An optical scattering technology capable of measuring the roughness of porous silicon

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Final Year Project Thesis
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Submitted: November 7th, 2011
Abstract

Porous silicon (PS) has been attracting rapidly increasing interest since the 1990’s, at which time the materials photoluminescence properties were first discovered. Since then, the interest in PS has continued due to its wide spectrum of potential applications such as its use in the field of electronics and optoelectronics. However in order to effectively use PS in these applications we need to more accurately understand its properties to obtain devices which work in a predictable manner.

Detailed models exist which can extract material properties from a reflectance measurement of PS. These depend on more than 7 parameters including refractive index, thickness, loss, wavelength dependence and roughness. However having a number of parameters can result in the over fitting of measured data creating a multitude of solutions. This issue needs to be addressed with the aim to uniquely and correctly determine the parameters of PS film.

To improve these models, the roughness of PS is required to be measured via another method. The method employed utilizes optical scattering. An angle-resolved scatterometer has been designed, manufactured, integrated and tested to enable the accurate characterization of PS roughness.
Letter of Transmittal

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22nd August, 2011

Winthrop Professor David Smith
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Dear Professor Smith,

I am pleased to submit this thesis, entitled “An optical scattering technology capable of measuring the roughness of porous silicon”, as part of the requirement for the degree of Bachelor of Engineering.

Yours Sincerely

Jason Cippitelli
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Acknowledgements

This thesis would not have been possible if it were not for the wisdom and guidance of the authors’ supervisor, Professor Adrian Keating. The thesis involved an in-depth understanding of many fields which the author, prior to the commencement of this project, possessed very little knowledge in. This included fields such as optics, electronics and computer science. Professor Keating’s assistance in these fields especially was greatly appreciated. His extensive knowledge in these areas proved motivational as the author set out to exceed the project objectives.

The author would also like to express his gratitude to Michael Armstrong and the UWA mechanical workshop team for their assistance in the manufacturing and fabrication process. The author would also like to thank Anthony at A1 Mechanical Services for providing various material offcuts at no cost which assisted in alleviating budgetary constraints.

Lastly, the author would like to thank his family and friends for all their support and encouragement throughout the project.
# Table of contents

1. Introduction ......................................................................................................................... 1

2. Literature Review .................................................................................................................. 3

   2.1 Light Scattering ................................................................................................................. 3

      2.1.1 Rayleigh vs Mei Scattering ......................................................................................... 4

2.2 Methods of Scattering .......................................................................................................... 5

      2.2.1 In-situ measurement and analysis ................................................................................. 5

      2.2.2 Total integrated scattering ......................................................................................... 7

      2.2.3 Angle-resolved scattering ......................................................................................... 8

2.3 Scattering Method Selection ............................................................................................... 10

2.4 Angle-Resolved Scattering ................................................................................................ 12

      2.4.1 Determining roughness .............................................................................................. 12

      2.4.2 Roughness model validation ...................................................................................... 15

2.5 Porous Silicon .................................................................................................................... 17

      2.5.1 Formation .................................................................................................................... 18

      2.5.2 Current research at UWA .......................................................................................... 19

      2.5.3 Applications ............................................................................................................... 20

3. Design Process ..................................................................................................................... 21

   3.1 Design Requirements ....................................................................................................... 21

   3.2 Design Constraints .......................................................................................................... 22

      3.2.1 Functional constraints ............................................................................................... 23

      3.2.2 Safety constraints ...................................................................................................... 23

      3.2.3 Manufacturing constraints ........................................................................................ 23

      3.2.4 Timing constraints .................................................................................................... 23

      3.2.5 Economics constraints ............................................................................................. 23

   3.3 Design Criteria .................................................................................................................. 24

      3.3.1 Mechanical design accuracy ...................................................................................... 24

      3.3.2 Component accuracy ................................................................................................ 24
3.4 Component Selection ................................................................. 24
    3.4.1 Servomechanism ............................................................ 24
    3.4.2 Detectors ......................................................................... 27
    3.4.3 Microprocessor ............................................................... 28
3.5 Preliminary Designs and Revisions ............................................. 28
    3.5.1 Preliminary design ............................................................ 28
    3.5.2 Redesign 1 ....................................................................... 29
    3.5.3 Redesign 2 ....................................................................... 30
4 Final Design, Results & Discussion .................................................. 32
    4.1 Final Design ......................................................................... 32
        4.1.1 Overview ..................................................................... 32
        4.1.2 Definition of model variables ........................................ 33
        4.1.3 System diagram ............................................................ 34
    4.2 Components in Detail ............................................................... 36
        4.2.1 Base ............................................................................. 36
        4.2.2 Instrument cover ........................................................... 37
        4.2.3 Arm ............................................................................ 38
        4.2.4 Sample holder ............................................................... 40
        4.2.5 Sample holder base ....................................................... 41
        4.2.6 Laser/chopper/lock-in amplifier assembly ....................... 42
        4.2.7 Detectors .................................................................... 47
    4.3 Safety ................................................................................... 50
        4.3.1 Laser safety precautions ................................................. 50
        4.3.2 Weight of design apparatus .......................................... 51
        4.3.3 Manufacturing and fabrication ..................................... 51
        4.3.4 Assembly and integration ............................................. 52
        4.3.5 Laboratory evacuation plan .......................................... 52
        4.3.6 Risk Assessment ......................................................... 53
4.4 Systems integration ................................................................. 56
4.4.1 Servomechanism ............................................................... 56
4.4.2 Detectors ........................................................................ 62
4.4.3 Instrument communications .............................................. 64
4.4.4 Debugging ....................................................................... 67
4.4.5 System parameters ............................................................ 67
4.5 Instrument testing .................................................................. 68
4.5.1 Instrument signature .......................................................... 68
4.5.2 Diffraction grating ............................................................ 71
5 Conclusions & Future work ..................................................... 76
6 References .............................................................................. 78
Appendix A – Torque calculation .................................................. 81
Appendix B – DMS44111MG data sheet ........................................ 85
Appendix C – BPW34 data sheet .................................................. 87
Appendix D – Workshop quotes ................................................... 88
Appendix E – Technical drawings ................................................ 90
Appendix F – Bill of materials ..................................................... 98
Appendix G – Circuit diagrams .................................................... 100
Appendix H – Class 3A Laser Equipment Local Working Rules ........ 103
Appendix I – Safe operating procedure for manual handling of instrument .................................................................................... 104
Appendix J – Safety guidelines for various tools ................................ 106
Appendix K – Safe operating procedure for soldering ....................... 109
Appendix L – Servo calibration data .............................................. 111
Appendix M – Firmware code ..................................................... 113
Appendix N – Software code ....................................................... 119
1 Introduction

Porous silicon was discovered in 1956, however it has only been the subject of intense research over the last 20 years at which time its photoluminescence properties were first discovered. Although it possesses a number of favourable properties such as mechanical robustness and chemical stability, this material also presents a number of challenges. One of these challenges is the disordered distribution of its nanocrystal sizes which hampers a real engineering of PS properties (Bisi, Ossicini & Pavesi 2000). We need to understand the properties of this material and hopefully the eventual mastering of these properties to obtain devices that work in a predictable manner. One of these properties, and the property investigated throughout this project, is surface roughness.

The precise control of roughness and thickness will allow the tailoring of the optical properties of porous silicon and open the door to a multitude of applications in optoelectronics technology (Dubey & Gautam 2009). With ever tightening device specifications, the accurate classification of PS roughness is critical to its applications.

Identifying the roughness of PS is a difficult task given the extremely small pore sizes. Electron microscopes often cannot provide an accurate view of the sample and do not capture the scattering profile that occurs at the PS-silicon interface. Therefore a different approach must be taken as it is this scattering profile which provides an accurate classification of the materials roughness. The primary objective of this project was to design a test that could be used to accurately measure the roughness of a sample of PS. This project approaches the task from the view of scattering; by measuring the intensity of a laser reflected off a sample at various angles, the scattering profile and roughness of the material can be determined.

In order to accurately measure the scattering properties caused by the roughness of PS interface a suitable scattering method must first be determined. The method selected after careful examination of the various scattering methods available and that deemed to be most appropriate for the project is the angle-resolved scattering (ARS) technique.

To characterise the roughness of PS using the ARS technique a scatterometer instrument has been designed, manufactured, integrated and tested along with a beam, chopper and lock-in amplifier package. A significant amount of attention has been given to the integration of the various mechanical, electronic and software components to produce a complete instrumentation package. The developed instrument is not only
capable of classifying the roughness of PS but also can be used to characterise other materials at UWA into the foreseeable future.

This project will advance current studies not only at UWA but on an industry level by creating the groundwork for the measurement of PS roughness. Because scatter is a fast, noncontact area measurement, it is an obvious choice for off-line (laboratory), on-line, and in-line instrumentation needed to characterise PS roughness in the semiconductor industry (Stover 1995). By designing, implementing and analysing a robust method to accurately measure this characteristic the project will assist in providing more accurate results from other models which rely on PS roughness as an input parameter, whilst also ultimately gaining a greater understanding of PS’s scattering properties. This will not only advance the semiconductor industry’s knowledge of this material but perhaps the optical industry will also benefit from this advancement in scatter based instrumentation from an economics perspective.
2 Literature Review

Light scattering theory has been selected as forming the foundation of characterising the roughness of PS. There are however several methods which apply this theory to characterise roughness. The theory of light scattering and of each method is presented.

2.1 Light Scattering

Light scattering can be thought of as a deflection of light from a straight path that takes place when an electromagnetic wave encounters an obstacle or non-homogeneities on a surface (Young & Freedman 2004). In geometric optics consider the situation whereby light is directed at a perfectly flat mirror, the reflected light will obey the laws of reflection. The angle which the incident ray ($\theta_i$) makes with the normal is equal to the angle which the reflected ray ($\theta_r$) makes to the same normal as shown in figure 2.1.

![Figure 2.1: Specular reflection.](image)

However if the interference is rough the reflected light is scattered in various directions with no single specular reflection due to imperfections on the surface. This scattered reflection from a rough surface is called diffuse reflection as shown in figure 2.2.

![Figure 2.2: Diffuse reflection.](image)
The process of light scattering is not simply the geometric optical situation described above but also consists of physical optics component. In this physical optics component a complex interaction between the incident EM wave and the molecular/atomic structure of the scattering object characterises light scattering.

As the EM wave interacts with a discrete particle of the scattering surface, the electron orbit within the particle’s constituent molecules are perturbed periodically with the same frequency ($\nu_0$) as the electric field of the incident wave (Hahn 2009). The oscillation or perturbation of the electron cloud results in a periodic separation of charge within the molecule resulting in an induced dipole moment. The oscillating induced dipole moment is manifested as a source of EM radiation, thereby resulting in scattered light illustrated in figure 2.3.

![Figure 2.3: Light scattering by an induced dipole moment due to an incident EM wave (Hahn 2009).](image)

The majority of light scattered by the particle is emitted at the identical frequency ($\nu_0$) of the incident light, a process referred to as elastic scattering. Two major theoretical frameworks exist for elastic scattering: Rayleigh scattering and Mei scattering.

### 2.1.1 Rayleigh vs Mei Scattering

In Rayleigh scattering the scattering of light is caused by particles much smaller than the wavelength of light (Rayleigh 1871). This is in comparison to Mei scattering which has no particular bound on particle size (Mie 1908). These two types of scattering produce different scatter patterns with Mei having more intense forward lobe as shown in figure 2.4.
Rayleigh scattering intensity also has a strong dependence on the size of particles (proportional to the sixth power of their diameter) and is inversely proportional to the fourth power of the wavelength light whereas Mie has a less dependence on the size of the particles (proportional to the square of their diameter) and is not strongly dependent on the wavelength light.

Due to the above mentioned characteristics and very small particle size, Rayleigh scattering is exhibited especially by porous materials such as PS. Nanoporous materials strongly exhibit this type of optical scattering due to a large contrast in the refractive index between the pores and solid parts of the materials (Svensson & Shen 2010).

2.2 Methods of Scattering
Several methods of scattering exist to determine the scattering properties and roughness of a material. Three main methods were encountered. These were examined in detail and critically analysed to determine the most appropriate method to be undertaken.

2.2.1 In-situ measurement and analysis
In-situ measurement and analysis is a laser reflection method based on interferometry with inherent scattering elements that can be used to determine the roughness of porous silicon. This method was first conducted to monitor the etch rate for tetramethyl ammonium hydroxide etching of silicon with very accurate and feasible results reported (Steinsland, Finstad & Hanneborg 2000).

In this process a sample of a silicon wafer is submerged into a volume of etchant which is commonly a 1:1 mixture of 48% aqueous HF and ethanol (Volk et al. 2005). As the porous silicon layer thickness increases as the etching progresses the oscillation frequency and amplitude of a backside reflected monochromatic infrared (IR) laser beam are measured in-situ.
The interaction of the beam with the layers can be represented by individual rays, each having an associated phase and amplitude. These individual rays contribute to the total signal measuring the total light reflected through interference at the same boundary as the laser as depicted in figure 2.5.

![Ray Trace Diagram](image)

**Figure 2.5:** Ray trace through the sample during etching. Scattering of light due to a rough PS-substrate is indicated.

The interferences in the reflected beam are then analysed using a short-time Fourier transform to extract different frequency components and obtain a spectrogram. From this analysis the PS film thickness, the etch rate, the refractive index, the porosity, profile, the average porosity and the interference roughness can be obtained (Foss, Kan & Finstad 2005).

This method of scattering measurement presents a number of strengths. The range of different process parameters of the sample that can be obtained, not just roughness, is a clear advantage. The method also allows real time automated feedback control of data as the etching occurs so that PS films with precise porosity are obtained.

However the data obtained from this method is dependent on the refractive index of the etchant and substrate. Through this method the refractive index is assumed to be independent of time and PS layer thickness. This assumption is inaccurate as the refractive index is dependent on these variables (Léondel, Romestain & Barret 1997).
Due to this assumption, a certain level of experimental uncertainty would be present in the data obtained.

2.2.2 Total integrated scattering

Total integrated scattering (TIS) is a method which is based on the principle of Coblentz spheres or integrating spheres to characterise the roughness of a surface (Wolfgang 2006). In this method TIS instruments operate by gathering a large fraction of scattered light into a hemisphere of a reflective sample and focusing it onto a single detector (Elson, Rahn & Bennett 1983). This is not before the incident beam is directed through a chopper and a beam preparation system.

Once the beam has been prepared, it enters the sphere through an opening and hits the sample surface. The specularly reflected beam passes through another opening in the sphere and its intensity is measured by a receiver. The scattered radiation which is reflected by the sphere’s diffuse highly reflective coating is then directed onto a separate receiver to measure the intensity of the diffuse reflectance as shown in figure 2.6.

![Schematic diagram of apparatus to measure TIS](image)

**Figure 2.6** Schematic diagram of apparatus to measure TIS (Bjuggren, Krummenacher & Mattsson 1997).

Given this data, the TIS can be calculated according to equation 2.1 which can then be related to the roughness of the surface through scalar scattering theory (Bennett & Porteus 1961).

\[
TIS = \frac{\text{diffuse reflectance}}{\text{specular + diffuse reflectance}}
\]  

(2.1)

The fast sample throughput, repeatable results and a single number to characterise the roughness of a surface are clear advantages of this scattering method (Stover 1995). However the method also presents some inherent flaws. Although through this
scattering instrument most of the scattered light is collected, the light that is scattered close to the incident and specular reflected beams aperture is lost along with the light that is scattered close to parallel of the surface (Elson, Rahn & Bennett 1983). Whilst the loss is considered to be relatively small it would result in some inaccuracies with the data obtained (Bjuggren, Krummenacher & Mattsson 1997).

The beam aperture and opening between the sample and sphere also define the minimum and maximum scatter angles and thus the minimum and maximum spatial frequency values at which scattering is measured. Since different TIS instruments have different spatial frequency bandwidths and it has become common practice to give only the TIS value from these instruments accurate comparisons of data cannot be obtained (Stover 1995). Difficulties in roughness comparisons also arise between TIS and other measurement systems due to the fact that TIS does not take into account polarization factors. The frequency components will scatter in all directions onto the detector in TIS whereas other roughness measuring systems such as interferometers and profilometers are sensitive to components parallel to the sampling direction (Stover 1995). TIS instruments also do not provide an accurate representation of high-frequency roughness. The analysis in TIS measurements assumes that the scattering angle is equivalent to the incident angle which is clearly not true at large scatter angles and thus at high-frequency (Davies 1954). Also, as incidence angle increases the light reflected and therefore not registered by the detector also increases which further exacerbates discrepancies at high frequencies (Bass et al. 2009).

The Coblentz sphere must also be manufactured to near-perfect specifications to ensure correct focusing of the beams. Allowing the sample to tilt in several directions can assist in correcting for any local inhomogeneities of the Coblentz sphere through evaluating the TIS data in a number of directions however it is critical that the sphere is of a high quality (Gliech, Steinert & Duparré 2002). Recent work has also suggested that the transmittance and reflectance values obtained for Coblentz spheres are only accurate when certain correction factors for sphere asymmetry are properly taken into account further underlying the need for a near-perfect specification sphere (Ronnow & Roos 1995).

2.2.3 Angle-resolved scattering

In angle-resolved scattering (ARS) a laser beam is initially directed through a chopper, polarizer and beam preparation system (Neubert et al. 1994). The incident beam is then
directed onto a sample and a detector system is rotated at various angles relative to the normal of the plane of the sample. The scattered intensity is measured at the various angles as illustrated in figure 2.7.

**Figure 2.7:** Schematic diagram of apparatus to measure ARS (Jacobson et al. 1992).

The scattered intensities measured can then be used to create a Bidirectional Scatter Distribution Function (BSDF) which measures the normalised beam intensity at various measured angles (Nicodemus 1965). This BSDF can then be related to roughness through vector scattering theory (Church, Jenkinson & Zavada 1977).

The ability to obtain a full roughness profile of a specified sample over a range of angles is a clear advantage of this method (Ronnow & Veszelei 1994). One drawback of this instrument is that the field of view of the detector system also includes part of the surrounding laboratory which can be illuminated by the scattered light from the uncaptured specular beam. This can be minimized however through the use of a black and absorbing surrounding area and limiting the field of view of the detector (Germer & Asmail 1999).

### 2.2.3.1 Angle-resolved scattering with Coblentz Sphere

The ARS scattering approach can also be used in conjunction with a Coblentz sphere. In this setup the detector system incorporates a Coblentz Sphere where the scattered light from the sample is directed into the sphere, reflected and then directed onto the receiver at various angles (Gliech, Steinert & Duparré 2002). The use of this sphere in the ARS
setup increases the accuracy of the data by more uniformly collecting all of the reflected light.

2.3 Scattering Method Selection

To determine the most appropriate scattering method determining factors were formed. The main factors considered in the selection of a scattering method were the correctness of the method, expense and ability to integrate the setup. Defining terms for these factors are presented below.

- Correctness: defines how well the theory providing the foundation for the method is constructed throughout the literature and whether or whether not discrepancies are present in the theory supporting the scattering method.
- Expense: defines the cost effectiveness of the chosen scattering method.
- Integration: defines the ease at which the chosen scattering method can be integrated into the UWA optics laboratory.

Each of these methods are ranked in table 2.1 in terms of these factors.
<table>
<thead>
<tr>
<th>Correctness (higher number indicates more correct method)</th>
<th>In-situ measurement and analysis</th>
<th>TIS</th>
<th>ARS</th>
<th>ARS + Coblentz sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
<td>5</td>
<td>8</td>
<td>10</td>
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</table>

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<tr>
<th>Expense (higher number indicates cheaper method)</th>
<th>In-situ measurement and analysis</th>
<th>TIS</th>
<th>ARS</th>
<th>ARS + Coblentz sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>1</td>
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</table>

<table>
<thead>
<tr>
<th>Integration (higher number indicates more easily integrated method)</th>
<th>In-situ measurement and analysis</th>
<th>TIS</th>
<th>ARS</th>
<th>ARS + Coblentz sphere</th>
</tr>
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<tr>
<td></td>
<td>2</td>
<td>10</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

|                                                                   | 17                              | 18  | 22  | 18                   |

Table 2.1: Scattering method ranking chart.

The main drawback of in-situ measurement and analysis in terms of the above presented factors was the great difficulty in integrating this setup at UWA. An integral part of this setup is submerging the sample of silicon into the substrate and this setup is not readily available in the UWA optics laboratory and would require a different testing environment. The theory supporting this method of measuring roughness was found to be good and the expense moderate with the main cost being an appropriate CCD detector. These factors combined to give an overall lowest score of 17.

It was evident that through the critical analysis formed that a TIS setup presented a number of flaws in the theory supporting this method which would result in inaccurate data. The integration of a TIS setup would be easily integrated with an appropriate reflecting sphere however the cost of this item was inappropriate for the given budget with quotes ranging from $2500 - $6000 (Newport 2011); (Edmund Optics 2011). These factors combined to give an equal second ranking score of 18.
Whilst the addition of a Coblentz sphere to an ARS setup would result in the most accurate data readings the cost in this setup is a significant issue with not only the cost of a Coblentz sphere but also an ARS setup having to be accounted for. However this setup could be relatively easily integrated. These factors combined to give an equal second ranking score of 18.

Through the scattering method selection process it was clear ARS was the most appropriate method. The theory supporting this method was found to be sound and this method could also be integrated and built in the UWA laboratories with a relatively low expense and accurate data readings.

2.4 Angle-Resolved Scattering

2.4.1 Determining roughness

Through the data obtained from an ARS instrument the RMS roughness of the sample surface can be calculated through a series of models. This is commonly referred to as the application of Rayleigh-Rice Perturbation theory to the inverse scatter problem: the calculation of reflector surface statistics from measured scatter data. In these applications a bidirectional scatter distribution function is initially formulated which is subsequently transformed into a power spectral density function. The RMS roughness of a surface is determined by the integration of this power spectral density function over the spatial frequency of the surface.

2.4.1.1 Bidirectional scatter distribution function

The bidirectional scatter distribution function (BSDF) is commonly used to characterise scattering. In this model a number of assumptions are made. It is assumed that the incoming beam is of uniform cross section, the surface is isotropic and all scatter comes from the surface and none from the bulk (Nicodemus et al. 1977). The defining geometry of the model is shown in figure 2.8.
The BSDF function is defined in radiometric terms as the surface radiance (light flux scattered through solid angle per unit illuminated surface area per unit projected solid angle) divided by the incident surface irradiance (light flux incident on the surface per unit illuminated surface area) which is equivalent to equation 2.2.

\[
BSDF \equiv \frac{\text{differential radiance}}{\text{differential irradiance}} = \frac{dP_s/d\Omega_s}{P_i \cos \theta_s} \approx \frac{P_s/\Omega_s}{P_i \cos \theta_s} \quad (2.2)
\]

Where \( P_s \) – scattered intensity;

\( P_i \) – incident intensity;

\( \Omega_s \) – system geometry factor;

\( \theta_s \) – scatter angle (degrees);

\( \varphi_s \) – azimuthal angle (degrees);

The system geometry factor is determined through equation 2.3 below.

\[
\Omega_s = \frac{\pi r^2}{R^2} \quad (2.3)
\]

Where \( r \) – detector aperture radius;

\( R \) – distance from detector to sample;
2.3.1.2 Power spectral density function

The power spectral density function (PSD) describes how the power of a signal or time series is distributed with frequency. This function is related to the BSDF through Rayleigh-Rice vector perturbation theory (Church, Jenkinson & Zavada 1977). The theory expresses the mean square value of the scattered plane wave coefficients of smooth, clean, front surface reflectors as a function of the surface power spectral density function. As is illustrated in equation 2.4 the BSDF is proportional to the PSD with the units of angstrom squared micrometres squared. The associated spatial wavelengths are calculated through the grating equation 2.5.

\[
PSD = S(f_x, f_y) = \left[ \frac{P_s/Q_s}{P_i \cos \theta_s} \right] \frac{10^6 \lambda^4}{16 \pi^2 \cos \theta_i \cos \theta_s Q_{\alpha \beta}} = \frac{(BSDF)10^6 \lambda^4}{16 \pi^2 \cos \theta_i \cos \theta_s Q_{\alpha \beta}}
\] (2.4)

\[
f_x = \frac{\sin \theta_s \cos \varphi_s - \sin \theta_i}{\lambda}, f_y = \frac{\sin \theta_s \sin \varphi_i}{\lambda}
\] (2.5)

Where \( \lambda \) – wavelength of incident light (\( \mu \)m);

\( \theta_i \) – incident angle (degrees);

\( Q_{\alpha \beta} \) – polarization factor;

The polarization factor \( Q_{\alpha \beta} \) is dependent on the incident light polarization \( (\alpha) \) and also the scattered light polarization \( (\beta) \).

Conjecture pertaining to the validity of the BSDF and PSD relationship has been rife in the recent past due to the fact the transformation often produces a high frequency peak (Stover & Harvey 2007). Altering of the source wavelength and/or incident angle results in changes in this peak clearly suggesting it is not a part of the surface PSD. However the validity of this relationship has very recently been confirmed through a series of experiments which substantiated the reason for this anomaly is the result of scatter from non-topographic surfaces (Stover 2010).

2.3.1.3 Root-Mean-Square roughness

The Root-Mean-Square (RMS) roughness provides a measure of the magnitude of variance in film roughness. It is typically utilised to describe surface finish of products in manufacturing. A high RMS value is indicative of a rough surface, while a relatively low RMS value describes a smooth surface.
The RMS roughness is determined from the PSD function through the integration of this function between its minimum and maximum spatial frequencies as per equation 2.6

\[ \sigma = \left[ \int_{f_{\min}}^{f_{\max}} \int_{f_{\min}}^{f_{\max}} S(f_x, f_y) \, df_x \, df_y \right]^{1/2} \]  

(2.6)

2.4.2 Roughness model validation

A pure Lambertian surface was evaluated to assist in model validation. For a Lambertian surface the scattered intensity is directly proportional to the cosine of the scattered angle. The surface is illustrated in figure 2.9 and can be represented by equation 2.7.

\[ P_s = P_i \times \cos \theta_s \]  

(2.7)

The BSDF of a Lambertian surface can then be calculated by substituting the above equation 2.7 into the BSDF equation 2.2. The result is illustrated in equation 2.8.

\[ BSDF_{lambertian} = \frac{1}{\Omega_s} = \frac{1}{\pi} \]  

(2.8)

As is evident from equation 2.8 the BSDF for a Lambertian surface is constant, with the system geometry factor \( \Omega_s \) equating to \( \pi \) due to the cosine weighted hemisphere sampling. This is to be expected since a Lambertian surface has a same apparent radiance when view from any direction. Although the emitted intensity from a given

---

**Figure 2.9**: Reflection from a Lambertian surface obeys the cosine law by distributing reflected energy in proportion to the cosine of the reflected angle.
area element is reduced as per equation 2.7, the apparent size of the observed area is also decreased by a corresponding amount. Therefore the radiance remains constant. This conforms to the radiance definition of the BSDF in equation 2.2.

With knowledge of the BSDF, the PSD of a Lambertian surface can be calculated by substituting equation 2.8 into the PSD equation 2.4 and assuming the incident angle \( \theta_i = 0 \), polarization factor \( Q_{\alpha\beta} = 1 \), wavelength of incident light \( \lambda = 0.650 \, \mu m \).

\[
PSD_{lambertian} = S(f_x, f_y) = \frac{1}{16\pi^2 \cos \theta_s} \left( \frac{1}{\pi} \right) 10^8 \lambda^4 \, (\mu m)^2
\]

(2.9)

Assuming the Lambertian surface behaves isotropically, the effective value of the PSD cone is obtained through equation 2.10. This is derived by integrating a slice through \( S(f_x, f_y) \) around 360 degrees as illustrated in figure 2.10.

\[
S_{iso}(f) = \int_0^{2\pi} S(f_x, f_y) f \, d\beta = 2\pi f S(f_x f_y)
\]

(2.10)

The effective PSD for the Lambertian surface is illustrated in figure 2.11 with the RMS roughness of the surface shaded and indicated by \( \sigma^2 \).
Figure 2.11: Power spectral density function for a pure Lambertian surface.

The plot from figure 2.11 suggests the power spectral density of the Lambertian surface increases with increasing frequency as would be expected. The calculation of the surface roughness value is trivial in this instance given the pure theoretical nature of the study.

2.5 Porous Silicon

Porous silicon (PS) is a material which has been rapidly gaining attention since the discovery of its photoluminescence properties in the 1990’s which lends itself to a number of potential applications. This photoluminescence property is due to the materials internal structure. The materials internal structure is characterised by a disordered web of nonporous holes within the surface microstructure of a silicon wafer which results in a large surface to volume ratio of more than 500 m²/cm³ (Bisi, Ossicini & Pavesi 2000). These features are illustrated in figure 2.12.
Whilst these properties are important, it is the light scattering that occurs at the PS-silicon interface however which is of most interest. During the formation of porous silicon (PS) on Si material, the bottom of the PS layer develops a roughness which is responsible for observed light scattering. This interface scattering is illustrated in figure 2.13.

![Figure 2.13: Light scattering occurs at the rough PS-silicon interface.](image)

The two other possible contributions to the scattering, the bulk PS and the interface between PS and air have been found to be negligible (<1%) compared with the interface scattering which has found to be independent of the layer thickness (Léondel et al. 1996).

### 2.5.1 Formations

Porous silicon is manufactured using a specific process as seen in figure 2.14. In this process silicon wafers are polished through standard anisotropic alkali etching using a 20% NaOH solution at 70°C for 5 minutes. A backing is then applied to the wafer which is then submerged in a 1:1 mixture of HF acid and ethanol electrolyte. The anodization time for this process is 3 minutes with a current density of 30 mA/cm² provided through a thin cylindrical cathode (Saha & Pramanik 2006).
Figure 2.14: Manufacturing of porous silicon.

Porosity is the ratio of voids or pores relative to the total volume of the sample of body. The HF-ethanol substrate is the action which creates these pores in the silicon resulting in porous silicon. The method outlined produces a sample of thickness and average porosity or 5 μm and 70% respectively (Saha et al. 1998); (Hossain et al. 2002).

2.5.2 Current research at UWA

The Sensors and Advanced Instrumentation laboratory at UWA is currently investigating the properties of porous silicon. This is being undertaken through a reflectivity testing setup as illustrated in figure 2.15.

Figure 2.15: Current reflectivity testing setup at UWA.
The data obtained from this testing setup can then be inputted through well established models to determine material properties. However these models depend on a number of inputs, one of which is the roughness of the surface. Determining PS scattering characteristics and precisely classifying the materials roughness will greatly assist in the accuracy of these models.

2.5.3 Applications

Porous silicon is a dielectric material with many different applications. The potential application areas of porous silicon are summarized in Table 2.2, where the property of porous silicon used for each application is shown.

<table>
<thead>
<tr>
<th>Application area</th>
<th>Role of porous silicon</th>
<th>Key property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optoelectronics</td>
<td>LED, Waveguide, Field emitter, Optical memory</td>
<td>Efficient electroluminescence, Tunability of refractive index, Hot carrier emission, Non-linear properties</td>
</tr>
<tr>
<td>Micro-optics</td>
<td>Fabry-Perot Filters, Photonic bandgap structures, All optical switching</td>
<td>Refractive index modulation, Regular macropore array, Highly non-linear properties</td>
</tr>
<tr>
<td>Energy conversion</td>
<td>Antireflection coatings, Photo-electrochemical cells</td>
<td>Low refractive index, Photocorrosion cells</td>
</tr>
<tr>
<td>Environmental monitoring</td>
<td>Gas sensing</td>
<td>Ambient sensitive properties</td>
</tr>
<tr>
<td>Microelectronics</td>
<td>Micro-capacitor, Insulator layer, Low-k material</td>
<td>High specific surface area, High resistance, Electrical properties</td>
</tr>
<tr>
<td>Wafer technology</td>
<td>Buffer layer in heteroepitaxy, SOI wafers</td>
<td>Variable lattice parameter, High etching selectivity</td>
</tr>
<tr>
<td>Micromaching</td>
<td>Thick sacrificial layer</td>
<td>High controllable etching</td>
</tr>
<tr>
<td>Biotechnology</td>
<td>Tissue bonding, Biosensor</td>
<td>Tunable chemical reactivity, Enzyme immobilization</td>
</tr>
</tbody>
</table>

Table 2.2: Potential application areas of porous silicon (Pérez 2007).
3 Design Process

The engineering design process is defined as “… a component, or process to meet desired needs. It is a decision making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation.” (Ertas & Jones 1996).

In order to achieve project objectives a systematic engineering design process was adhered to based on the fundamental elements of design. Eight elements were formulated and tailored to the design of the instrument. The steps in the process were as follows:

1. Identify design requirements;
2. Identify design constraints;
3. Identify design criteria;
4. Component selection;
5. Preliminary design and revisions;
6. Final design;
7. Manufacturing, assembly and integration; and
8. Testing and evaluation.

Steps 6 through to 8 are depicted in section 4 Final Design, Results & Discussion.

3.1 Design Requirements

The instrument was designed as to ensure that all necessary inputs into the models are available to characterise the roughness of a surface. The BSDF and PSD models are used to characterise roughness which are outlined in section 2 Literature Review. In order to obtain the most accurate representation of the profile roughness, the accuracy of the inputs into the models are critical. The instrument was designed to optimize the accuracy of these inputs.

The required inputs are characterised in table 3.1. The factors which determine the accuracy of each input are also described.
<table>
<thead>
<tr>
<th>Input</th>
<th>Notation</th>
<th>Accuracy limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattered intensity</td>
<td>$P_s$</td>
<td>Detector quality</td>
</tr>
<tr>
<td>Incident intensity</td>
<td>$P_i$</td>
<td>Detector quality</td>
</tr>
<tr>
<td>System geometry factor</td>
<td>$\Omega$</td>
<td>The ability to accurately measure detector size and detector distance from sample</td>
</tr>
<tr>
<td>Detector angle</td>
<td>$\theta_s$</td>
<td>Accuracy and calibration of motor</td>
</tr>
<tr>
<td>Incident angle</td>
<td>$\theta_i$</td>
<td>The ability to accurately measure incident angle</td>
</tr>
<tr>
<td>Polarization factor</td>
<td>$Q_{\alpha\beta}$</td>
<td>Alignment of s and p polarization films</td>
</tr>
</tbody>
</table>

Table 3.1: Required inputs and accuracy limitations.

It was clear in order to establish these inputs the design would require the following components:

- A laser to provide the necessary incident light;
- A housing for the incoming laser and angle alignment mechanism;
- A detector to measure incident intensity;
- Polarized detectors to measure the scattered intensity at various angles in the s and p polarization directions;
- A arm which would rotate around the sample at minimum 90 degrees;
- A servomechanism to drive the arm to various angles;
- A sample holder (pre-existing); and
- A sample holder base.

Each of the designs included at minimum these components to ensure sufficient data is available to model surface roughness. The material chosen in discussion with the UWA mechanical workshop staff was Aluminium due to a combination of its lightweight nature, cost effectiveness and workability. All designs were rendered through the 3D CAD design software package Solidworks®.

3.2 Design Constraints

A number of constraints were imposed on the instrument design. The instrument design and the selection of various components were chosen with reference to these constraints. The constraints are categorised and described below.
3.2.1 Functional constraints
The chief functional constraint imposed on the design of the instrument was its overall geometry. The instrument was required to be transported to various locations and laboratories with relative ease and as such was required to be of a reasonable size and weight which a single person can transport. The instrument was required to be mobile.

3.2.2 Safety constraints
The operation of the laser is a key safety concern for the instrument. The instrument was required to be designed as to mitigate the risk of stray laser light entering into the surrounding environment. A laser housing was required to ensure correct laser alignment and a box to cover the instrument during operation. This box also placed a constraint on the size of the instrument.

3.2.3 Manufacturing constraints
The UWA workshops time is limited and therefore designs were required to be presented well in advance. The tools which the UWA workshop had available were also considered in the design stage to ensure specific design elements were able to be manufactured. A higher quality and accuracy of manufacturing also coincides with increased cost and this was also a constraint imposed on the instrument.

3.2.4 Timing constraints
The instrument was required to have a preliminary design and revisions, final design, and manufacturing, assembly and integration combined schedule of a maximum of 5 months to allow sufficient time for instrument testing and evaluation. This timing constraint placed a constraint on the quality of the accuracy of the instrument that could be developed.

3.2.5 Economics constraints
The budget for the project was $600 in workshop time and $400 in materials. The design cost was nil since this is performed by the author. The $600 in workshop time was solely channelled to manufacturing costs and as such the cost to manufacture the instrument was required to be equal to or less than this amount. The $400 in materials was used to purchase the components for the instrument and as such the sum of the component costs was required to be equal to or less than this amount.
3.3 *Design Criteria*

The key criteria used to establish the success of the design is its accuracy. The instrument accuracy is dependent on both mechanical design accuracy dimensions and component accuracy. A clear trade-off exists between accuracy and cost and the latter is a key constraint imposed on the design.

3.3.1 *Mechanical design accuracy*

The mechanical design accuracy is dependent on the accuracy on the instrument component locations and also the error margin tolerances in the manufacturing of these components. The main point of interest is ensuring the detector height is equal to the incident laser beam height to certify measurement of data readings occurs in the same plane.

3.3.2 *Component accuracy*

The component accuracy is dependent on the specifications of the components chosen. Key selection criteria were developed for critical components to ensure the best possible accuracy was achieved with respect to cost.

3.4 *Component Selection*

3.4.1 *Servomechanism*

The driving mechanism of the arm is a critical element of the overall instrument. This is due to the fact that the angle of the arm and consequentially the detectors is a direct input into the BSDF model. Therefore ensuring the most appropriate driving mechanism is selected is a critical element to achieving instrument accuracy. Key selection criteria were developed to assist in this selection.

3.1.1.1 *Selection criteria*

The key selection criteria for the servomechanism are discussed below from highest to lowest priority.

1. Accuracy: the angle of the arm is a key input into the BSDF model. Therefore ensuring the driving mechanism would output accurate and repeatable angles when given specific commands is the most critical element.

2. Resolution: choosing a servomechanism with the finest resolution available would result in significantly more data points to analyse and increase model accuracy.
3. Reliability: if the driving mechanism is susceptible to breaking or is not of high quality with cheap internal components then the reliability of the entire instrument is severely compromised.

4. Cost: the budget for the servomechanism was $100 and therefore the chosen mechanism needed to be within this budget.

5. Availability: it is preferred if the driving mechanism is readily available should the component fail and needs to be replaced.

6. Torque requirement: it is preferred to have a torque rating of above 5 kgcm although theoretical calculations suggested that any standard size hobby servo would more than provide the necessary torque (see Appendix A)

### 3.1.1.2 Encoders

Standard servomechanisms utilise a potentiometer which control the circuitry to monitor the current angle of the servo. However over time these potentiometers become worn out leading to decreased accuracy. The use of an encoder eliminates this issue by accurately defining the position of the servo arm.

Two types of external encoders are available; incremental and absolute. Incremental encoders generate pulses proportional to position whereas absolute encoders generate a unique code for each position. The disadvantage of incremental encoders is that every time the power to the instrument is reset the home position must also be reset whereas absolute encoders do not suffer from this issue.

A clear price/feature trade-off exists between incremental and absolute encoders. A similar specification absolute encoder which can provide an angular resolution of 0.2° is approximately $100 dearer than the equivalent incremental encoder (Omron Industrial Automation 2011). Given the budgetary constraints and the need to reset the home position each time at instrument power up being relatively insignificant to the instrument incremental encoders were considered in more detail. Servomechanisms with inbuilt magnetic rotary encoders were also considered in the selection process.

### 3.1.1.2 Comparisons and selection

The servomechanism selection was narrowed down to three options. This included a standard HiTec HS-311 with an external Omron E6B2-C incremental rotary encoder, a HiTec M7990TH magnetic encoder servo and the BlueArrow DMS47111MG magnetic
encoder servo. These three options were analysed using the servomechanism key selection criteria on a scale of 1-10 with 10 being most appropriately satisfies criteria. Each criterion is also given a weighting factor from 6 to 1 to determine the most appropriate servomechanism as detailed below in table 3.2.

<table>
<thead>
<tr>
<th></th>
<th>HiTec HS-311 + E6B2-C encoder</th>
<th>HiTec M7990TH</th>
<th>BlueArrow DMS47111MG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>The encoder can provide sub-degree accuracy however this also dependent on the quality of the coupling between the servo and encoder.</td>
<td>High accuracy and repeatability through the magnetic encoder</td>
<td>Sub-degree accuracy and repeatability through the magnetic encoder</td>
</tr>
<tr>
<td><strong>Rating:</strong></td>
<td><strong>8</strong></td>
<td><strong>8</strong></td>
<td><strong>10</strong></td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>Servo: 1° per pulse width</td>
<td>Claimed as “high” with no specific resolution available from the manufacturer</td>
<td>.09° per pulse width</td>
</tr>
<tr>
<td><strong>Rating:</strong></td>
<td><strong>5</strong></td>
<td><strong>7</strong></td>
<td><strong>10</strong></td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Servo: cheap plastic gears</td>
<td>High quality metal gears</td>
<td>High quality metal gears</td>
</tr>
<tr>
<td><strong>Rating:</strong></td>
<td><strong>5</strong></td>
<td><strong>10</strong></td>
<td><strong>10</strong></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Servo: $25</td>
<td>$180</td>
<td>$70</td>
</tr>
<tr>
<td><strong>Rating:</strong></td>
<td><strong>5</strong></td>
<td><strong>4</strong></td>
<td><strong>10</strong></td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Servo is readily available</td>
<td>Special order</td>
<td>Special order</td>
</tr>
<tr>
<td><strong>Rating:</strong></td>
<td><strong>7</strong></td>
<td><strong>5</strong></td>
<td><strong>5</strong></td>
</tr>
<tr>
<td><strong>Torque</strong></td>
<td>3.5 kgcm @ 6.0V</td>
<td>36 kgcm @ 6.0V</td>
<td>12 kgcm @ 6.0V</td>
</tr>
<tr>
<td><strong>Rating:</strong></td>
<td><strong>7</strong></td>
<td><strong>10</strong></td>
<td><strong>9</strong></td>
</tr>
</tbody>
</table>

$6(8) + 5(5) + 4(5) + 3(5) + 2(7) + 1(7) = 129$

$6(8) + 5(7) + 4(10) + 3(4) + 2(5) + 1(10) = 155$

$6(10) + 5(10) + 4(10) + 3(10) + 2(5) + 1(9) = 199$

**Table 3.2:** Servomechanism ranking chart.
It was clear from the table 3.2 that the BlueArrow DMS47111MG was the most appropriate servomechanism. A clear advantage of this servo which was not captured in the comparison analysis is that it is described by the manufacturer as being very suitable for micro robot full-angle controlling and industrial automation precise controlling, which is exactly the application it is required for. Therefore the data for this servo in terms of accuracy and resolution was readily available whereas for other servos this was not the case even through directly contacting the manufacturer. The specification sheet and servo product description is available in Appendix B.

3.4.2 Detectors

The detectors which provide an intensity reading for the incident and scattered light are an integral part of the instrument. The intensity recorded by the detectors are direct inputs into the BSDF model. Therefore ensuring the most appropriate detectors are selected is a critical element to achieving instrument accuracy. Key selection criteria were developed to assist in this selection.

3.1.2.1 Selection criteria

The key selection criteria for the detectors are discussed below from highest to lowest priority.

1. Accuracy: the intensity of the light is a key input into the BSDF model and therefore ensuring the most appropriate detector chosen is the most critical element.
2. Cost: the budget for the detectors was $50 and therefore the chosen mechanism needed to be within this budget.
3. Availability: it is preferred if the detectors are readily available should the component fail and needs to be replaced.

3.1.1.2 Comparisons and selection

The detector selection was narrowed down to two options. The first option was to utilise a silicon sensor and the second a charge-coupled device (CCD). Both detectors were readily available which negated this criterion. Literature suggested that CCD’s are commonly used in spectroscopy experiments whilst silicon sensors more commonly used in scattering experiments. The CCD would provide an array of intensities not required whilst the silicon diode would provide an
appropriate output to an accurate level. It was also critical that the detector chosen was effective in the visible and near infrared ranges of radiation given than a red laser was being used as a source.

The detector chosen was a BPW34 silicon photodiode which is very effective in the visible and near infrared ranges of radiation (Bayhan & Ozden 2007). It was well within budget at a cost of $2 per detector. The specification sheet can be found in Appendix C.

3.4.3 Microprocessor
The microprocessor of the instrument is a very important aspect as it controls all of the inputs and outputs of the system. It was very clear that the most appropriate microprocessor based on the criteria of functionality, availability and cost was the open-source electronics prototyping platform Arduino. In terms of functionality the Arduino board can provide all the necessary inputs and outputs to control the entire system with a wide range of libraries and literature being available. The board is also readily available and the cost a relatively low $30. The specific board utilised for this instrument is an Arduino Duemilanove.

3.5 Preliminary Designs and Revisions
The design process was iterative with 2 redesigns occurring before a final design was established which satisfied the key criteria and constraints. Each design and the reasoning behind the redesign are outlined.

3.5.1 Preliminary design
The initial preliminary design of the instrument made use of pre-existing mounting solution for the sample holder base and a pre-existing base in the form of an optical table. The instrument was designed around this setup. A schematic of the preliminary design is illustrated in figure 3.1.
Figure 3.1: Isometric view of preliminary design.

On further investigation it was decided the more effective option was to integrate the entire instrument as a standalone package. This was due to a number of reasons:

1. Access to the room with the pre-existing sample holder base was limited;
2. The room was extremely cramped and crowded and the space to design the instrument around the pre-existing sample holder base was very small;
3. On further investigation using the pre-existing sample holder base would mean the instrument arm would not be able to achieve a full 90° rotation as it would interfere with the sample holder base thus limiting results; and
4. Dimensional accuracy of the instrument in this setup was compromised due to the fact the instrument would require precise alignment to the pre-existing sample holder base.

3.5.2 Redesign 1

The first redesign of the instrument integrated the entire setup as a standalone package. The machining of a new redesigned sample holder was incorporated into this design which would allow the detection of scattered light at extreme angles without interference from the sample holder mounting ring. A sample holder base to position the sample holder correctly was also incorporated along with a laser/chopper/lock-in amplifier package. The design used dowel pins to precisely and accurately locate the various components at an error of less than .01mm. A schematic of redesign 1 is illustrated in figure 3.2.
Figure 3.2: Isometric view of redesign 1.

The quote received from UWA mechanical engineering workshop to manufacture the instrument was well over budget at $2450 which clearly did not satisfy the cost constraint imposed on this project. The quote for the design is presented in Appendix A. In order to reduce the cost the dimensional accuracy of the instrument needed to be reduced and components simplified.

3.5.3 Redesign 2

The second redesign of the instrument decreased the mechanical accuracy to 1.0mm by removing the pins and dowels locating system. It also mounted the motor directly to the base removing the need for the manufacturing of a motor base. This also acted to reduce the height of the entire instrument and decrease required material. A schematic of redesign 2 is illustrated in figure 3.3.
Figure 3.3: Isometric view of redesign 2.

This design still did not satisfy the cost constraint with the UWA mechanical engineering workshop quoting $1100. The quote for the design is presented in Appendix A. To further reduce the cost material offcuts were obtained free of charge from various workshops and components which were not critical to the functionality of the instrument removed. The final design is detailed in section 4 Final Design, Results & Discussion.
4  Final Design, Results & Discussion

The final design is described in detail. Drawings and schematic illustrations of the final design are depicted, material and component specifications are provided, and systems integration are detailed. The results of testing the design in practice are also presented.

4.1  Final Design

4.1.1  Overview

A schematic of the final design is presented in figure 4.1. As is evident the instrument is comprised of a number of different components which integrate to form a complete standalone package capable of determining surface roughness characterisation. Each of these components are detailed in section 4.2. Technical drawings for each component are provided in Appendix E. A bill of materials for the entire system is also detailed in Appendix F.

**Figure 4.1:** Isometric view of the final design. Figure does not include instrument cover for illustrative purposes.

A photo of the instrument is also shown in figure 4.2.
Figure 4.2: Photograph of instrument. Photograph does not include instrument cover for illustrative purposes.

4.1.2 Definition of model variables

The instrument is designed to provide the necessary data for input to the BSDF and PSD models. The final design is defined in terms of the relevant spatial variables in figure 4.3.
Figure 4.3: Top view wire diagram of final design indicating incident intensity angle and scatter intensity angle as defined by the BSDF and PSD models.

The range of the spatial measurement is designed to be $90^\circ$ for this instrument which is typically sufficient to characterise surface roughness (Stover 1995). To ensure this is achieved the incoming laser beam strikes the sample on a predetermined angle $\theta_i$ as shown in figure 4.3. This is to make certain the maximum possible range of angles can be detected without interference between the incoming laser and the servo arm. If the laser were to strike the sample at $\theta_i = 0^\circ$, the incident beam would be obstructed by the servo arm and the s and p detectors therefore limiting the spatial range of angles measured. The incident angle is also adjustable through using a clamping system on the chopper/lock-in amplifier package assembly.

4.1.3 System diagram

The system diagram outlines the inputs, processes and outputs of the instrument and its components. The operation and integration of the various instrument components is outlined in figure 4.4.
Figure 4.4: System diagram of final design detailing instrument operation.

The detailed processes that occur in the system are as follows:

1. Power is supplied to the laser, signal processing circuit and microprocessor at 15 volts;
2. The laser beam passes through a polarizer which defines the incident intensity polarization and is necessary to characterise $\alpha$ in the polarization factor $Q_{\alpha \beta}$;
3. The polarized laser beam proceeds through a chopper which modulates the beam. The frequency of modulation is detected by the lock-in amplifier;
4. The arm is rotated at a predetermined angle less than 0 degrees by the servo through the microprocessor to ensure the modulated polarized beam is coincident on the incident intensity photodiode;
5. The photodiode detects a current reading, this is converted to a voltage value through the signal processing circuit;
6. This data is sent to the microprocessor and to the computer;
7. Data is sent from the computer, through to the microprocessor to set the arm angle to 0 degrees to begin scatter intensity readings;
8. At angle from 0 to 90 degrees the modulated polarized beam is not obstructed and is incident on the sample specimen;
9. The arm rotates at an specified angle increment;
10. Detected scattered intensity from the sample specimen passes through a s polarized film. This is necessary to characterise β in the polarization factor $Q_{\alpha\beta}$; 

11. Detected scattered intensity from the sample specimen passes through a p polarized film. This is necessary to characterise β in the polarization factor $Q_{\alpha\beta}$; 

12. Both the s and p polarized light pass through separate photodiodes; 

13. The photodiodes detect a current reading, this is converted to a voltage value through the signal processing circuit; 

14. This data is sent to the microprocessor and to the computer; and 

15. Steps 9 through to 15 are repeated until $\theta_s = 90$ degrees.

This process is illustrated through an animation rendered in SolidWorks on the enclosed CD.

4.2 Components in Detail 

4.2.1 Base 

The base provides the necessary support for the entire instrument. An isometric exploded view of the base and associated components is illustrated in figure 4.5.

![Isometric exploded view of base](image)

**Figure 4.5:** Isometric exploded view of base. Key points of interest are labelled. Dotted lines represent route lines which connect entities.

Key points of interest from figure 4.5 are described in detail below.
- Filleted edges: Ensures the instrument is safe for all users and no sharp edges are exposed.
- Electrical wiring grommet: If metal has a hole drilled through it the hole may have sharp edges. Electrical wires passing through the hole can become abraded or cut, or electrical insulation may break due to repeated flexing at the exit point. An electrical wiring grommet was used to avoid and mitigate this risk. The smooth inner surface of the grommet shields the wire from damage.
- Sorbothane® feet: Vibrations from the surrounding environment contribute to unavoidable background noise in optical systems leading to a decrease in experimental accuracy (Thor Labs 2011). Vibration isolation supports in the form of Sorbothane® material are used to isolate the instrument from any ambient vibrations from the surrounding environment.
- Laser/chopper/lock-in amplifier swivel pin and clamp: This is allows the angle adjustment and locking of the incident beam angle ($\theta_i$).

4.2.2 Instrument cover

The instrument cover is used to shield the instrument from any ambient light not from the instrument laser beam during operation. This is to ensure the detectors register only light scattered from the sample specimen and not from other sources. A standard storage crate is used for the instrument. The crate is black to minimize any reflection. A photo of the instrument cover is shown in figure 4.6.

![Instrument cover](image)

**Figure 4.6:** Picture of crate used to isolate the instrument from the surrounding environment.
4.2.3 *Arm*

The arm provides the means at which the instrument is able to detect scattered intensity off a sample at various angles. An isometric exploded view of the arm and associated components is illustrated in figure 4.7.

![Isometric exploded view of arm. Key points of interest are labelled. Dotted lines represent route lines which connect entities.](image)

**Figure 4.7:** Isometric exploded view of arm. Key points of interest are labelled. Dotted lines represent route lines which connect entities.

Key points of interest from figure 4.7 are described in detail below.

- Detector slots: Machined with an interference fit to the detectors to allow removability. Should the detectors need to be replaced, for example due to a reliability failure or a perhaps a different standard of detector is required, the mounting system used facilitates this process.
- Arm cantilever support: Ensures that the arm does not wilt and remains parallel to the instrument base at all times. This is critical to ensure scattered intensity readings occur in the sample plane as the incident intensity beam. The support is lined with polyethylene which provides a low coefficient of friction between the
arm and instrument base. This makes certain the least possible resistance is experienced by the servo during operation.

The alignment of the arm and consequentially the detectors to the sample specimen are a key priority in the design. A top view wire diagram of the arm and its alignment to the sample specimen are illustrated in figure 4.8.

![Top view wire diagram of arm alignment to sample holder base and sample holder.](image)

**Figure 4.8:** Top view wire diagram of arm alignment to sample holder base and sample holder.

To obtain consistent results from the S and P polarized detectors it is critical to ensure both detectors line of sight are incident on a common sample specimen coordinate during the arms full range of motion. For this to be achieved the pivot of the arm is aligned directly beneath the sample and the detectors are offset on calculated angles to ensure line of sight convergence at this pivot point. The effect of this offset is factored into the scatter data whereby \( \theta_s(p) = \theta_s - 3.7^\circ \) and \( \theta_s(s) = \theta_s + 3.7^\circ \).
4.2.4 Sample holder

A pre-existing sample specimen holder was available. The holder functions through a clamping mechanism. This is illustrated in figure 4.9.

![Isometric exploded view of sample holder](image1.png)

**Figure 4.9:** Isometric exploded view of sample holder. Key points of interest are labelled. Dotted lines represent route lines which connect entities.

However an issue exists with the pre-existing sample holder. At extreme angles the clamping ring obstructs the detection of any scatter intensity from the sample specimen. This is illustrated in figure 4.10.

![Clamping ring and scattered beam interference](image2.png)

**Figure 4.10:** Clamping ring and scattered beam interference.

In order to eliminate this issue the sample holder ring was redesigned. This is illustrated in figure 4.11.
Figure 4.11: Redesigned sample holder to eliminate scattered beam interference.

However due to cost constraints this redesigned sample holder could not be implemented.

4.2.5 Sample holder base
The sample holder base provides the alignment and support for the sample holder and sample specimen. The sample holder base was designed to accommodate the pre-existing sample holder. An isometric exploded view of the sample holder base associated components is illustrated in figure 4.12.

Figure 4.12: Isometric exploded view of sample holder base. Key points of interest are labelled. Dotted lines represent route lines which connect entities.
Key points of interest from figure 4.12 are described in detail below.

- “L” shape design: Ensures a full range of motion can be achieved by the instrument arm without any interference.
- Set screws: Used to hold the sample holder firmly in place.
- Sample holder recess: Allows the sample holder to slide within the recess to allow data readings from various sample specimen coordinates.
- Limit switches: Should the maximum angle limit coded within the software fail hardware limit switches cut the power to the servo prior to any interference between the arm and the sample holder base to prevent damage to the servo and mitigate any safety hazards.

4.2.6 Laser/chopper/lock-in amplifier assembly

The assembly provides the necessary housing and alignment of the laser diode and circuit, and also the chopper and lock-in amplifier system.

4.2.6.1 Construction

An isometric exploded view of the laser/chopper/lock-in amplifier assembly and its associated components is illustrated in figure 4.13.
**Figure 4.13:** Isometric exploded view of the laser/chopper/lock-in amplifier assembly. Key points of interest are labelled. Dotted lines represent route lines which connect entities.

Key points of interest from figure 4.13 are described in detail below.

- **Housing:** Standard aluminium die-cast box modified with various holes for components.
• Supports: Standard bolts which were rethreaded to allow height adjustability of the housing and therefore the incoming laser beam. Support 1 has a hole drilled in the base to allow an interference fit between the support and the swivel pin.

• Laser intensity adjustment circuit: A circuit was developed to allow the intensity of the incoming laser beam to be adjusted. The circuit diagram is depicted in Appendix G.

• Laser intensity adjustment hole: The hole allows the adjustment of the intensity of the incoming laser beam to be tuned without disassembling the entire housing. A screw driver is simply placed through the hole and rotated to adjust the variable resistor.

• Circuit mounting plate: A thin aluminium sheet was cut to specification to allow the mounting of circuits.

• Laser: Obtained by stripping the outer casing of a common laser pointer and extracting the laser diode and circuit.

• Polarizer mounting plate and polarizer: A rectangular piece of aluminium was cut with a hole drilled through the centre and a polarizer sheet applied. The rotation of the plate determines the polarization state of the incoming beam.

A photo of the assembly is also shown in figure 4.14.

![Photo of the assembly](image)

**Figure 4.14:** Photograph of the laser/chopper/lock-in amplifier assembly. Note the assembly lid is removed for illustrative purposes.
4.2.6.2 Assembly shield

A shield was fabricated in order to minimize scattering that occurs between the sample and the assembly due to its reflective case. This unwanted scattering is illustrated in figure 4.15.

**Figure 4.15:** Unwanted scatter leading to decreased accuracy of results is shown by light arrows.

The shield was fabricated from a thin piece of aluminium cut and bent to specification. In order to reduce this scattering a black rough surface with a pinhole for the laser to travel through was required to disperse and diffuse any scattering near the housing. Sandpaper painted black and cut to size was bonded to the piece of aluminium. The result of the shield is illustrated in figure 4.16.

**Figure 4.16:** The shield prevents any unwanted scatter being detected.
4.2.6.3 Alignment of laser

The incident angle ($\theta_i$) at which the laser strikes the sample is a key input into the roughness models. Therefore ensuring a minimal straight line accuracy error is crucial. Straight line accuracy is a measurement of the amount of error that a linear positioner will deviate from a perfectly straight line (Edmund Optics 2011). It is characterised by the maximum deviation error in the horizontal and vertical planes for the overall length of travel. Given its importance an experimental apparatus and procedure was developed to ensure minimal straight line accuracy error as illustrated in figure 4.17.

**Figure 4.17:** Experimental setup for laser alignment. As is evident the laser beam is not aligned with the reference point indicating further adjustment is required.

1. Laser/chopper/lock-in amplifier housing is first checked for manufacturing intolerances by verifying squareness using straight edge. This is crucial as the edge of the box is used to align the laser.
2. A straight edge tool is aligned perpendicular to a flat surface in the $z$-direction such as a wall with a piece of paper taped to it.
3. The distance from the centre of the laser to the edge of the box is measured.
4. A reference point is drawn on the paper with the same distances as those measured in the previous step.
5. The edge of the box is aligned with the edge of the straight edge.
6. The laser is powered.
7. The laser is manipulated so the laser dot strikes the same position as the point
drawn on the paper.
8. Slow drying epoxy glue is applied to the laser and housing to seat the laser
housing in place.
9. The box is then moved back and forth along the straight edge in the z-direction.
10. If the laser dot deviates from the point drawn on the paper when moving back
and forth the laser is not aligned correctly and should be adjusted until the laser
dot does not deviate from the dot drawn on the paper.

Straight line accuracy in the y and x direction was measured as .1mm and .05mm
respectively with relation to the z plane.

4.2.7 Detectors
Three light detectors in the form of photodiodes are used in the instrument. Two of
these photodiodes detect S and P polarized scattered light intensity respectively and the
third photodiode measures the laser beam incident intensity.

4.2.7.1 Alignment of polarizers

Polarized films were bonded to the scatter intensity detectors to adhere to the
requirements of the BSDF and PSD models. The polarisation film obtained was pre-
aligned in the s and p light polarization directions with respect to a datum as shown in
figure 4.18.

![Figure 4.18: Polarization film. S and P polarizations are pre-aligned with respect to the
datum.](image-url)
Aligning the polarizers to components with respect to this datum provides sufficient accuracy. The alignment can have a maximum misalignment of ±5.74° and still provide 99% of its filtering capabilities (Robot Room 2010).

4.2.7.2 Detector shield

A detector shield was fabricated to minimise scattering that occurs at the detectors due to its reflective case which can cause detection inaccuracies. This inter-component scattering is illustrated in figure 4.19.

![Figure 4.19: Scattering and reflection from the detector case.](image)

In order to reduce this scattering a black rough surface with a pinhole was required to disperse and diffuse any scattering near the detector photodiode. Sandpaper painted black and cut to size was used. The hole through the centre of the detector shield was achieved through the use of a hole punch in order to minimize any burring around the edges of the hole. The diameter of the s and p detector shield holes were measured using a microscope to ensure consistency between the two detectors. The aperture of the detector is also a variable which determines the system geometry factor in the BSDF model and therefore the accuracy of this measurement is crucial. The hole diameter for the s and p shields was found to be 2.2mm as measured through a microscope. The shields were bonded to the front of the polarization films as illustrated in figure 4.20.
Figure 4.20: Detector shield attached to the front of the polarization film.

The backside of the polarization films were subsequently s and p direction aligned using the film datum as a reference and bonded to the detector faces. The final result is a much cleaner scatter detection as illustrated in figure 4.21.

Figure 4.21: Detector shield and polarizer used to refine detected scattered intensity.

4.2.7.3 Mounting

Each detector is mounted on a precisely cut piece of protoboard. The main advantage of this method is that the optical cables (used to decrease noise in the system) which detect the signal from the detectors can be soldered to the board rather than the detectors themselves. Due to the rotation of the arm, this method of mounting the detectors ensures the optical cables do not exert a force on the detectors when in motion which would result in misalignment and perhaps even the removal of the detectors from the board. The mounting of the detectors is illustrated in figure 4.22.
4.3 Safety

There exists potential for severe consequences if the stringent safety protocols applicable to the design, manufacturing, fabrication and integration of the instrument are not followed. This section identifies pre-existing safety precautions which were observed over the course of the project. Depending on the nature of the safety issue safe operating procedures (SOP’s) were developed. Specific safety issues and mitigation strategies to individual components are identified in section 4.2 Components in Detail. The risk assessment conducted during the project proposal phase, and subsequently revised as the objectives expanded, is also discussed.

4.3.1 Laser safety precautions

The laser employed in the instrument is specified as a class 3A laser. By definition, a class 3A laser is one which can cause serious damage to the retina of the eye if viewed directly for more than 2 minutes (The Australian National University 2008). In addition to complying with the relevant sections of AS 2211 – Laser safety, a number of precautions were implemented to ensure laser safety was paramount at all times.

A circuit was designed to allow the regulation of the laser power output. This allowed the laser output to be used at very safe levels during development stages of the project where full power was not required and could during the later stages of the project be dialled up when required.

During development stages and debugging of the design the power output of the laser was significantly reduced to ensure safety. The power output was independently tested at an output of less than 1 mW. By definition this places this laser in the class 1
category. Laser devices in this category are safe for use under all conditions of exposure, based upon current medical knowledge (The Australian National University 2008).

During the final development stages of the project the output of the laser was increased to up to 5 mW. By definition this places the laser still within the class 3A category. Laser devices in this category present a marginal eye hazard. At this category the beam must be expanded to an irradiance of less than 25 Wm\(^2\), to ensure that only 1 mW or less can enter the 7 mm pupil (The Australian National University 2008). The Working Rules described by AS 2211 – Laser Safety were followed in this instance (Appendix H).

A number of considerations were also incorporated into the design to ensure optimal safety conditions. Aspects such as ensuring the correct alignment of the laser beam, the use of a pinhole shield and covering the entire apparatus with a black crate all reduce laser exposure and are discussed in detail in section 4.2 Components in Detail.

4.3.2 Weight of design apparatus

The design apparatus was required to be moved to various laboratories. Whilst the weight of the design apparatus is only approximately 15kg after a prolonged period of time this can begin to cause fatigue. A SOP was developed to control and mitigate this risk (Appendix I).

4.3.3 Manufacturing and fabrication

Manufacturing and fabrication of the various components of the design were performed by both the author and the UWA mechanical workshop staff. The workshops staff safety is also the responsibility of the designer and therefore the SOP’s for the equipment used by the staff were also considered.

The following tools were used throughout the manufacturing and fabrication process:

- Drilling machine (UWA workshop staff only);
- Milling machine (UWA workshop staff only);
- Metal-cutting guillotine (UWA workshop staff only);
- Hand-held drill;
- Hand-held saw; and
- Tap and die set.
The SOP’s for the above tools can be found in Appendix J.

4.3.4 Assembly and integration

The main safety consideration in the assembly and integration phase of the project was the soldering of the various electrical components. When done improperly soldering can be dangerous. The potential for severe burns, poisoning or even starting a fire exist and as such developing SOP’s for this tool are critical in mitigating risks. The SOP for this tool can be found in Appendix K.

To further mitigate any electrical damage to the equipment and prioritise safety input and output connections were tagged and labelled appropriately. Heatshrink was also applied to any exposed electrical connections.

4.3.5 Laboratory evacuation plan

The majority of the authors’ time was spent in the Sensory & Advanced Instrumentation Laboratory (SAIL) which is located at G.55 in the UWA mechanical engineering building. It was therefore important to be familiar with the surroundings and also the emergency exists in the event of an accident. The emergency evacuation map is illustrated in figure 4.23 below.

![Emergency Evacuation Map](image)

**Figure 4.23:** G.55 emergency evacuation map.

The following evacuation procedure was formalised:

1. Turn off all electrical equipment;
2. Close all windows;
3. Leave work area and close door behind ensuring no-one is left in the workplace;
4. Proceed to the closest exit at a fast walk (do not run) and make your way to the pre-determined assembly area; and
5. Perform duties as instructed by the Wardens (e.g. help mobility impaired persons).

4.3.6 Risk Assessment

The following section identifies the potential risks associated with this project and strategies that should be implemented to mitigate these risks. By undertaking a thorough risk assessment, including the establishment of risk management strategies, adversities may be dealt with in an appropriate and timely manner.

The risks associated with this project are identified in Table 4.1. Each risk was assessed in accordance with the UWA Safety Risk Management Procedure (The University of Western Australia 2010) and mitigation strategies were identified.

One project outcome-related risk throughout the project was realised: lack of funds. Initial designs were significantly over budget. As indentified in table 4.1 to control the risk the initial designs went through a number of redesign stages to reduce costs. This is further discussed in section 3 Design Process.
<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Aspect</th>
<th>Impact</th>
<th>C</th>
<th>L</th>
<th>E</th>
<th>R</th>
<th>Control</th>
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<td>Electrical equipment</td>
<td>Electric shock from electrical equipment, such as computers, servo’s,</td>
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<td>2</td>
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<td>Regular checks of power cords for fault, fraying or wear and regular</td>
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<td>photodiodes etc</td>
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<td>electrical safety checks. This maintenance to be performed only by</td>
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<td>Eye damage from lasers (UV and visible lasers)</td>
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<td>authorised UWA staff.</td>
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<td>Design, fabrication and manufacturing</td>
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<td>L</td>
<td>Detailed training required.</td>
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<td>Most important point to not look directly into the light source.</td>
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<td>curtains etc.</td>
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<td>Environmental</td>
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<td>No significant environmental risks.</td>
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<td>Financial</td>
<td>Design components</td>
<td>Increase in the cost of design components such as servo’s, diodes etc</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>L</td>
<td>Source components from alternative sources or factor extra cost into</td>
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<td></td>
<td>Porous Silicon</td>
<td>Cost of products rise</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>L</td>
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<td>Technique failure</td>
<td>Failure of scattering method to deliver results</td>
<td>25</td>
<td>3</td>
<td>2</td>
<td>M</td>
<td>Use allocated budget ($400 in cash expenditures) provided by school to</td>
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<td></td>
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<td>Failure of chosen model to deliver results</td>
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<td>Review of literature to identify other possible methods available to</td>
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<td>deliver the desired results.</td>
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<td>Risk Factor</td>
<td>Description</td>
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<td>Design apparatus</td>
<td>Design is inadvertently damaged</td>
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<td>L</td>
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<td>Ensure experimental apparatus is always stored safely and away from any</td>
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<td>Lack of funds</td>
<td>Unavailability of funds to create experimental facilities and achieve</td>
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<td>0.5</td>
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<td>project objectives</td>
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<td>Simplify design where possible.</td>
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<td>Supervisor absence</td>
<td>Unforeseen absence of supervisor</td>
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<td>Make the best use of time available with Dr Keating.</td>
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<td>Loss of data</td>
<td>Data loss through computer malfunction</td>
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<td>Create multiple backups of files. Save files both on UWA server personal</td>
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<td>Failure of author to understand</td>
<td>Inability for the author to understand the concepts required to make</td>
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<td>Time mismanagement</td>
<td>Not using time correctly resulting in not achieving weekly objectives</td>
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<td>Continually review current project status to original project timeline and</td>
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<td>If more time is needed, factor into lifestyle.</td>
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<td>Make the best use of time available with Dr Keating.</td>
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Table 4.1: Project risk assessment matrix developed using the UWA Safety Risk Management Procedure.
4.4 Systems integration

The integration of the various mechanical, electronic and software components of the instrument are crucial. The assimilation of these components is described in detail. The system circuit is depicted in Appendix G.

4.4.1 Servomechanism

4.4.1.1 Control

The servo is controlled by sending a variable pulse width commonly referred to as pulse width modulation (PWM). The angle of the servo is determined by the duration of that pulse that is applied through the control wire. Each servo has a valid maximum and minimum pulse which determines the angular range over which it can travel. For the DMS47111MG the minimum pulse width is .9ms and maximum 2.1ms as illustrated in figure 4.24.

![Diagram of PWM control of the servo.](image)

**Figure 4.24:** PWM control of the servo.

4.4.1.2 Calibration

The servomechanism was calibrated using three separate experimental methods to determine accuracy and repeatability. Data from each of the methods is tabulated in Appendix L.

4.4.1.2.1 Method 1

A calibration piece was fabricated for this method. The calibration piece and setup is illustrated in figure 4.25.
An “L” piece was fabricated which was coincident and parallel with both the arm and the base. The servo was then rotated to various angles and a line drawn on the base in line with the calibration piece at these angles. By incrementing the PWM values in steps of 25 μs the angle between the lines drawn for these increments can be determined and the relative accuracy of the servo investigated. The results of this test are illustrated in figure 4.26.

The results suggest that the servo does not operate in a perfectly linear manner as the angle differences for a constant change in PWM value vary. The data obtained from this method has a maximum deviation of 1° from the median. The trend line indicates a slight increase in angle difference for a decreasing PWM. These unfavourable results
however could potentially be due to the limitations of the testing method. Such errors may include human error in measuring data, limitations in using a protractor to measure the angle difference between PWM values and also the fact that when drawing the angle line a small but apparent force is exerted on the arm which could cause it to move slightly. Error bars indicate an approximated error margin of $\pm 0.5^\circ$.

4.4.1.2.2 Method 2

In this setup a laser pointer was attached to the servo arm and projected onto a flat surface. The experimental setup is illustrated in figure 4.27.

![Experimental setup for servo calibration using method 2.](image)

**Figure 4.27:** Experimental setup for servo calibration using method 2.

The PWM value of the servo was incremented in steps of 25 $\mu$s and a point marked on the surface. The distance from the arm pivot point to the laser point on the flat surface was measured for each PWM value (denoted by $r_1$ and $r_2$ in figure 4.27). The distance between two consecutive points was also measured (denoted by $d$ in figure 4.27). Using this data the angular difference between PWM values can be determined using the cosine rule as detailed in Appendix L. The results of the test are illustrated in figure 4.28.
The data obtained through this method has a maximum deviation of 0.25° from the median. Sub degree servo accuracy is required and the data obtained through this fulfils this requirement. The small deviation recorded could also be due to human error and inherent test limitations such as measuring inaccuracies.

In comparison to method 2, this method appears to be a more accurate test. The angle difference spread and the deviation from median measured through this method is considerably less than that measured in method 1. This is also indicated by the smaller gradient of the trend line.

4.4.1.2.3 Method 3

The purpose of method 3 was to test for servo repeatability. That is, to ensure the servo can be moved to a repeatable angular position at any time. The more repeatable the result the more the servo can be relied to move to a certain position accurately. In order to test this objective a laser pointer was attached to the servo arm as described in method 2. The laser pointer was projected onto a flat surface and the initial position marked. The servo was then rotated to a certain PWM value and thus angle and the laser pointer position also marked. This process was repeated 25 times with the difference in laser pointer positions measured. These deviations from the datum are converted to angular deviation using the same procedure as method 2. The results from this test are illustrated in figure 4.29.
The results suggest the servo has good repeatability. The deviation from the datum does not increase with increasing test number. If the deviation from the data were to increase with increasing test number this would indicate the servo loses accuracy the more it is used. This is certainly not the case with the DMS47111MG. The histogram in figure 4.30 also supports these findings.

**Figure 4.29:** Plot indicating repeatability of servo.

**Figure 4.30:** Histogram indicating repeatability of servo.
The histogram in figure 4.30 indicates the frequency of the angular deviations is randomly spread with no direct trend further emphasising good servo repeatability. The calculated standard deviation of .15 indicates the data spread is low and therefore indicating good servo accuracy.

4.4.1.2.4 Conversion of PWM to Angle

From the data obtained through the tests undertaken the PWM value which is sent to the servo can be converted to an angle in degrees. The data obtained through method 2 was deemed to be the most accurate and thus is the basis for this conversion. Since the servo behaves in a linear manner as indicated by an R² value of .9999, the angle can be calculated using equation 4.1.

\[ \theta_s = \text{slope} \times \text{PWM} + \text{PWM}_{\text{offset}} \pm \text{error margin} \quad (4.1) \]

The slope can be obtained from figure 4.31 below.

![PWM to angle conversion](image)

**Figure 4.31:** Conversion from PWM to angle in degrees.

\[ \text{Slope} = \frac{\text{rise}}{\text{run}} = \frac{\Delta(\text{cumulative relative angle})}{\Delta\text{PWM}} = \frac{(48.95 - 8.3)}{(1475 - 1600)} = -0.3252 \quad (4.2) \]

The PWM\text{offset} can be calculated by knowing an absolute point and substituting this into equation 4.2. From method 1 a PWM value of 1330 corresponds to 90 degrees.

\[ \text{PWM}_{\text{offset}} = \text{PWM} \times \text{slope} - \theta_s = (1330)(-0.3252) - 90 = 522.5160 \quad (4.3) \]

Thus the final equation for angle \(\theta_s\) in terms of a given PWM value is;
4.4.2 Detectors
4.4.2.1 Control

Photodiode detectors produce current as an output. This current output is proportional to the amount of light being registered. Three circuits were designed to convert the current output of each of the detectors into a usable voltage value; one to measure the incident intensity and two to measure s and p polarization scattered intensity. A simplified version of these circuits are depicted in figure 4.32 to outline general operation.

![Simplified circuit of photodiode operation.](image)

**Figure 4.32:** Simplified circuit of photodiode operation.

The main component of the photodiode circuit is the operational amplifier (op amp) current-to-voltage converter otherwise known as a transimpedance amplifier. The primary job of this amplifier is to adjust the output such that the inverting input equals the non-inverting input.

As no current flows through the op amp itself the generated photocurrent flows through $R_f$ which is fixed. The resultant voltage is therefore linearly dependent on the incident radiation level ($V_{out} = I_{sc} x R_f$). One way to achieve sufficiently low load resistance, and an amplified output voltage, is by feeding the photocurrent to an operational amplifier virtual ground as shown. The circuit has a linear response and has low noise due to the almost complete elimination of leakage current.

If we set the open loop gain of the operational amplifier as $A$, the characteristics of the feedback circuit allows the equivalent resistance to be $R_f/A$ which is several orders of
magnitude smaller than $R_f$. Thus this circuit enables ideal $I_{sc}$ measurement over a wide range.

The value of $R_f$ controls the gain of the circuit. The gain of the incident intensity circuit is the lowest due to the fact it is measuring the greatest intensity of light in the system. For the s and p polarization circuits a relay is used to switch between a high gain and low gain state. The high gain state of the s and p circuits is lower than the gain state of the incident intensity circuit and is used to measure smaller scattering readings. The low gain state of the s and p circuits is significantly lower than the gain state of the incident intensity circuit and is used to measure larger scattering readings.

The photodiodes are also operated in photovoltaic mode as opposed to photoconductive mode to reduce dark current and minimize noise levels. With zero-bias operation, dark current offset errors are not generated by this current. Zero bias is a slower but higher sensitivity mode of operation. For this application detector sensitivity is preferable over speed further justifying the selection of this mode state.

The specific circuit diagrams for incident, p polarization and s polarization intensity are detailed in Appendix G.

4.4.2.2 Calibration

The calibration of each of the detector circuits is a key element in obtaining accurate results. Each of the detector circuits has a different gain value and therefore each must be calibrated with respect to one another.

The detector circuits were calibrated through the use of a constant reference light source. By placing this light source incident on the various detectors and recording the intensity readings, gain ratios between the various detectors can be determined. The calibration plot is illustrated in figure 4.33.
As is evident from figure 4.33 for a common light source the S,P detectors will record a reading of 59 times the incident intensity in high gain state and 3 times the incident intensity in the low gain state. Therefore for any scatter data recorded the inverse of these gain states should be applied to ensure correct scaling.

The ceiling apparent on the plot at a value of 1023 represents the detector saturation point. At this point even if incident light is increased on the detector face the reading will remaining unchanged. This is identified in the system and signals to the microprocessor that the gain state must be changed to the low gain state.

The calibration of incident intensity ($P_i$) in terms of an absolute intensity measurement such as watts per square meter ($\text{W/m}^2$) is not necessary for the system. This is due to the fact that all data examined is normalised to the incident intensity ($P_s/P_i$).

4.4.3 Instrument communications

The instrument interfaces with 3 separate communication channels. These are the firmware in the form of the Arduino microprocessor, the software in the form of MATLAB and a graphical user interface (GUI). The relationship between these channels is detailed in figure 4.34 below.
4.4.3.1  Firmware

The firmware controls the basic functionality of the instrument. This includes the servo angle, s and p detector relay states and the reading of the detector intensity values. This communication is achieved through a computer's serial monitor interface with the character ‘x’ used as a terminating command. The following are examples of commands are used:

- m1600x – move servo to PWM value to 1600 (digital write port 8)
- p1x – set P relay high (digital write port 3)
- p0x – set P relay low (digital write port 3)
- s1x – set S relay high (digital write port 4)
- s0x – set S relay low (digital write port 4)
- rx – read detector values (analogue read ports 0 1 2)

The firmware code is available in Appendix M.

4.4.3.2  Software

MATLAB is used as the software package for the instrument. It communicates with the firmware by initialising its own serial communications interface. Through this the firmware commands can be directly used within the software.

The following basic procedures occur during initialisation of the software:

1. Set initial detector gain state;
2. Move arm such that incident intensity detector is coincident with incoming beam and read data;
3. Move arm to initial position of 90°;
4. Read detector data for angles from 90° to 0°;
   a. During data readings check for detector saturation. If so switch gain state.
5. Calibrate angle and detector data; and
6. Tabulate data.

The software code is available in Appendix N.

4.4.3.3 Graphical user interface

A graphical user interface was developed in MATLAB to assist in data acquisition and analysis. Since the instrument is covered and not visible during operation the GUI is especially useful to provide real time instrument feedback to the user. Each of the GUI’s parameters are explained below. A screen capture of the GUI is illustrated in figure 4.35.

![GUI for the scatterometer.](image)

**Figure 4.35:** GUI for the scatterometer.

- User control: allows the user to start and stop the instrument.
- Running information: provides the current status of the instrument, the progress percent and the estimated time remaining of the data acquisition process.
- Data acquisition: provides real time data feedback of a number of variables which correspond to the GUI labels in table 4.2.
<table>
<thead>
<tr>
<th>GUI label</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>Scatter angle $\theta_s$</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Incident intensity</td>
</tr>
<tr>
<td>$P_s(p)$</td>
<td>P polarization scatter intensity</td>
</tr>
<tr>
<td>$P_s(s)$</td>
<td>S polarization scatter intensity</td>
</tr>
<tr>
<td>$NP_s(p)$</td>
<td>Normalised p polarization scatter intensity ($P_s(p)/P_i$)</td>
</tr>
<tr>
<td>$NP_s(s)$</td>
<td>Normalised s polarization scatter intensity ($P_s(s)/P_i$)</td>
</tr>
</tbody>
</table>

**Table 4.2:** GUI labels and corresponding variable associations.

- Data plots: provides real time visual feedback of the p polarization and s polarization scatter intensity data.

**4.4.4 Debugging**

Debugging is a methodical process of finding and reducing the number of bugs, or defects, in a computer program or a piece of electronic hardware, thus making it behave as expected. Significant issues were realised in the integration of the various mechanical, electronic and software fields of the instrument. When developing an instrument which requires the integration of these fields, the system never functions correctly the first, the second or even the tenth time and a methodical process of elimination needs to be followed to ensure the instrument functions correctly.

**4.4.5 System parameters**

The system parameters of the instrument define its operating conditions. These are acknowledged in table 4.3.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incidence angle ($\theta_i$)</td>
<td>$0^\circ \leq \theta_i \leq 20^\circ$; $\Delta \theta_i = 1^\circ$; $\theta_i = 10^\circ$</td>
</tr>
<tr>
<td>Scatter angle ($\theta_s$)</td>
<td>$-90^\circ \leq \theta_s \leq 90^\circ$; $\Delta \theta_s = 0.3252^\circ$</td>
</tr>
<tr>
<td>Sample movements</td>
<td>$28 \text{ mm} \leq x \leq -28 \text{ mm}$</td>
</tr>
<tr>
<td>Wavelength of incident light ($\lambda$)</td>
<td>650 nm</td>
</tr>
<tr>
<td>Detector aperture radius ($r$)</td>
<td>1.1 mm</td>
</tr>
<tr>
<td>Distance from detector to sample ($R$)</td>
<td>69.2 mm</td>
</tr>
<tr>
<td>System geometry factor ($\Omega_s$)</td>
<td>0.000794</td>
</tr>
<tr>
<td>Dynamic range of scattered light ($P_s(\text{max})/P_s(\text{min})$)</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Table 4.3: Principle parameters of scatterometer.

4.5 Instrument testing

4.5.1 Instrument signature

Instrument signature is the intensity data which the scatterometer outputs that does not directly correlate to the sample specimen. The signature can be due to a combination of varying factors including stray laser light, any light emitting electrical components and surrounding room light. In order to ascertain an accurate representation of the scattering and intensity characteristics of the sample specimen itself the instrument signature must be removed from the profile.

The instrument signature was measured by scanning the incident beam through an empty sample holder. This measurement was taken for both the low and high detector gain states. The low detector gain state did not register any intensity readings which suggests if any instrument scatter is present it is not of a high enough intensity to interfere with a sample scattering profile at this detector state.

This is in contrast to the high detector gain state which did register intensity readings. The logged data is presented in figure 4.36 below.
High detector gain - empty sample holder

Figure 4.36: High detector gain state with an empty sample holder.

It is clear from figure 4.36 that the detectors are reading nonzero intensity values over the entire angular range. However the range of the normalised intensity values is very small (0.6) with 85% of the data having a normalised intensity value of 0.0158. This suggests that the detector intensity reading is due to relatively constant instrument scatter which is acting over the entire angular range. It is highly unlikely however that this is the case as the detection of even a constant instrument scatter would have significantly more variance due to the large deviation in angular range and therefore field of vision of the detectors.

The data presented in figure 4.37 outlines the recorded normalised intensity with the detectors completely covered.
Figure 4.37: High detector gain state with covered detectors.

It is evident in comparison of figures 4.36 and figures 4.37 that, with the exception of the location of the intensity fluctuations, they are almost identical. From this a number of conclusions can be drawn. Firstly, the data suggests that either no instrument signature is apparent (unlikely) or the detectors’ amplification is not high enough to register any instrument signature. Secondly, the data suggests that the intensity readings are due to the increased electrical noise that the high detector gain state causes. Electrical noise is statistical in nature and the fact that figures 4.36 and 4.37 are very similar but appear to have random intensity fluctuations, along with the notion intensity is registered even when the detectors are covered confirm these readings are in fact due to electrical noise. Operational amplifiers also generate a random output voltage even when no signal is applied which becomes pronounced at high gain levels which further acts to support this conclusion (Texas Instruments 1998).

This noise floor must be deducted from any measured data to create an accurate sample profile. The BSDF is calculated for this data, termed the noise-equivalent BSDF (NEBSDF) in figure 4.38.
4.5.2 Diffraction grating

A diffraction grating is an optical component with a periodic structure, which splits and diffracts light into several beams travelling in different directions. This optical component was used as a test sample specimen for the instrument.

The diffraction grating was placed in front of a mirror and into the instrument sample holder so that the incident beam passing onto the grating would be diffracted and reflected, rather than transmitted, such that the diffracted light was coincident on the detectors.

Diffraction by a grating can be visualized from the geometry in figure 4.39. The figure shows an incident light ray at $\theta_i$ with wavelength $\lambda$ which is diffracted by a grating with a pitch $d$ along a set of angles $\theta_{d(n)}$ where $n$ represents the diffraction order. The sign convention of the angles depends on whether diffraction occurs on the same side of the incident light and all angles are measured from the surface normal as the figure illustrates.

**Figure 4.38**: Noise-equivalent BSDF.
Figure 4.39: Diffraction grating geometry and sign conventions.

The dispersion of the grating is governed by the grating equation 4.5.

\[ n \times \lambda = d \times (\sin \theta_i + \sin \theta_d) \]  

(4.5)

Two separate diffraction gratings were tested. Both gratings possessed a different grating pitch. The grating pitch refers to the distances between each of the grooves in the grating. The pitch for each grating was measured through the use of a microscope. The diffraction gratings are illustrated in figure 4.40.

Figure 4.40: Microscopic view and measurement of pitch size for various gratings.

The pitch determines the spread of diffracted light. A large pitch results in a relatively small diffraction spread and a small pitch in a relatively large diffraction spread. The results obtained for diffraction grating 1 for an angle of incidence \( \theta_i = 10^\circ \) are illustrated in figure 4.41.
It is clear from figure 4.41 as would be expected a number of diffraction peaks are apparent. These intensity peaks represent the point at which the diffracted beam is directly coincident on the detector face. The diffraction order \( n = 0 \) represents the purely reflected beam and as is expected registers the greatest intensity reading. First order lines \( n = \pm 1 \) are expected to diffract the greatest intensity not inclusive of the purely reflected beam and subsequent higher orders diffract light at an increasingly lower intensity than the first order lines (Palmer 2005). This is validated in figure 4.41 with the exception of the diffraction order \( n = -3 \).

The case of the intensity peak at \( n = -3 \) is an intriguing aspect and can be explained through diffraction grating efficiency theory. It is generally observed that the intensity of light diffracted by a grating changes slowly as the diffraction order is varied however occasionally a sharp change in intensity is observed (Wood 1902); (Stewart & Gallaway 1962). These sharp changes in intensity are referred to as diffraction grating efficiency anomalies (Wood 1935). These anomalies are an inherent part of the diffraction grating itself and occur at observed wavelengths for which light of the same wavelength is diffracted in another order which grazes the surface of the grating resulting in an intensity anomaly.

The data from figure 4.41 can also be used in conjunction with the grating equation to validate servo calibration. Using equation 4.6 and setting \( \lambda = 650\text{nm} \), \( d = 5\mu\text{m} \), \( \theta_i = 10^\circ \), \( \theta_{d(n)} \) can be solved for.
\[ \theta_d = \sin^{-1}\left[\frac{n \times \lambda}{d} - \sin \theta_i \right] \] (4.6)

<table>
<thead>
<tr>
<th>Measured ( \theta_d )</th>
<th>Calculated ( \theta_d )</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.2</td>
<td>-2.5</td>
<td>0.3</td>
</tr>
<tr>
<td>-9.7</td>
<td>-10</td>
<td>0.3</td>
</tr>
<tr>
<td>-17.5</td>
<td>-17.7</td>
<td>0.2</td>
</tr>
<tr>
<td>-25</td>
<td>-25.7</td>
<td>0.7</td>
</tr>
<tr>
<td>-34</td>
<td>-34.3</td>
<td>0.3</td>
</tr>
<tr>
<td>-43.5</td>
<td>-43.9</td>
<td>0.4</td>
</tr>
<tr>
<td>-55.6</td>
<td>-55.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Table 4.5:** Comparison of measured diffraction angle to calculated diffraction angle.

The data in table 4.5 compares the measured diffracted angle from figure 4.41 to the calculated diffraction angle using equation 4.6. The data suggests a maximum servo error of 0.7° which is an indication of good servo calibration.

A diffraction grating with a pitch \( d = 20 \mu m \) was also used as a sample specimen. The results obtained for diffraction grating 2 for an angle of incidence \( \theta_i = 10^\circ \) are illustrated in figure 4.42.
Figure 4.42: Detected diffracted light for diffraction grating 2.

The above plot for diffraction grating 2 appears vastly different from that of diffraction grating 1 in figure 4.41. It would be expected the plot would be very similar to figure 4.41 in terms of having a number of distinct diffraction peaks with the exception of decreased spread however this is certainly not the case. On visual inspection the reason for the atypical data plot is due to the small diffraction spread resulting in multiple diffraction orders coincident with the detector face at a specific angle.
5 Conclusions & Future work

Classifying the scattering properties and roughness of PS is a difficult task given the materials porosity. Common roughness measurement methods such as the use of electron microscopes cannot capture the significant scattering that occurs in PS at the PS-silicon interface. As such, the project approached this issue from a less well known roughness characterisation technique, yet nevertheless a technique that has proven time and time again to be just as effective. The technique explored was optical scattering which has proven to be very accurate in the past in the roughness characterisation of silicon wafers. Numerous methods which employed optical scattering to accurately capture the scattering profile of PS were reviewed in detail. Through the development of key selection criteria the method deemed to be the most appropriate was the angle-resolved scattering (ARS) technique.

The design of the ARS focused on maximising the accuracy of scattering profile data obtained from the instrument and therefore the roughness characterisation which is obtained through a series of models. This involved the comprehension of the inputs required to the BSDF and PSD models and designing a setup which maximised the accuracy of these inputs. Extensive research was undertaken to ensure the best possible instrument design considering the cost constraints and through numerous redesigns the maximum possible accuracy given this constraint was achieved. As such, the accuracy of the instrument is seen to be a success.

After the successful design phase, the ARS was manufactured, integrated and tested. It was the integration stage of the process that linked the various mechanical, electronic and software aspects to establish the success of the instrument.

Instrument testing with a sample specimen suggested the instrument is well calibrated and capable of providing accurate results. However, noise also appears to be an issue in the system and to further increase the accuracy of this instrument the noise must be reduced.

As the work done is this project was preliminary in nature and given the development nature of the project, a large scope exists for future work arising from the project. The scope for future work can be separated into the fields of mechanical, electrical and software engineering.
The existing mechanical design can be improved by manufacturing a sample holder which does not limit the field of view of the detectors at extreme angles. The modified sample holder has already been designed however due to cost constraints this could not be implemented in the project. Additionally redesigning the sample holder base to allow 3 or more rotational degrees of freedom would allow the sample to be adjusted for angle of incidence, out-of-plane tilt, and rotation about the sample normal facilitating the ability to obtain data readings in various planes further enhancing results. The sample holder base axes could also potentially be motorized to allow the sample area to be raster-scanned, to automate sample alignment, or to measure reference samples. Furthermore anodizing the instrument black would also decrease instrument signature.

The existing electrical design and software can be improved by the integration of the chopper and lock-in amplifier package which would certainly improve instrument accuracy by reducing both optical and electrical noise. This is accomplished through the use of lock-in detection in the electronics package that suppresses all signals except those at the chopping frequency. This package has already been to some extent developed but requires further attention.

The project objectives were to select an appropriate method which was capable of characterising the roughness of PS and design, manufacture, integrate and test this method. Both of these objectives were achieved. It is hoped that the work presented in this report will be used to assist in the accurate classification of PS’s scattering profile, roughness parameters and ultimately provide a greater understanding of this complex material so it can be used more effectively in its extensive applications.
6 References


Bayhan, H & Ozden, S 2007, 'Frequency dependence of junction capacitance of BPW34 and BPW41 p-i-n photodiodes', Pranama, vol 68, no. 4, pp. 701-706.


Rayleigh, L 1871, 'On the light from the sky, its polarization and colour', Philos. Mag., vol 41, pp. 107-120.


Steinsland, E, Finstad, T & Hanneborg, A 2000, 'Etch rates of (100), (111) and (110) single-crystal silicon in TMAH measured in situ by laser reflectance interferometry', *Sensors and Actuators A: Physical*, vol 86, no. 1-2, pp. 73-80.


Appendix A – Torque calculation

The mass of the arm needs to be accelerated and therefore requires a torque. Once the arm is moving no torque is required to continue motion at constant speed except to counter the bearing friction. Therefore this becomes a problem of rotational dynamics.

From rotational dynamics the sums of the moments about the rotational axis is given by the mass moment of inertia of the body multiplied by the angular acceleration of the body:

\[ \sum M_o = I_o \alpha \]

\[ \therefore T_m - T_f = I_o \alpha \]

where;

\( T_m \) = motor torque

\( T_f \) = friction from bearings

The mass moment of inertia of a rectangular plate of any thickness is given by:

\[ I = \left( \frac{4a^2 + b^2}{12} \right)m \]

where;
a = perpendicular distance from rotational axis

b = perpendicular distance through the rotational axis

m = mass of the rectangular plate

The depth of the plate used for the arm is 5mm.

The material is aluminium given by a density \( \rho = 2.7 \text{ g/cm}^3 \)

\[
m = (height)(width)(depth)(\rho)
\]

To calculate the mass moment of inertia of the entire structure, the mass moment of inertia of each component is calculated, brought to a common rotational axis using the parallel axis theorem and then additively combined.

The mass moment of inertia of a component on a parallel axis is given by:

\[
I_p = I_c + md^2
\]

where;

\( I_p \)= mass moment of inertia at the parallel axis

\( I_c \)= mass moment of inertia at the centroidal axis

\( m \)= mass of the component

\( d \)= the perpendicular distance between the centroidal axis and the parallel axis

Therefore splitting the structure into three basic separate components;

**Component 1**

\( a = 95 \text{mm}, \ b = 20 \text{mm} \)
\[ m_1 = (9.5)(2)(.5)(2.7) = 25.65 \text{ g} = 0.02565 \text{ kg} \]

\[
I_1 = \left( \frac{4(0.95)^2 + (0.02)^2}{12} \right) m_1
\]

\[ \therefore I_1 = \left( \frac{4(0.95)^2 + (0.02)^2}{12} \right)(0.02565) = 7.8 \times 10^{-5} \text{ kg.m}^2 \]

\[ m_2 = (6.27)(2)(.5) = 16.92 \text{ g} = 0.01692 \text{ kg} \]

\[
I_2 = \left( \frac{4(0.02)^2 + (0.005)^2}{12} \right) m_2 + m_2(0.0975)^2
\]

\[ \therefore I_2 = \left( \frac{4(0.02)^2 + (0.02)^2}{12} \right)(0.01692) + (0.01692)(0.0975)^2 \]

\[ = 1.6322 \times 10^{-4} \text{ kg.m}^2 \]
Component 3

The angular acceleration is not a given parameter of motors, as such it is estimated an angular acceleration of 100 radians/s$^2$ is sufficient for this application including factors such as bearing friction and wire routing resistance. A safety factor of 2 is also assumed.

Therefore minimum required torque to drive the arm is estimated as:

$$\sum M_o = (3.9386 \times 10^{-4})(100)(2) = .079 \, Nm = .81 \, kg\, cm$$
Appendix B – DMS44111MG data sheet

Available from:

Product Features:

- Precision. Inconceivable “zero” centering accuracy.
- High resolution. Resolution of less than 0.001ms dead zone “zero dead-zone.”
- Precise about travel. “Zero error.”
- High precision electromagnetic sensor. 360 non-contact type, high-resolution angle position encoder.
- All-digital circuit processor.
- Output gear can be rotated 360.
- High-quality coreless motor.
- Precision machining of titanium and aluminium alloy gear tooth combinations
- O-type rubber ring, shock, dust, oil
- 3 high precision metal bearings.
- Middle case: aluminium-alloy
- Standard servo dimensions

Detailed specifications:

Control System: PWM Pulse Width Control
Processor: Digital IC
Required Pulse: 3 to 5 V Peak to Peak Square Wave
Working frequency: 1520 μs /333 Hz
Rotation angle sensor: MAGNETIC INDUCTION
Rotation: Left Rotation: 46, Right Rotation: 46
Voltage: 4.5V to 6.0V
Temperature Range: -20℃ to 60℃
Driver Type: MOSFET
Operating Angle: 45 Deg. one side pulse travelling 400μs
Direction: Clockwise/Pulse Travelling 900μs-2100μs
Pulse Width Scope: 900-2100μs
Neutral pulse: 1500μs
Resolution: Minimum resolution:0.088°/0.9μs
Minimum resolution: Maximum resolution: 0.350°/4μs
Rotational speed of magnet: Maximum 600RPM (r / min)
Magnetic offset: ±10mT
Magnetic input field amplitude: 45 to 75mT
Speed:(No-load ): 0.08sec/ 60° @ 4.8V, 0.06sec/ 60° @ 6.0V
Torque: (Stall Full load): 9.50 kgcm @ 4.8V, 12.00 kgcm @ 6.0V
Idle Current: <0.05 A/ 4.8V <0.05 A/ 6.0V
Running Current: <0.10 A/ 4.8V <0.20 A/ 6.0V
Stall Current: 1.8 A/ 4.8V 2.9 A/ 6.0V
Motor Type: Coreless Motor
Bearings: 3 Ball Bearings
Bearing Type: MR74 (4mmX7mmX2mm)
         MR106 (6mmX10mmX2.5mm)
         MR06ZZ (6mmX10mmX3mm)
Gear Material: Titanium Gear
Servo case: (Aluminium Radiator) Metal Centre
Plug: "J" type
Connector Wire Length: 300.00 mm
Connector Wire SPEC: OD1.4mm/60 x 0.08mm 3p x 300mm "J" type
Weight: 60.00 g
Dimensions (L x W x H): 40.00*20.00*39.20 mm
Appendix C – BPW34 data sheet

Available from:
http://www.vishay.com/docs/81521/bpw34.pdf

BPW34, BPW34S
Vishay Semiconductors

Silicon PIN Photodiode, RoHS Compliant

FEATURES
• Package type: leaded
• Package form: top view
• Dimensions (L x W x H in mm): 5.4 x 4.3 x 3.2
• Radiant sensitive area (in mm²): 7.5
• High photo sensitivity
• High radiant sensitivity
• Suitable for visible and near infrared radiation
• Fast response time
• Angle of half sensitivity: α = 65°
• Lead (Pb)-free component in accordance with RoHS 2002/95/EC and WEEE 2002/96/EC

APPLICATIONS
• High speed photo detector

DESCRIPTION
BPW34 is a PIN photodiode with high speed and high radiant sensitivity in miniature, flat, top view, clear plastic package. It is sensitive to visible and near infrared radiation. BPW34S is packed in tubes, specifications like BPW34.

PRODUCT SUMMARY

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>t_n (μA)</th>
<th>φ (deg)</th>
<th>λ_c (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPW34</td>
<td>50</td>
<td>≤ 65</td>
<td>430 to 1100</td>
</tr>
<tr>
<td>BPW34S</td>
<td>50</td>
<td>≤ 65</td>
<td>430 to 1100</td>
</tr>
</tbody>
</table>

Note
Test condition see table “Basic Characteristics”

ORDERING INFORMATION

<table>
<thead>
<tr>
<th>ORDERING CODE</th>
<th>PACKAGING</th>
<th>REMARKS</th>
<th>PACKAGE FORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPW34</td>
<td>Bulk</td>
<td>MOQ: 3000 pcs, 3000 pcs/bulk</td>
<td>Top view</td>
</tr>
<tr>
<td>BPW34S</td>
<td>Tube</td>
<td>MOQ: 1800 pcs, 45 pcs/tube</td>
<td>Top view</td>
</tr>
</tbody>
</table>

Note
MOQ: minimum order quantity

ABSOLUTE MAXIMUM RATINGS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITION</th>
<th>SYMBOL</th>
<th>VALUE</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse voltage</td>
<td>V_Rn</td>
<td>60</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>P_V</td>
<td>215</td>
<td></td>
<td>mW</td>
</tr>
<tr>
<td>Junction temperature</td>
<td>T_J</td>
<td>100</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>T_Theta</td>
<td>-40 to + 100</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Storage temperature range</td>
<td>T_S</td>
<td>-40 to + 100</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Soldering temperature</td>
<td>t ≤ 3 s</td>
<td>T_s</td>
<td>260</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal resistance junction/ambient</td>
<td>R_JA</td>
<td>Connected with Cu wire, 0.14 mm²</td>
<td>350</td>
<td>KW</td>
</tr>
</tbody>
</table>

Note
T_Theta = 25 °C, unless otherwise specified
Appendix D – Workshop quotes

Date: 29.06.2011

Ref – MECH-01-07-11-0003; Scatterometer

Please accept our quotation as detailed below.

If the quotation is acceptable send an email to
Michael.armstrong@uwa.edu.au with confirmation to proceed, stating E/U and
PG number.

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacture of Scatterometer as detailed below:</td>
<td></td>
</tr>
<tr>
<td>Labour 30 hrs @ $75.00 per hour</td>
<td></td>
</tr>
<tr>
<td>Material will be aluminium.</td>
<td></td>
</tr>
<tr>
<td>Material Cost $200</td>
<td></td>
</tr>
<tr>
<td>Design will be agreed with customer prior to cutting metal.</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$2450</strong></td>
</tr>
</tbody>
</table>

All prices are *only an estimate* due to the Research and Development nature
of the work. We withhold the right to add additional cost to the manufacture if
extra hours are needed but will also pass on a reduction in cost if not all the
quoted hours are used.

If you have any queries with the above don’t hesitate to contact us.

Many Thanks

Michael

Acting Chief Technician
FECM Workshop
Michael.armstrong@uwa.edu.au  Ph: 08 6488 3065
Date: 05.07.2011

Ref: MECH-01-07-11-0003-Z: Scatterometer

Please accept our quotation as detailed below.

If the quotation is acceptable send an email to Michael.armstrong@uwa.edu.au with confirmation to proceed, stating E/U and PG number.

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost $</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
<tr>
<td>Labour 12 hrs @ $75.00 per hour</td>
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</tr>
<tr>
<td>Material will be aluminium.</td>
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<tr>
<td>Material Cost $200</td>
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<tr>
<td>Design will be agreed with customer prior to cutting metal.</td>
<td>TOTAL</td>
</tr>
<tr>
<td></td>
<td>$1100</td>
</tr>
</tbody>
</table>

All prices are only an estimate due to the Research and Development nature of the work. We withhold the right to add additional cost to the manufacture if extra hours are needed but will also pass on a reduction in cost if not all the quoted hours are used.

If you have any queries with the above don’t hesitate to contact us.

Many Thanks

Michael

Acting Chief Technician
FECM Workshop
Michael.armstrong@uwa.edu.au Ph: 08 6488 3085
Appendix E – Technical drawings
Appendix F – Bill of materials
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>COMPONENT</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
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<tbody>
<tr>
<td>1</td>
<td>Base</td>
<td>DMS47111MG</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Motor</td>
<td>BPW34</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Arm</td>
<td>BPW34</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Sample holder base</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Detector (S&amp;P)</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Detector (incident)</td>
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<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Sorbothane foot</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Pin</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Clamp</td>
<td></td>
<td>1</td>
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<td>10</td>
<td>Supports</td>
<td>M6x90 threaded bolt</td>
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<td>11</td>
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<td>12</td>
<td>Allen bolt</td>
<td>M5</td>
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<td>13</td>
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<tr>
<td>14</td>
<td>Shield</td>
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</tr>
<tr>
<td>15</td>
<td>Laser/chopper/lock-in housing</td>
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<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Laser/chopper/lock-in circuit support</td>
<td></td>
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<tr>
<td>17</td>
<td>Chopper support</td>
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<td>18</td>
<td>Chopper circuit</td>
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<td>1</td>
</tr>
<tr>
<td>19</td>
<td>Laser/chopper/lock-in housing lid</td>
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<td>20</td>
<td>Laser</td>
<td></td>
<td>1</td>
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<td>21</td>
<td>Allen bolt</td>
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<td>4</td>
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<td>22</td>
<td>Screw</td>
<td>M3x15</td>
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<td>23</td>
<td>Lock-in amplifier circuit</td>
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<td>Spacer</td>
<td>Nylon tapped hex</td>
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<td>25</td>
<td>Laser adjustment circuit</td>
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<td>26</td>
<td>Chopper wheel</td>
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<td>27</td>
<td>Chopper support</td>
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<td>28</td>
<td>Source polarizer</td>
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<td>29</td>
<td>Set screw</td>
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<td>30</td>
<td>Cover</td>
<td></td>
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<td>31</td>
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<td>M4</td>
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<td>32</td>
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<td>33</td>
<td>Signal processing circuit</td>
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<td>34</td>
<td>Sample holder</td>
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<td>35</td>
<td>Allen bolt</td>
<td>M2</td>
<td>2</td>
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<td>36</td>
<td>Screws</td>
<td>M1x10</td>
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<td>37</td>
<td>Grommet</td>
<td>1</td>
<td>1</td>
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</table>
Appendix G – Circuit diagrams

System circuit
Power supply circuit

Incident intensity circuit

P polarization photodiode circuit
$S$ polarization photodiode circuit

Laser power circuit
Appendix H – Class 3A Laser Equipment Local Working Rules

The following safety guidelines were obtained from:
Australian Standard 2211 - 1981 "Laser Safety"

Working rules are essential for all Class 3A lasers to ensure they may be used with a high standard of safety. Australian Standard AS 2211 details the main procedures and check lists which are appropriate for these Lasers. The Standard specifies the following working rules which are common to all Class 3A lasers.

1. Do not look into the laser beam. (For any class of laser this is a hazardous practice).

2. The laser must be used within a controlled area from which the laser beam cannot escape. Ensure that the controlled area is clearly defined with signs, and all windows are blocked etc.

3. Use beam stops to terminate the beam and prevent its uncontrolled transmission.

4. Enclose beam paths with interlocked covers so that the laser beam cannot escape from the controlled area.

5. Remove specular reflecting surfaces.

6. Immediate measures must be taken to remove potentially hazardous situations arising from laser beams that may be emitted due to equipment defect, misalignment or any other reason.

7. Additional working rules, specific for each laser must, where necessary, be documented to ensure the safe operation of the unit.

8. Visual alignments or adjustments must not be carried out whilst the laser on full power, unless suitable goggles are used which prevent exposure to the eyes.

9. Accidents and incidents must be reported to the UWA Safety and Health.

10. The School Laser Safety Officer in your section is: Adrian Keating.
Appendix I – Safe operating procedure for manual handling of instrument

1. Disconnect all power sources to the apparatus following below procedure.
   a. Switch off power
   b. Disconnect lead from socket

2. Ensure all elements on the apparatus are secured.

3. Check environment. Ensure no direct obstacles. If so, clear obstacles before attempting to move apparatus.

4. Lift apparatus following the below procedure
   a. Grip item securely with both hands
   b. Keep feet apart for stability
   c. Keep item close to body
   d. Keep back straight
   e. Bend knees
   f. Straighten knees to stand upright and lift apparatus
   g. Do not twist body when carrying an item – move feet instead

5. Move item to desired location following the below procedure
   a. Move item to desired location
   b. Keep watch for any obstructions
   c. Warn bystanders to move if necessary

6. Lower apparatus safely
   a. Use same safety principles as for lifting
   b. Bend knees to lower
   c. Keep back straight

7. If obstacles are encountered such as doors when moving the apparatus from one location to another follow the below procedure
   a. Lower apparatus safety using step 6 before obstacle is encountered
   b. Remove/pass obstacle
c. Lift apparatus using step 4

8. If fatigued from carrying equipment after prolonged period of time
   a. Lower apparatus safety using step 6 as fatigue sets in
   b. Rest
   c. Lift apparatus using step 4
Appendix J – Safety guidelines for various tools

The following safety guidelines are based on:

General Requirements of Safety in Workshops Policy

The following rules apply to all workshop personnel, whether they are permanently employed in the workshop or just occasional users:

- Keep the workshop clean and tidy at all times;
- Always seek instruction before using an unfamiliar piece of equipment;
- Only use tools and machines for their intended purpose;
- Report all damaged equipment and do not use it until it has been repaired by a qualified person;
- Where machine guards are provide they must be kept in place;
- Never distract the attention of another staff member when that person is operating equipment and never indulge in horseplay;
- Always use the appropriate personal protective devices and check that they are clean and in good repair before and after use;
- Long hair needs to be restrained by either a tie or hat;
- Never use compressed air for cleaning clothing and machinery;
- Report all hazards and unsafe conditions and work practices.

It is the responsibility of the officer in charge of the workshop to ensure that staff who use the workshop only occasionally adopt the same safety precautions and procedures as full-time workshop personnel.

Drilling Machines

- A properly designed drift should be used to remove tapered drills or chucks from the spindle.
Fixtures, machine vices or workpieces should be clamped to the table or set against stop bars.

Strip material or non-ferrous material should not be drilled unless it is securely clamped or held against a stop.

When the flutes of a drill become choked with swarf, the machine must be stopped before the swarf is removed.

Hinged guards should be provided to completely enclose the upper part of the drill spindle, pulleys and belt drives.

Operators need to be aware of the danger of leaving chuck keys in the chuck after removing or replacing a drill.

**Milling Machines**

Operators of milling machines should observe the following:

- Exercise care when using fast traverse levers in order to avoid running the job into the cutter and never attempt to remove the arbor nut by applying power to the machine;
- Clamp the job or vice firmly on the table before starting the machine, and, where necessary, to provide steady supports to prevent vibration;
- The use of the correct type of handling equipment when heavy cutters are involved and the use of a chip guard when a fly cutter is used;
- When an unguarded cutter is in motion, the hands and fingers must be kept well away from the cutters.

**Metal-Cutting Guillotines**

The following requirements apply to the safe use of metal-cutting guillotines:

- Guards must be provided to prevent the operator's fingers from contacting the knife or clamp from either the front or rear of the machine. Only one person should be allowed to operate the machine at the one time and where long material is being cut and cannot be adequately supported by the work table, additional supports should be provided.
- A hand-operated guillotine should be made inoperative when not in use either by removal of the handle or by the use of a locking or similar device.
• The shear edges of the blades should be maintained in good condition and blade clearance must be adjusted in accordance with the manufacturer's recommendation appropriate to the thickness of the material being cut.

• Waste scrap metal provides a hazard for the hands and protective gloves should be worn when the metal is handled. A container should be provided for waste material from the guillotine.
Appendix K – Safe operating procedure for soldering

The following safety guidelines are based on:
http://naples.cc.sunysb.edu/Admin/HRSForms.nsf/pub/EHSD0348/$File/EHSD034.pdf

Soldering iron safety:

- Never touch the element or tip of the soldering iron. They are very hot (about 400°C) and will burn. Hold wires to be heated with tweezers or clamps.
- Keep the cleaning sponge wet during use.
- Always return the soldering iron to its stand when not in use. Never put it down on your workbench.
- Turn unit off or unplug it when not in use.

Work safely with solder, flux and cleaners:

- Wear eye protection. Solder can “spit”.
- Use lead free solder.
- Keep cleaning solvents in dispensing bottle to reduce inhalation hazards.
- Always wash your hands with soap and water after soldering.
- Read and understand the MSDS for all materials before beginning work.

Avoid toxic fumes:

- Work in a well-ventilated area. The smoke formed is mostly from the flux which can be irritating, a sensitizer and aggravates asthma. Avoid breathing it by keeping your head to the side of, not above, your work.
- A benchtop fume extractor may be necessary to remove harmful fumes caused by solder and flux from the soldering workstation by filtering the air.

Reduce risk from electricity:

- Always use a grounded outlet and grounding prong to reduce the risk of electrical damage if a short circuit occurs in the equipment.
- Prevent damage to electrical cords during soldering. Keep them away from heated tips.
Fire prevention:

- Work on a fire-proof or nonflammable surface that is not easily ignited.
- Wear nonflammable or 100% cotton clothing that covers your arms and legs to help prevent burns.
- Know where your fire extinguisher is and how to use it.

First aid:

- Immediately cool the affected area under cold water for 15 minutes.
- Do not apply any creams or ointments. Cover with a band-aid.
- Seek medical attention if the burn covers an area bigger than 3 inches across.
Appendix L – Servo calibration data

Method 1

<table>
<thead>
<tr>
<th>PWM (μs)</th>
<th>Angle difference (degrees°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600-1575</td>
<td>7.5</td>
</tr>
<tr>
<td>1575-1550</td>
<td>8</td>
</tr>
<tr>
<td>1550-1525</td>
<td>8.5</td>
</tr>
<tr>
<td>1525-1500</td>
<td>8</td>
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<td>1500-1475</td>
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</tr>
<tr>
<td>1450-1425</td>
<td>8.5</td>
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<tr>
<td>1425-1400</td>
<td>9.5</td>
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<td>1400-1375</td>
<td>9</td>
</tr>
<tr>
<td>1375-1350</td>
<td>8</td>
</tr>
</tbody>
</table>

Method 2

The angular difference between PWM values can be calculated in this method using the cosine rule.

\[
d^2 = (r_1)^2 + (r_2)^2 - 2(r_1)(r_2) \cos(\theta)
\]

\[
\therefore \theta = \cos^{-1} \left[ \frac{(r_1)^2 + (r_2)^2 - d^2}{2(r_1)(r_2)} \right]
\]
<table>
<thead>
<tr>
<th>PWM (μs)</th>
<th>R (mm)</th>
<th>X (mm)</th>
<th>θ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>358</td>
<td>60</td>
<td>8.3048</td>
</tr>
<tr>
<td>1575</td>
<td>368</td>
<td>64</td>
<td>8.2848</td>
</tr>
<tr>
<td>1550</td>
<td>400</td>
<td>140</td>
<td>0/2 = 8.0371</td>
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<tr>
<td>1500</td>
<td>470</td>
<td>92</td>
<td>8.4 89</td>
</tr>
<tr>
<td>1475</td>
<td>526</td>
<td>141</td>
<td>7.8 57</td>
</tr>
<tr>
<td>1450</td>
<td>91</td>
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</tr>
</tbody>
</table>

**Method 3**

<table>
<thead>
<tr>
<th>PWM (μs)</th>
<th>Deviation (mm)</th>
<th>Deviation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1590</td>
<td>-0.3</td>
<td>-0.178</td>
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<td>0.3</td>
<td>0.178</td>
</tr>
<tr>
<td>1590</td>
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<td>-0.06</td>
</tr>
<tr>
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<td>0.1</td>
<td>0.06</td>
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<td>0</td>
<td>0</td>
</tr>
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<td>1590</td>
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<td>-0.06</td>
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<td>0.2</td>
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<tr>
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<td>-0.3</td>
<td>-0.178</td>
</tr>
<tr>
<td>1590</td>
<td>-0.2</td>
<td>-0.1188</td>
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</table>
Appendix M – Firmware code

// This code provides the firmware support for the scatterometer

// Rev: 7A

boolean DEBUGFLAG=false;  // true = prints test data, false = no verbose mode

/** Adjust these values for your servo and setup, if necessary **/

int servoPin     = 8;    // control pin for servo motor
int minPulse     = 1330;  // minimum servo position to prevent hitting holder
int maxPulse     = 1880; // maximum servo position to prevent hitting holder
int turnRate     = 1;  // servo turn rate increment (larger value, faster rate, less resolution)
int refreshTime  = 20;   // time (ms) between pulses (50Hz)
int centerServo = 1605;         // center servo position

long pulseWidth;          // servo pulse width
long lastPulse   = 0;    // recorded time (ms) of the last pulse

int PGainRelay=3;   // Digital port that controls the gain of the P-polarization detector
int P_PhotodetectorAin=2;  // Analogue input port for the P-polarization detector
int P_PhotodetectorVal; // Analogue input VALUE for the P-polarization detector

int SGainRelay=4;  // Digital port that controls the gain of the S-polarization detector
int S_PhotodetectorAin=1;  // Analogue input port for the S-polarization detector
int S_PhotodetectorVal;  // // Analogue input VALUE the S-polarization detector

int Laser_PhotodetectorAin=0 ;  // Analogue input ports for the Input light detector
int Laser_PhotodetectorVal ;  // Analogue input VALUE for the Input light detector

int Bytes2Read=0;
long Number=0;

void setup() {

    // initialize serial communication:

    pinMode(servoPin, OUTPUT);   // sets the pin as output
    pinMode(PGainRelay, OUTPUT);   // sets the pin as output
    pinMode(SGainRelay, OUTPUT);   // sets the pin as output

    Serial.begin(9600);
    Serial.flush();
}

void loop() {

    // read the sensor:

    //if (DEBUGFLAG==true) Serial.println("Enter Command:");  // send an initial string
    Bytes2Read=Serial.available();

    // if (DEBUGFLAG==true) Serial.print(inByte, DEC);  // this line only required for DEBUGGING
if (Bytes2Read > 0) {
    int inByte = Serial.read();

    // if (DEBUGFLAG==true) Serial.println(inByte, DEC); // this line only required for DEBUGGING

    // do something different depending on the character received.
    // The switch statement expects single number values for each case;
    // in this example, though, you're using single quotes to tell
    // the controller to get the ASCII value for the character. For
    // example 'a' = 97, 'b' = 98, and so forth:

    if (inByte>96) inByte=inByte-32; //convert to upper case

    switch (inByte) {

        case 'M': //Move Command

            pulseWidth=GetNumber2(Bytes2Read);

            // if (DEBUGFLAG==true) Serial.println(Bytes2Read, DEC); // this line only required for DEBUGGING

    }

    if (Number<256) analogWrite(PWM1Pin, int(Number)); // analogWrite values from 0 to 255

    if (DEBUGFLAG==true) Serial.println(Number,DEC);   // send an initial string

    break;

    case 'R':    //Read Photodetector Command
S_PhotodetectorVal=analogRead(S_PhotodetectorAin);
P_PhotodetectorVal=analogRead(P_PhotodetectorAin);
Laser_PhotodetectorVal=analogRead(Laser_PhotodetectorAin);

if (DEBUGFLAG==true) Serial.println("LaserIn=");
Serial.println( Laser_PhotodetectorVal, DEC);
Serial.println( "\t");
if (DEBUGFLAG==true) Serial.println("P=");
Serial.println( P_PhotodetectorVal, DEC);
Serial.println( "\t");
if (DEBUGFLAG==true) Serial.println("S=");
Serial.println( S_PhotodetectorVal, DEC);
break;

case 'S':  //S-Polarization Relay 1= on, anything else =off
    // set the gain of the S photodetector
    Number=GetNumber2(Bytes2Read);
    if (Number ==1) {
        digitalWrite(SGainRelay, HIGH);
    }else {
        digitalWrite(SGainRelay, LOW);
    }
break;

case 'P':  //P-Polarization Relay 1= on, anything else =off
    // set the gain of the P photodetector
    Number=GetNumber2(Bytes2Read);
if (Number ==1) {

digitalWrite(PGainRelay, HIGH);
}

}else {

digitalWrite(PGainRelay, LOW);

break;

//default:
// do nothing

}

// ignore any other characters in the receive buffer
Serial.flush();
long val=0;

int chval;

while ( ExitFlag==false) {

    chval = Serial.read();

    if(chval >= '0' && chval <= '9') {  // is ch a number?
        val = val * 10 + chval - '0';  // yes, accumulate the value
    }
    else if (chval == 'x' || chval==13 ){
        ExitFlag=true;
    }
}

return val;
}
Appendix N – Software code

% About: The following GUI is designed to facilitate data analysis from the scatterometer
% Date: 2011

function varargout = GUI(varargin)

% Last Modified by GUIDE v2.5 20-Oct-2011 11:50:49

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFcn', @GUI_OpeningFcn, ...
    'gui_OutputFcn', @GUI_OutputFcn, ...
    'gui_LayoutFcn', [], ... 
    'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end
if nargout
    varargout{1:nargout} = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before GUI is made visible.
function GUI_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to GUI (see VARARGIN)

% Choose default command line output for GUI 
handles.output = hObject;

%-------------
set(hObject,'toolbar','figure');
%-------------

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes GUI wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = GUI_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure

119
varargout{1} = handles.output;

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)

set(handles.txt_status,'String','Closing open ports'); % update current status display
delete(instrfindall); % close existing serial objects

format short g
MinValIntensity=1; % set min value to accept before increasing gain on the detectors
MaxValIntensity=700; % set max value to accept before increasing gain on the detectors
data_pts=1330; % set starting PWM value
SettlingTime=2; % resting time in seconds between readings
incident_intensity_PWM = 1690; % set PWM value to read incident intensity of beam

s1 = serial('COM7'); % define serial port
s1.BaudRate=9600; % define baud rate
fopen(s1); % connect to the serial port

scalefactor=-.3252; % conversion of PWM value to angle
offset=522.5160;
AllData=[]; % clear data;
GainS=1;GainP=1; % set calibration gain values of detectors

set(handles.txt_status,'String','Setting detector gain state'); % update current status display

    pause(2);
SerialCMD='s1x'; % start s detector in the high gain state
sGAIN = 'High';
    pause(2);
fprintf(s1,'%s',SerialCMD); % send high gain state command to serial port
    pause(2);
SerialCMD='p1x'; % start p detector in the high gain state
pGAIN = 'High';
    pause(2);
fprintf(s1,'%s',SerialCMD); % send high gain state command to serial port
    pause(2);
set(handles.txt_status,'String','Reading incident intensity'); % update current status display
SerialCMD=sprintf('m%dx',incident_intensity_PWM);
fprintf(s1,'%s',SerialCMD); % send PWM value to serial port
    pause(2)
data = ReadIntensity(s1);
incident_intensity = data(1);
pause(2);

progresspct = 10; % update progress percent
etr = 10; % update estimated time remaining

set(handles.txt_progresspercent,'String',progresspct); % update progress percent display
set(handles.txt_status,'String','Reading scattered intensity'); % update estimated time remaining display

for i = 1606:-1:data_pts
    SerialCMD=sprintf('m%dx',i);
    fprintf(sl,'%s',SerialCMD); % send PWM value to serial port
    pause(SettlingTime); % allow a little time after the motor moves
    until next reading
    ReReadFlag=false;
    data=ReadIntensity(sl); % get the photodiode data
    P_Light=data(2);
    S_Light=data(3);

    % check if the intensity is too low or too high and change the relay
    if (P_Light<MinValIntensity) % if intensity reading from diode is lower than minimum value then set HIGH gain
        SerialCMD='p1x'; % set gain HIGH
        fprintf(sl,'%s',SerialCMD); % send to relay
        pause(1); % give it time to process
        GainP=.1; % calibration value
        ReReadFlag=true;
    elseif (P_Light>MaxValIntensity) % if intensity reading from diode is higher than maximum value then set LOW gain
        SerialCMD='p0x'; % set gain LOW
        fprintf(sl,'%s',SerialCMD); % send to relay
        pause(1); % give it time to process
        GainP=1;
        ReReadFlag=true;
    end
    if (S_Light<MinValIntensity) % if intensity reading from diode is lower than minimum value then set HIGH gain
        SerialCMD='s1x'; % set gain HIGH
        fprintf(sl,'%s',SerialCMD); % send to relay
        pause(1); % give it time to process
        GainS=.1; % calibration value
        ReReadFlag=true;
    elseif (S_Light>MaxValIntensity) % if intensity reading from diode is higher than maximum value then set LOW gain
        SerialCMD='s0x'; % set gain LOW
        fprintf(sl,'%s',SerialCMD); % send to relay
        pause(1); % give it time to process
        GainS=1;
        ReReadFlag=true;
    end

    % if the relay was changed, reread the data
    if (ReReadFlag==true)
        data=ReadIntensity(sl);
        P_Light=data(2);
        S_Light=data(3);
angle=i*scalefactor+phen; \% angle calibraton
CurrentData=[angle,incident\_intensity,P\_Light*GainP,S\_Light*GainS,
(P\_Light*GainP)/incident\_intensity,
(S\_Light*GainS)/incident\_intensity];

AllData=[AllData;CurrentData]; \% update current data
set(handles.tbl_data,'data',AllData); \% update table display

xdata\_p = AllData(:,1); \% extract angle from array
ydata\_p = AllData(:,5); \% extract normalised P readings from array

xdata\_s = AllData(:,1); \% extract angle from array
ydata\_s = AllData(:,6); \% extract normalised P readings from array

\% plot
plot(handles.plot\_p,xdata\_p,ydata\_p);
axes(handles.plot\_p);
title('P polarization')
xlabel('Angle (Degrees)')
ylabel('Normalised Intensity')

plot(handles.plot\_s,xdata\_s,ydata\_s);
axes(handles.plot\_s);
title('S polarization')
xlabel('Angle (Degrees)')
ylabel('Normalised Intensity')

progresspct = progresspct + 0.3; \% update progress percent
etr = etr - 0.035; \% update estimated time remaining

set(handles.txt\_etr,'String',strcat(num2str(etr),' minutes'));
set(handles.txt\_progress\_percent,'String',progresspct);

end

set(handles.txt\_status,'String','Closing open ports'); \% update status display
fclose(s1); \% close the serial port
delete(instrfindall); \% remove all instances

progresspct = 100; \% update progress percent
set(handles.txt\_progress\_percent,'String',progresspct);
set(handles.txt\_status,'String','Idle'); \% update status display
set(handles.txt\_etr,'String',''); \% update estimated time remaining display

clear all; \% clear all variables and handles