurements show clear resemblance with each other. The high signal compared to the MLM sample gives less visible noise, also Figure 6.16 shows better agreement between the two measurements. Still for 455 nm the discrepancy is largest.

![Figures showing measurements of Si/SiO calibration wafer.](image)

*Figure 6.14 Measurements of the Si/SiO calibration wafer.*
Figure 6.15 Woollam reference measurements, AOI = 70°.
Figure 6.16  
Graph comparing the results from the IE with Woollam reference measurement.
6.3 VACUUM CHAMBER MEASUREMENTS

After the measurements in the table top configuration the setup was moved to the vacuum chamber. The setup was mounted on the vacuum chamber and aligned. This alignment was more complicated, because the sample could not be rotated freely inside the vacuum chamber. So some degrees of freedom were missing. This made it harder to create a completely uniform reflection from the sample on the detector. Apart from this two extra components were added to the optical path, the windows of the vacuum chamber. First the influence of those windows will be investigated. The windows exhibit a small birefringence which might be stress dependent. The windows will be tested under atmospheric pressure and vacuum condition and the influence of a single window will be determined.

After the first measurements it became know that the windows were probably not specified for ellipsometry. They were replaced by a set of low birefringence fused silica windows calibrated in paragraph 5.4. In Figure 6.17 are the results from these windows. The measurements with the first windows are in 8.2 Appendix A

![Figure 6.17 Fused silica windows.](image)

The results in \( \psi \) show now more details than before, and the \( \Delta \) values show less spread than before. It is reduced from around 7° to 4°. This makes more details visible. This is also confirmed by the not averaged measurements in Figure 6.18.
The difference in $\psi$ is about half compared to the other windows, but it shows a gradient across the whole surface, which almost disappears with averaging. The $\Delta$ values are also closer, but mainly the reduction in individual spread is an improvement. The difference between $\pm 45^\circ$ is comparable.

In order to confirm that the gradients are indeed due to window effects another series of measurements was performed. By changing one parameter each time, the influence of the windows was further investigated. First a measurement was performed with low pressure, vacuum conditions, hereafter the setup was vented and another measurement was performed under atmospheric conditions. This would show if the low pressure adds any strain to the windows, increasing any gradients. In Figure 6.19 are the two measurements for comparison, there is no difference between the two measurements. This would imply that the strain is constant after mounting. Note the two blue spots in the measurements, these are depositions caused by testing the electron gun.

Figure 6.18  Not averaged measurement with the fused silica windows.

Figure 6.19  Influence of pressure on the measured parameters with left vacuum and right atmospheric pressure.
After venting the vacuum chamber, the window before the analyzer was removed. The system was re-aligned and a measurement was performed. In Figure 6.20 is the result from this measurement, the result is less detailed than then the measurement with two windows. It appears the windows were compensating each other. Near the top and bottom of the sample the gradient in $\psi$ is less, but in $\Delta$ a large gradient is visible, rendering the measurement less useful. On the right side is a measurement with the window rotated over 180°, this clearly shows the influence of the window. The $\psi$ picture is similar, but the large gradient in $\Delta$ is perfectly rotated.

For next measurement was the polarizer window removed and the analyzer window mounted. This showed similar results as the with only the polarizer window, the results are shown in Figure 6.21.

In Figure 7.1 is on the left side a measurement without both windows, this looks very comparable to the measurements on the table. In $\Delta$ the initial red spot is visible again and is not disappearing in the background. On the right is a measurement with both windows mounted again. The large gradient in $\Delta$ is still visible due to the rotated polarizer window.
Figure 6.22  Influence of the windows, with left the analyzer window and right both windows mounted. Note the influence of the rotated polarizer window. Bottom the measurement with no windows, but still mounted on the vacuum chamber.

After these measurements the polarizer window was rotated to his original position and the optics were aligned for the right zone. Next are the measurements with e-beam induced carbon growth.
7 RESULTS AND DISCUSSION

After completing the calibration measurements, the imaging ellipsometer can be used for measuring thin overlayers. Typically contamination is of sub nanometer thickness and can be detected very well with ellipsometry. One process of interest is carbon growth under EUV irradiation, which can be mimicked by electrons with a hydrocarbon background pressure. Here, the carbon growth rate for two different electron currents will be measured.

First the sample was cleaned. It was exposed to atomic hydrogen for 24 hours with a 33% duty cycle. By exposing it to atomic hydrogen, the sample was brought back to a pristine state. The results from cleaning are shown in Figure 7.1. The field of view was reduced in order to speed up the measurements and the center of the sample was selected so the influence of the top and bottom gradients was reduced. The measurements show some more noise, because the number of rotations was reduced again in order to speed up measurement. After these adaptations, the measurement time for one averaged image was between 70 and 90 seconds, which varied because the time to write data to the disk appeared to be fluctuating. For carbon deposition, 1 keV electrons are used with different currents, as precursor a dodecane filled reservoir with needle valve is used. The pressure ranged from $4 \cdot 10^{-9}$ mbar with no precursor and fluctuated between $5 \cdot 10^{-5}$ mbar to $5 \cdot 10^{-4}$ mbar with the precursor gas switched on.

The measurement shows the sample could be cleaned to a uniform state. In $\psi$ a light contour of the spot in the bottom is still visible. The $\Delta$ pictures do not show any details, only a gradient towards the bottom is visible.

![Figure 7.1](image_url)  
*Figure 7.1  Left, before cleaning. Right, after cleaning with atomic hydrogen.*
Figure 7.2 The sample after the first growth, plotting these rather large signals make the gradients less significant.

For simplicity and readability in the next part only the 590 nm results will be shown. In the next part the step wise carbon deposition and oxidation of the surface will be shown. A cross section that is used for calculations is indicated with a red line for $\psi$ and blue for $\Delta$. The cross section for $\psi$ and $\Delta$ are shown in the lower right corner and the calculated carbon and oxide thickness is shown in the top right corner. The scale for $\psi$ and $\Delta$ is fixed on 21° to 23° for $\psi$ and from 105° to 130° for $\Delta$.

Figure 7.3 Fitting of optical constants of the surface

For fitting the measured data a Fresnel reflection model was implemented in Matlab with a least squares fitting algorithm in order to calculate the optical constants of the substrate. The results for this fit are shown in Figure 7.3. The MSE for this system is 3.0, in general a fit with a MSE below 20 is considered acceptable, and a MSE below 10 is a very good fit.

With the calculated optical constants the optical model can be used to calculate the layer thicknesses. This has been done time resolved, the results are shown in the following pictures.
The sample right before growth.

At the beginning of the measurement a small amount of carbon is modeled, this shows the sensitivity limitations of the system. The noise visible in $\psi$ and $\Delta$ leads to an absolute error in in the carbon and oxidation thickness of 0.07 nm. The model also shows a small gradient of carbon on the surface.

First the electron gun was powered on with 60.0 $\mu$A, after 15 minutes of exposure with the electron gun the carbon visible on the area of impact is completely removed. This is shown in Figure 7.5, this implies the cleaning with atomic hydrogen is limited, while the high energy electron are able to remove the last contamination.
When the precursor gas supply is turned on, the cleaning changes quickly to deposition, the first measurement after the precursor is turned on shows a peak of 0.35 nm of carbon, Figure 7.6. Hereafter the growth quickly stabilizes as will be shown later. For this very small thickness no signal is visible in $\psi$, while $\Delta$ already shows a 0.5° shift, this can be expected from the sensitivity.
Figure 7.6  The sample right after the precursor gas is turned on.

After two hours of exposure 4.0 nm of carbon has been deposited on the sample, the data is shown in Figure 7.7. Now oxidation of the surface is visible as well, around 0.1 nm.
Figure 7.7 The sample after 2 hours of exposure. The carbon grows gradually and oxidation starts to show.

The sample was exposed in total exposed for 3 hours, the fit of the final measurement is shown in Figure 7.8. Here the MSE is 3.4, all fits had a MSE below 4.0. This gave confidence in the model and data processing. Finally the imaging ellipsometer is compared to the calibrated Woollam ellipsometer.

Figure 7.8 The fitting of carbon and oxide show typically a MSE smaller than 4
In Figure 7.9 is the comparison between the calculated thicknesses from the Woollam ellipsometer in the top and from the imaging ellipsometer in the bottom. The carbon thickness looks very similar, the peak value of about 6.2 nm is consistent. The shape is very similar, only the imaging ellipsometer shows more sharp peaks. This could be explained by the averaging with the Woollam data, the scan was measured with a step size of 300 μm and interpolated. Both have a similar spotsize versus resolution, the Woollam spotsize is 130 x 100 μm, the imaging ellipsometer measures with a lateral resolution of 90 μm per pixel. This makes the Woollam data naturally smoother. For the oxidation of the surface data the imaging ellipsometer shows more noise. The signal for the oxide is very small and this gives the Woollam an advantage with 1000 wavelength points instead of 4. And the Woollam uses a higher number of samples for each measurement, applying more averaging. Still both show a maximum of 0.2 nm, although opposite in sign. This can be explained by the way the model was applied. For both models the substrate was used for modeling the bottom layer of the

![Figure 7.9](image-url)

*Figure 7.9 On top are the carbon and oxidation thickness calculated ex-situ with the Woollam and bottom with the imaging ellipsometer.*

optical model and this differs for both measurements. During the in-situ measurements, with the imaging ellipsometer, the surface of the sample has near zero natural oxides. These have been removed with the hydrogen cleaning. After the real time measurements the sample was taken out of the vacuum chamber and measured on the Woollam ellipsometer. As soon as the sample is in an ambient environment the surface starts to form a natural oxide of several nanometers. When after the measurement the model is created by the same method of creating a substrate from the surface and adding two variable thickness layers for the carbon and oxidation this sign difference can appear. The sample does not grow any natural oxide where the carbon is deposited forming a protective top layer.
After the model verification the growth rate with different currents was calculated. Three measurements were performed, but only two will be used. The third measurement had some problems with the precursor gas supply and showed some steps in the growth. The results are shown in Figure 7.10, the 80.0 μA measurement is very linear, the 40.0 μA shows some curvature near the beginning and end. For the calculation of the growth rate the edges of each measurement were ignored, the results are given in Table 7.1. The growth rate doubles within the uncertainty when current is doubled, like expected from theory.

**Carbon deposition versus time**

![Graph showing carbon deposition versus time for two different currents.](image)

**Figure 7.10** The carbon deposition versus time for two different currents.

**Table 7.1** Carbon growth rate

<table>
<thead>
<tr>
<th>$I_{\text{gun}}$ (μA)</th>
<th>Growth rate (nm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.0</td>
<td>0.027 ± 0.001</td>
</tr>
<tr>
<td>80.0</td>
<td>0.056 ± 0.001</td>
</tr>
</tbody>
</table>
8 CONCLUSION

8.1 SETUP

The main goals of this research in creating a device that could measure in-situ layer deposition with spatial information in real-time have been achieved. The developed imaging ellipsometer uses less wavelength information than the Woollam spectroscopic ellipsometer, but is still capable of high sensitivity measurements. The imaging ellipsometers showed a gradient in the images due to the birefringence of the windows of the vacuum chamber. This influence could be minimized, but not eliminated. It is only possible to calculate window correction with a double rotating compensator design, with the current setup there are not enough independently measured sample parameters. Another solution by measuring the window birefringence before mounting is not very viable, not only is it very likely that the birefringence will change due to stress while mounting, also is it not possible to determine the exact path the light will travel beforehand for such a correction to be accurate.

For the time resolved measurements the center of the frame is selected, reducing the influence of the windows, and the signals are relatively large compared to the gradients. This also has the positive side effect of a shorter measurement time, one measurement takes between the 70 and 90 seconds. This is enough for the multiple hours time frames used for the measurements.

For flexibility it could be interesting to have a higher time resolution for faster processes like the first moment after the precursor is turned on. The measurement time is now limited by the frame rate of the camera, with a faster camera the stepper motor speed can be increased from 30 °/s to the maximum 50 °/s. This only would reduce the measurement time by almost 15 seconds, secondly if the number of images per degree of rotation could be increased, then one or a half rotation of the compensator could provide enough data for images with similar quality. The one image per degree setting used for current measurements makes two rotations necessary in order to suppress noise.

Another relatively straightforward improvement can be found in increasing the lateral resolution of the system, this could be achieved with a camera with smaller sensor or a longer focal length lens. A possible downside of a smaller sensor with equal number of pixels would be an increase of noise. Another optical improvement to the setup could be an Scheimpflug lens, it would eliminate the image skew and increase the horizontal resolution.

8.2 MEASUREMENTS

The test measurements show agreement with the Woollam data, only for 455 nm the deviation is larger, because of the lower polarization degree of the light for 455 nm. The bandwidth of the source could also play a role, although this is not confirmed by the 530 nm data. The degree of polarization could be improved by using higher quality polarizers. Filters might be interesting in order to reduce the bandwidth of the source and increase the contrast.

The optical model created for calculating the layer thicknesses shows good agreement with the spectroscopic Woollam ellipsometer, this leads to the conclusion that the setup is accurate enough for high precision measurements and can be even improved in the future by options from the previous paragraph.

Next the setup can be moved to an EUV test source for measuring EUV induced carbon deposition.
REFERENCE DOCUMENTS


APPENDIX A SUPPLEMENTARY DATA

First set of windows

Figure 9.1 First measurement on the vacuum chamber

In Figure 9.1 is the first measurement on the vacuum chamber after alignment. The difference between the measurements in table top configuration is clearly visible. Compared to Figure 6.10 the vacuum chamber measurements show no information in ψ. In the Δ images is the spot still visible, but the contrast is reduced due to edge gradients at the top and bottom of the image.

In order to further investigate the effect of the windows and isolate their influence, next the not averaged measurement for 455 nm is shown in Figure 9.2. Here the large differences becomes apparent. For the ψ values in without windows there is 0.1° degree difference between A = ±45°, on the contrary to with windows when the difference is approximately 15°, but the image is also inverted.

For Δ is the influence also very clear, without windows the spread is about 1°, with windows the values are about 30° apart. The image is not inverted, but A = +45° seems to show a larger gradient near the edges of the sample.
Ex-situ

Figure 9.2  Comparison not averaged in-situ and ex-situ results.
The other wavelength data from Figure 7.1.

Figure 9.3  Left, before cleaning. Right, after cleaning with atomic hydrogen.
The other wavelength data from Figure 7.2.

Figure 9.4  The sample after the first growth, plotting these rather large signals make the gradients less significant.
APPENDIX B HARDWARE

In this section the details of the power supply of the light source will be discussed. This can be used for servicing the power supply, upgrading the firmware or current adjustments of the LEDs. First is the electrical diagram in Figure 9.5, on the left side are the high power LEDs with series resistors, in the middle is the micro controller and on the right side are the buttons and indicators for user interaction.

Next in Figure 9.6 is the implementation of the power supply with an overview of all connectors. Most useful are P1..P10 for adjusting the current through the LEDs by changing the series resistors and header H15 is used for in-circuit programming of the microcontroller.

For each LED two resistors can be placed, the header on the left, for example P2 is connected to the LED and the with right header P1 are the two outputs connected. So the wire and larger resistor visible are connected in series. The same is used with P9 and P10, this is the common series resistor. The top and bottom output of P10 are the input and output, the other connections are in a series configuration adding up directly for the total resistance.
Figure 9.5   The schematic of the power supply and the parts.
Figure 9.6 The connectors.
Table 9.1  List of the different headers in the power supply.

<table>
<thead>
<tr>
<th>Header</th>
<th>Function</th>
<th>Header</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Cathodes of LEDs</td>
<td>H11</td>
<td>Buttons</td>
</tr>
<tr>
<td>H2</td>
<td>Anodes of LEDs</td>
<td>H12</td>
<td>Reset indicator Blue LED</td>
</tr>
<tr>
<td>H3</td>
<td>Power connector</td>
<td>H13</td>
<td>Future expansion header</td>
</tr>
<tr>
<td>H4</td>
<td>Power supply connector</td>
<td>H14</td>
<td>Camera I/O</td>
</tr>
<tr>
<td>H5</td>
<td>Power for µC</td>
<td>H15</td>
<td>In Circuit Programmer header</td>
</tr>
<tr>
<td>H6</td>
<td>High Power warning red LED</td>
<td>P1 – P2</td>
<td>R1, 455 nm series resistor</td>
</tr>
<tr>
<td>H7</td>
<td>Light color indicator LEDs</td>
<td>P3 – P4</td>
<td>R2, 530 nm</td>
</tr>
<tr>
<td>H8</td>
<td>Signal connector</td>
<td>P5 – P6</td>
<td>R3, 590 nm</td>
</tr>
<tr>
<td>H9</td>
<td>Switches</td>
<td>P7 – P8</td>
<td>R4, 627 nm</td>
</tr>
<tr>
<td>H10</td>
<td>Trigger</td>
<td>P9 – P10</td>
<td>R5, general series resistor</td>
</tr>
</tbody>
</table>

The orientation and numbering of the headers is shown in Figure 9.7. The black connectors are flat on one side and have a plastic pin on the other side. The plastic pin should always be facing down or two the right if the power supply is oriented as in Figure 9.6. The white connectors have only one possible orientation.

Figure 9.7  The pin numbers of the connectors.

Next are the pin-outs of all the headers listed in Table 9.2

Table 9.2  The pin-outs of the different headers.

<table>
<thead>
<tr>
<th>Header</th>
<th>Pin</th>
<th>Properties</th>
<th>Header</th>
<th>Pin</th>
<th>Properties</th>
<th>Header</th>
<th>Pin</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>1</td>
<td>+ 455 nm</td>
<td>H6</td>
<td>1</td>
<td>+ 12V</td>
<td>H12</td>
<td>1</td>
<td>Gnd</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>+ 530 nm</td>
<td></td>
<td>2</td>
<td>Gnd</td>
<td></td>
<td>2</td>
<td>Pin 3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>+ 590 nm</td>
<td></td>
<td>1</td>
<td>+ 12V</td>
<td></td>
<td>1</td>
<td>H14 – 1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>+ 627 nm</td>
<td></td>
<td>2</td>
<td>nc</td>
<td></td>
<td>2</td>
<td>H14 – 2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>nc</td>
<td></td>
<td>3</td>
<td>Blue</td>
<td></td>
<td>3</td>
<td>H14 – 3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>nc</td>
<td></td>
<td>4</td>
<td>Green</td>
<td></td>
<td>4</td>
<td>H14 – 4</td>
</tr>
<tr>
<td>H2</td>
<td>1</td>
<td>nc</td>
<td></td>
<td>5</td>
<td>Yellow</td>
<td></td>
<td>5</td>
<td>H14 – 5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>6</td>
<td>Red</td>
<td></td>
<td>6</td>
<td>H14 – 6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>- 455 nm</td>
<td>H8</td>
<td>1</td>
<td>Pin 13</td>
<td></td>
<td>7</td>
<td>Pin 9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>- 530 nm</td>
<td></td>
<td>2</td>
<td>Pin 12</td>
<td></td>
<td>8</td>
<td>Pin 8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>- 590 nm</td>
<td></td>
<td>3</td>
<td>Pin 11</td>
<td></td>
<td>9</td>
<td>Pin 5</td>
</tr>
</tbody>
</table>
Last are the external controls and connectors of the power supply. They are shown and listed in Figure 9.8.

<table>
<thead>
<tr>
<th>Pin</th>
<th>Function</th>
<th>Pin</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Manual/Auto (Up/Down)</td>
<td>10</td>
<td>+5 V</td>
</tr>
<tr>
<td>2</td>
<td>High Power/Normal (Up/Down)</td>
<td>11</td>
<td>Gnd</td>
</tr>
<tr>
<td>3</td>
<td>Color select</td>
<td>12</td>
<td>+5 V</td>
</tr>
<tr>
<td>4</td>
<td>Reset indicator</td>
<td>13</td>
<td>VDD</td>
</tr>
<tr>
<td>5</td>
<td>Reset</td>
<td>14</td>
<td>VPP/MCLR</td>
</tr>
<tr>
<td>6</td>
<td>High Power Warning</td>
<td>15</td>
<td>ICSPCLK</td>
</tr>
<tr>
<td>7</td>
<td>Trigger-in</td>
<td>16</td>
<td>ICSPDAT</td>
</tr>
<tr>
<td>8</td>
<td>Light source</td>
<td>17</td>
<td>VSS</td>
</tr>
<tr>
<td>9</td>
<td>Power</td>
<td>18</td>
<td>VPP/MCLR</td>
</tr>
</tbody>
</table>

Figure 9.8 The externals of the power supply.
APPENDIX C  MATLAB FOR ELLIPSMETRY

Different Matlab routines have been used. The most interesting will be presented here. This is the most used script for calculating $\psi$ and $\Delta$. First it loads images, next the direct Fourier transformation gives the important frequency components. These Fourier components are used for calculating $\psi$ and $\Delta$. Finally the results are plotted.

Ellipsometer_PCrSA_Multi_Auto.m

```matlab
% Rotating compensator script
% PCrSA configuration
% P = 0 deg.
% A = +/ - 45 deg.
% C rotates
% Takes the average of three measurements
% And calculates the A = +/ - 45 deg. average
% Automatic multiwavelength calculation

% Measurement parameters
% Wavelength
% Test number
test = 39;
% Measurement
measurement = 1;
% Number of measurements in multi scan
number_measurement = 4;
% start number
start = 0;
% file location
location = ['D:\Calibration\'];
% Degrees per image
deg = 1;
% Number of half rotations
half = 10;

%Number of images (starts at zero)
n = half * 180 / deg - 1;
ave=0;

Psi_455 = cell(1,n);
Delta_455 = cell(1,n);
Psi_530 = cell(1,n);
Delta_530 = cell(1,n);
Psi_590 = cell(1,n);
Delta_590 = cell(1,n);
Psi_627 = cell(1,n);
Delta_627 = cell(1,n);

for n2 = start:2:start+number_measurement-1
  % A = +45 deg. 455 nm
  Array = cell(1,n);
  for k = 0:1:3 %loop for 4 wavelengths
  ```
% selecting retardance
if k == 0
    Retarder_Delta = 123.81;
elseif k == 1
    Retarder_Delta = 108.22;
elseif k == 2
    Retarder_Delta = 96.49;
elseif k == 3
    Retarder_Delta = 90.56;
end

for i = k:4:n
    temp = ['image_test_' num2str(test) '_multi_' num2str(measurement) '_' num2str(n2) '_tiff'];
    filename = ['location Test' num2str(test) '\temp'];
    ave = double(imread(filename, 'tiff'));
    Array{i+1} = double(ave); % read data to double
end

for i = k:4:n
    Array{i+1} = Array{i+1} - background;
end

a0 = 0;
a2c = 0;
a4c = 0;
a2s = 0;
a4s = 0;
N = n + 1;
DB = deg;

for i = k+1:4:N
    a0 = a0 + 1 ./ N .* Array{i};
    B = (i-1).*DB.*pi./180;
    a2s = a2s + 2 ./ N .* Array{i} .* sin(2.*B);
    a4s = a4s + 2 ./ N .* Array{i} .* sin(4.*B);
    a2c = a2c + 2 ./ N .* Array{i} .* cos(2.*B);
    a4c = a4c + 2 ./ N .* Array{i} .* cos(4.*B);
end

clear Array;

% Calculate Psi and Delta
Factor_Delta = (1 - cos(Retarder_Delta.*pi./180))./(2.*sin(Retarder_Delta.*pi./180));
Factor_Psi = 4 .* Factor_Delta.^2;

Delta_tan = Factor_Delta.*a2s./a4s;
Psi_tan = -sqrt(Factor_Psi.*([a2s.^2+a2c.^2]+a4s.^2)./(2.*a4c));

Delta1 = atan(Delta_tan).*180./pi;
Psi1 = 1./2.*atan(Psi_tan).*180./pi;

% Zone corrections
n1 = size(Psi1,1); % Y size
m1 = size(Psi1,2); % X size

for i = 1:n1
    for j = 1:m1
        if Psi1(i,j) < 0
            Psi1(i,j) = Psi1(i,j) + 45; % pi/2/2
        end
    end
end
for i = 1:n1
for j = 1:m1
    if Delta1(i,j) < 0 %& Delta_Sin >= 0
        Delta1(i,j) = Delta1(i,j) + 180;
    elseif Delta_Cos(i,j) < 0 & Delta_Sin < 0
        Delta(i,j) = Delta(i,j) - 180;
    end
end
end

if k == 0
    Delta1_455 = Delta1;
    Psi1_455 = Psi1;
elseif k == 1
    Delta1_530 = Delta1;
    Psi1_530 = Psi1;
elseif k == 2
    Delta1_590 = Delta1;
    Psi1_590 = Psi1;
elseif k == 3
    Delta1_627 = Delta1;
    Psi1_627 = Psi1;
end
end %end of four wavelength loop

% A = -45 deg.
Array = cell(1,n);

for k = 0:1:3 %loop for 4 wavelengths
    %selecting retardance
    if k == 0
        Retarder_Delta = 123.81;
    elseif k == 1
        Retarder_Delta = 108.22;
    elseif k == 2
        Retarder_Delta = 96.49;
    elseif k == 3
        Retarder_Delta = 90.56;
    end
    for i = k+4:n
        temp = ['image_test_' num2str(test) '_multi_' num2str(measurement) '_' num2str(n2+1) '_' num2str(i) '.tiff'];
        filename = [ 'Test' num2str(i) '\temp' ];
        ave = double(imread(filename, 'tiff'));
        Array(i+1) = double(ave); %read data to double
    end
    for i = 1:n1
        Array(i+1) = Array(i+1)-background;
    end
    if k == 0
        Testx = nan(N/4,1);
        Testy = nan(N/4,1);
        %check fit with pixel data
    for i = 0:1:N/4-1
        Testx(i+1)=i*deg*4;
        Testy(i+1)=Array(i*4+1)(175,175);
for i = 1:1:n/4
    C0 = C0 + 1 / N * 4 * Testy(i);
    B = (i-1) * DB * pi./180 * 4;
    C2 = C2 + 2 / N * 4 * Testy(i) * cos(2 * B);
    C4 = C4 + 2 / N * 4 * Testy(i) * cos(4 * B);
    S2 = S2 + 2 / N * 4 * Testy(i) * sin(2 * B);
    S4 = S4 + 2 / N * 4 * Testy(i) * sin(4 * B);
end

Y_new = C0 * sin(2 * 0.0175 * Testx) + C2 * cos(2 * 0.0175 * Testx) + S4 * sin(4 * 0.0175 * Testx) + C4 * cos(4 * 0.0175 * Testx);
end

a0 = 0;
a2c = 0;
a4c = 0;
a2s = 0;
a4s = 0;

N = n + 1;
DB = deg;

for i = k+1:4:N
    a0 = a0 + 1 ./ N .* Array{i};
    B = (i-1) * DB * pi./180;
    a2s = a2s + 2 ./ N .* Array{i} .* sin(2 * B);
    a4s = a4s + 2 ./ N .* Array{i} .* sin(4 * B);
    a2c = a2c + 2 ./ N .* Array{i} .* cos(2 * B);
    a4c = a4c + 2 ./ N .* Array{i} .* cos(4 * B);
end

clear Array;

% Calculate Psi and Delta
Factor_Delta = (1 - cos(Retarder_Delta * pi./180)) / (2 * sin(Retarder_Delta * pi./180));
Factor_Psi = 4 * Factor_Delta.^2;

Delta_tan = Factor_Delta .* a2s ./ a4s;
Psi_tan = -sqrt(Factor_Psi .* (a2s.^2 + a2c.^2 + a4s.^2 ./ a4c).^2 ./ (2 .* a4c);

Delta1 = atan(Delta_tan) * 180 ./ pi;
Psi1 = 1 ./ 2 .* atan(Psi_tan) * 180 ./ pi;

% Zone corrections
n1 = size(Psi1, 1); % (Y size)
m1 = size(Psi1, 2); % (X size)

for i = 1:n1
    for j = 1:m1
        if Psi1(i,j) < 0
            Psi1(i,j) = Psi1(i,j) + 45; % pi/2/2
        end
    end
end

end
for i = 1:n1 
    for j = 1:m1 
        if Delta1(i,j) < 0 && Delta_Sin >= 0 
            Delta1(i,j) = Delta1(i,j) + 180; 
        elseif Delta_Cos(i,j) < 0 && Delta_Sin < 0 
            Delta(i,j) = Delta(i,j) - 180; 
        end 
    end 
end 

if k == 0 
    Delta2_455 = Delta1; 
    Psi2_455 = Psi1; 
elseif k == 1 
    Delta2_530 = Delta1; 
    Psi2_530 = Psi1; 
elseif k == 2 
    Delta2_590 = Delta1; 
    Psi2_590 = Psi1; 
elseif k == 3 
    Delta2_627 = Delta1; 
    Psi2_627 = Psi1; 
end 

end %end of four wavelength loop 

% Average 

Psi_455{n2+1} = (Psi1_455+Psi2_455)./2; 
Delta_455{n2+1} = (Delta1_455+Delta2_455)./2; 
Psi_530{n2+1} = (Psi1_530+Psi2_530)./2; 
Delta_530{n2+1} = (Delta1_530+Delta2_530)./2; 
Psi_590{n2+1} = (Psi1_590+Psi2_590)./2; 
Delta_590{n2+1} = (Delta1_590+Delta2_590)./2; 
Psi_627{n2+1} = (Psi1_627+Psi2_627)./2; 
Delta_627{n2+1} = (Delta1_627+Delta2_627)./2; 

end 

figure 

subplot(3,3,1); %plot position 
imagesc(aO); 
%colormap(gray); %gray 
axis image; 
title('aO'); %title 
colorbar; 

subplot(3,3,2); 
imagesc(a2c); 
axis image; 
title('a2c'); %title 
colorbar; 

subplot(3,3,3); 
imagesc(a4c); 
axis image; 
title('a4c'); %title 
colorbar; 

subplot(3,3,4);
The next script is used for calculating the layer thickness, it employs a brute force least squares fitting of the data. Note that first N3, the substrate, is fitted with a slightly different version of this file.

Ellipsometer_Fresnel_Model_Fit_Line.m

% Fresnel reflection model from fujiwara
% Full script with lines

% Select line
x = 100;
y = 250;

% number of pixels
I = 100;

% read files create cell array with psi delta 4 deep with wavelength and % length I
number_plot = 2;
pixel_number = 53;

% effective divided by 2
start_number_m = 286;
number_m = 288;

x_lambd = [455 530 590 627];

y_psi = [25.44 24.34 23.77 23.53];
y_delta = [104.15 109.53 112.47 114.13];
% wavelength dependent refractive indices

N0=[1 1 1];
N1=[2.15-1i*.65 2.24-1i*.62 2.28-1i*.60 2.30-1i*.60];
N2=[4.89-1i*.66 4.95-1i*.35 4.90-1i*.85 4.85-1i*.24];
N3=[4.16-1i*.44 4.40-1i*.31 4.19 4.49-1i*.06 4.52-1i*.30]; %square substrate

% angles of incidence per wavelength

theta0 = 72.1/180*pi.*N0;
theta1 = asin((sin(theta0).*N0./N1));
theta2 = asin((sin(theta1).*N1./N2));
theta3 = asin((sin(theta2).*N2./N3));

% reflection components

rOlp = (N1.*cos(theta0)-N0.*cos(theta1))./(N1.*cos(theta0)+N0.*cos(theta1));
r12p = (N2.*cos(theta1)-N1.*cos(theta2))./(N2.*cos(theta1)+N1.*cos(theta2));
r23p = (N3.*cos(theta2)-N2.*cos(theta3))./(N3.*cos(theta2)+N2.*cos(theta3));

rOls = (N0.*cos(theta0)-N1.*cos(theta1))./(N0.*cos(theta0)+N1.*cos(theta1));
r12s = (N1.*cos(theta1)-N2.*cos(theta2))./(N1.*cos(theta1)+N2.*cos(theta2));
r23s = (N2.*cos(theta2)-N3.*cos(theta3))./(N2.*cos(theta2)+N3.*cos(theta3));

% beta exponents

beta1 = 2.*pi.*d1.*N1.*cos(theta1)./x_lamda;

beta2 = 2.*pi.*d2.*N2.*cos(theta2)./x_lamda;

r0123p = (r01p+r12p.*exp(-1i.*2.*beta1)+r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2));

r0123s = (r01s+r12s.*exp(-1i.*2.*beta1)+r01s.*r12s+exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2));

psi_model = (1./2.*acos(-((r0123p.*conj(r0123p)-r0123s.*conj(r0123s)))/(r0123p.*conj(r0123p)+r0123s.*conj(r0123s)))).*180./pi;

delta_model = (atan(-imag((r0123s.*conj(r0123p)))/real((r0123s.*conj(r0123p))))).*.180./pi+180);

for m = start_number_m+2:2:number_m

number_plot = m/2;

d1 = 0;
d2 = 0;
carbon = 0;
oxide = 0;
psi_line = 0;
delta_line = 0;

for k = 1:1:1

%d1 = 0;
%d2 = 0;

pixel_number = k;

for j = 0:1:20

%d1 regression loop

for i = 0:1:100
beta1 = 2.*pi.*d1.*N1.*cos(theta1)/x_labda;
beta2 = 2.*pi.*d2.*N2.*cos(theta2)/x_labda;
ro123p = (r01p+rl2p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2))./(1+r01p.*r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2));
ro123s = (r01s+r12s.*exp(-1i.*2.*beta1)+(r01s.*r12s+exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2))./(1+r01s.*r12s.*exp(-1i.*2.*beta1)+(r01s+r12s.*exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2));
psi_model = (1./2.*acos((-r0123p.*conj(r0123p)-r0123s.*conj(r0123s))/(r0123p.*conj(r0123p)+r0123s.*conj(r0123s)))).*180./pi);
delta_model = (atan(-(imag((r0123s.*conj(r0123p)))./real((r0123s.*conj(r0123p))))).*180./pi+180);

%calculate deviation model and data
r_psi = data_psi{pixel_number,number_plot} - psi_model;
r_delta = data_delta{pixel_number,number_plot} - delta_model;
r1 = 1/8 *(r_psi(1)^2+r_psi(2)^2+r_psi(3)^2+r_psi(4)^2+r_delta(1)^2+r_delta(2)^2+r_delta(3)^2+r_delta(4)^2);
d1 = d1 + 0.0001;

beta1 = 2.*pi.*d1.*N1.*cos(theta1)/x_labda;
beta2 = 2.*pi.*d2.*N2.*cos(theta2)/x_labda;
ro123p = (r01p+r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2))./(1+r01p.*r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2));
ro123s = (r01s+r12s.*exp(-1i.*2.*beta1)+(r01s.*r12s+exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2))./(1+r01s.*r12s.*exp(-1i.*2.*beta1)+(r01s+r12s.*exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2));
psi_model = (1./2.*acos((-r0123p.*conj(r0123p)-r0123s.*conj(r0123s))/(r0123p.*conj(r0123p)+r0123s.*conj(r0123s)))).*180./pi);
delta_model = (atan(-(imag((r0123s.*conj(r0123p)))./real((r0123s.*conj(r0123p))))).*180./pi+180);

r_psi = data_psi{pixel_number,number_plot} - psi_model;
r_delta = data_delta{pixel_number,number_plot} - delta_model;
r2 = 1/8 *(r_psi(1)^2+r_psi(2)^2+r_psi(3)^2+r_psi(4)^2+r_delta(1)^2+r_delta(2)^2+r_delta(3)^2+r_delta(4)^2);

if r1 >= r2
d1 = d1 + 0.001;
else
d1 = d1 - 0.001;
end
end
% d2 regression loop
for i = 0:1:100

beta1 = 2.*pi.*d1.*N1.*cos(theta1)/x_labda;
beta2 = 2.*pi.*d2.*N2.*cos(theta2)/x_labda;
ro123p = (r01p+r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2))./(1+r01p.*r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2));
ro123s = (r01s+r12s.*exp(-1i.*2.*beta1)+(r01s.*r12s+exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2))./(1+r01s.*r12s.*exp(-1i.*2.*beta1)+(r01s+r12s.*exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2));
psi_model = (1./2.*acos((-r0123p.*conj(r0123p)-r0123s.*conj(r0123s))/(r0123p.*conj(r0123p)+r0123s.*conj(r0123s)))).*180./pi);
delta_model = (atan(-(imag((r0123s.*conj(r0123p)))./real((r0123s.*conj(r0123p))))).*180./pi+180);

%calculate deviation model and data
r_psi = data_psi{pixel_number,number_plot} - psi_model;
r_delta = data_delta{pixel_number,number_plot} - delta_model;
r2 = 1/8 *(r_psi(1)^2+r_psi(2)^2+r_psi(3)^2+r_psi(4)^2+r_delta(1)^2+r_delta(2)^2+r_delta(3)^2+r_delta(4)^2);
d2 = d2 + 0.0001;
end

% d2 regression loop
for i = 0:1:100

beta1 = 2.*pi.*d1.*N1.*cos(theta1)/x_labda;
beta2 = 2.*pi.*d2.*N2.*cos(theta2)/x_labda;
ro123p = (r01p+r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2))./(1+r01p.*r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2));
ro123s = (r01s+r12s.*exp(-1i.*2.*beta1)+(r01s.*r12s+exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2))./(1+r01s.*r12s.*exp(-1i.*2.*beta1)+(r01s+r12s.*exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2));
psi_model = (1./2.*acos(-(r0123p.*conj(r0123p)-r0123s.*conj(r0123s))./(r0123p.*conj(r0123p)+r0123s.*conj(r0123s))).*180./pi);
delta_model = (atan(-(imag((r0123s.*conj(r0123p)))/real((r0123s.*conj(r0123p)))).)*180./pi+180);

r_psi = data_psi(pixel_number,number_plot) - psi_model;
r_delta = data_delta(pixel_number,number_plot) - delta_model;
r2 = 1/8 *(r_psi(1)^2+r_psi(2)^2+r_psi(3)^2+r_psi(4)^2+r_delta(1)^2+r_delta(2)^2+r_delta(3)^2+r_delta(4)^2);

if r1 >= r2
d2 = d2 + 0.001;
else
d2 = d2 - 0.001;
end

carbon(k) = d1;
oxide(k) = d2;
psi_line(k) = data_psi{k,number_plot}(3);
delta_line(k) = data_delta{k,number_plot}(3);
end

%elapsed time in measurement with 0 formatting

time_h = 0;
time_m = 0;
time = 266/345*m;
while time > 60
    time = time - 60;
time_h = time_h + 1;
end
time_m = round(time);
if time_m < 10
    zero_m = ['0'];
else
    zero_m = [''];
end
if time_h < 10
    zero_h = ['0'];
else
    zero_h = [''];
end

%Collection of time dependant values

carbon_time(number_plot) = carbon(53);
oxide_time(number_plot) = oxide(53);

pixel_number = 53;
d1 = carbon(pixel_number);
d2 = oxide(pixel_number);

beta1 = 2.*pi.*d1.*N1.*cos(theta1)/x_labda;
beta2 = 2.*pi.*d2.*N2.*cos(theta2)/x_labda;
r0123p = (r01p+r12p.*exp(-1i.*2.*beta1)+(r01p.*r12p+exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2))./(1+r01p.*r12p.*exp(-1i.*2.*beta1)+(r12p+r01p.*exp(-1i.*2.*beta1)).*r23p.*exp(-1i.*2.*beta2));
r0123s = (r01s+r12s.*exp(-1i.*2.*beta1)+(r12s+r01s.*exp(-1i.*2.*beta1)).*r23s.*exp(-1i.*2.*beta2));
psi_model = (1./2.*acos(-(r0123p.*conj(r0123p)-r0123s.*conj(r0123s))./(r0123p.*conj(r0123p)+r0123s.*conj(r0123s))).*180./pi);
delta_model = (atan(-(imag((r0123s.*conj(r0123p)))/real((r0123s.*conj(r0123p)))).)*180./pi+180);
Ne = cos(2.*data_psi(pixel_number,number_plot).*pi./180);
Se = sin(2.*data_psi{pixel_number,number_plot} .*pi./180) .* cos(2.*data_delta{pixel_number,number_plot} .*pi./180); 
Ce = sin(2.*data_psi{pixel_number,number_plot} .*pi./180) .* sin(2.*data_delta{pixel_number,number_plot} .*pi./180); 
Ng = cos(2.*psi_model.*pi./180); 
Sg = sin(2.*psi_model.*pi./180) .* cos(2.*delta_model.*pi./180); 
Cg = sin(2.*psi_model.*pi./180) .* sin(2.*delta_model.*pi./180); 
MSE(number_plot) = sqrt(1/((3*4)-2)*sum((Ne-Ng).^2+(Se-Sg).^2+(Ce-Cg).^2))*1000; 

% total plotting

set(gcf,'Visible','off');
figure;

subplot(6,9,[1:3 10:12 19:21])
imagesc(Psi_590{m-1},[21 23]);
axis image;

ylabel('Psi - 590 nm')
title1 = ['Time: ' num2str(time_h) ':' num2str(time_m) ' E-Gun: 80 uA Gas: on'];
title(title1); % title
%colorbar;

subplot(6,9,[28:30 37:30 46:48]);
imagesc(Delta_590{m-1},[105 130]);
axis image;

ylabel('Delta - 590 nm')
title(title1);
%title
%colorbar;

subplot(6,9,[5 6 14 15 23 24]);
plot(carbon);
axis;
title1 = ['Carbon (nm)'];
title(title1);
subplot(6,9,[8 9 17 18 26 27]);
plot(oxide);
title2 = ['Oxidation (nm)'];
title(title2);

subplot(6,9,[41 42 50 51]);
plot(psi_line);
ylabel('Psi')
subplot(6,9,[44 45 53 54]);
plot(delta_line);
ylabel('Delta')

temp = ['Total_Test_38_1 ' num2str(m/2) '.png'];
temp = ['D:\Calibration\Pictures\' temp];
print('-r250','-dpng',temp)