An Angle Resolved Method of Measuring Scattering

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Part 1: Executive Summary

This purpose of this project was to create a platform for accurate scattering measurements to be made on a sample of porous silicon. The desired outcome of this project was to design an experimental setup that could accurately measure the scattering properties of porous silicon without interfering with the current reflectivity testing setup. Through thorough research the Angle Resolved Scattering (ARS) method was selected. ARS is essentially the process in which a laser beam is directed towards a sample of porous silicon, and a detector measures the intensity of the reflected beam at various angles. The scattering properties of porous silicon are desired as they can be useful in determining the roughness of the sample.

After proving the success of ARS in the optics laboratory using a manual testing method, a semi-automated system that attached the detector to an arm controlled by a small motor was devised by Dr Keating. This system increased the accuracy of the measurements, and helped to design a final model. The final design detailed by the author which is yet to be manufactured has an additional 2 detectors, allowing accurate normalisation of the intensities, as well as detection of the polarised reflected beam. The implementation of this design, along with creating a fully automated experimental setup would allow highly accurate scattering readings to be taken with a large number of data points. This investigation is a base upon which new techniques can be added and current methods can be modified to create an accurate and fast scattering experimental setup.
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Part 2: Introduction and Literature Review

In order to measure the scattering properties of porous silicon, initially a thorough investigation was required to understand the material itself, what scattering is and common testing procedures. The following section will investigate these questions, and will describe why a scattering profile is important to the characterization of porous silicon and why an Angle Resolved Scattering testing method was chosen.

2.1 Formation of Porous Silicon

This project focuses on the scattering properties of porous silicon, and it is therefore important to have a basic understand of the material and the ways in which it is produced. Saha (2006) succinctly describes a method in which porous silicon can be manufactured as shown in Figure 1, and this is the method used at UWA and therefore the technique used to create the samples that were tested. A silicon sample is polished using an alkali etchant, Saha choosing to use 20% NaOH at 70°C for 7 minutes. A backing is then applied to the wafer, and is then submerged in a 24% 1:1 mixture of HF acid and ethanol for 3 minutes with a current density of 30mA/cm² provided by a cathode. The HF-ethanol substrate creates pores in the silicon, with the porosity defined as the ratio of voids or pores relative to the total volume of the sample or body. The method described here produces a silicon wafer of 70% porosity to a depth of 5µm.
2.2 Definition of Scattering

To design a rig to test scattering, it must be known what scattering is, what causes scattering, and why it is desired to know this property. In essence, scattering is a phenomenon which indicates the roughness of a surface. If we could attain a perfectly flat mirror and directed a laser beam at the mirror at some angle of incidence $\theta_i$, it would be expected that the reflected beam would have the same intensity at an angle of reflection $\theta_r$ equal to the angle of incidence, as shown in the diagram of a perfect mirror, as shown in Figure 2.

However, when light hits a rough surface, the imperfections on the face reflect a beam in a scattered manner, as shown in Figure 3. The rougher the surface, the more scattering the beam will experience. As such, if one can detect the intensity of light at various angles in the plane of incidence, the roughness of the surface can be calculated (usually quantified by the RMS value of the surface’s deviation away from the mean). When the silicon sample is immersed in the HF-ethanol substrate, as has been stated in section 2.1 a reaction occurs and as a result the silicon develops pores in its structure. There is a layer that develops between the porous silicon and the unreacted silicon. This is the feature that creates scattering in porous silicon. The beam penetrates the porous silicon and is reflected off the rough boundary layer. The longer the sample is left in the anodisation cell, the rougher the boundary. As such, through calculation the roughness and porosity can be calculated from scattering results.
2.3 Current Research on Porous Silicon

Currently at the University of Western Australia, the Sensors and Advanced Instrumentation Laboratory is researching the properties of porous silicon. A current testing procedure is shown in Figure 4, a test which measures the reflectivity of a sample of porous silicon. This will help to gain an understanding of the roughness of the sample. Similarly, the research being undertaken in this project on scattering will help to characterize a sample of porous silicon by determining the scattering characteristics.

![Figure 4: Reflectivity Testing](image)

2.4 Applications of Porous Silicon

Porous silicon has an extremely large surface area to volume ratio, greater than 500 m$^2$ per cm$^3$ according to Saha (2006). Combined with its compatibility with other silicon based microelectronic devices, Saha suggests that one possible application could be in the area of smart sensors. For example, Das (2003) presents a method in which PS can be used in a hygrometer, a sensor that detects humidity. The PS absorbs the vapour in the air and this in turn changes the dielectric constant of the silicon. This change is measured and can provide a
humidity reading accurate to 2%. Föll (2002) describes another possible application in the field of X Ray machines. There is often blurring on an X Ray image due to inelastically scattered photons. By creating a filter that is transparent in the optical direction and not transparent in the other directions, this blurring can be greatly reduced. A solution that has been considered is to fill the voids or pores of porous silicon with lead.

In the field of Micro-Electro-Mechanical Systems (MEMS), PS could also have great benefits. MEMS are extremely small mechanical devices that can be used to sense the surrounding environment, and control the surroundings. They are a revolutionary creation, and are likely to be a major aspect in the future of electronics. Baglio (2008) describes the requirement of a sacrificial layer in the manufacture of MEMS. To help envisage the method of manufacture of MEMS, one can liken it to the process of Sand Casting, an idea much easier to visualise. A shape is imprinted in the sand, the liquid metal is poured into the mould and the sand is then broken away, resulting in a metal component formed in the desired shape. Similarly, a sacrificial layer with the desired shape etched out of it is deposited or grown on a surface, the material (for example, silicon) is applied to that space and the sacrificial layer is then removed, leaving only the desired material bonded to the surface below. As is shown in the diagram, the sacrificial layer can be used to create a bridge over other components, shown in Figure 5. With the advancement of this technology, Bell (1998) suggests that the use of PS as the sacrificial layer would be advantageous, given how easily it is dissolved in simple solutions such as NaOH.

2.5 Introduction to Testing Procedures

There are several ways to determine the scattering properties of a material each of which can each produce accurate results. The most important part of this investigation was to
consider the many methods’ advantages and disadvantages and decide upon which approach would be appropriate. After some investigation, it became evident that there are three major methods in which scattering can be measured, and these will be discussed in the following section. Factors such as expense, appropriate level of accuracy, and how easily the method could be integrated into the current reflectivity testing setup previously described were all considered in the research.

2.6 Goniometric/Angle Resolved Scattering

Thomas Germer (1999) describes a method that is (with slight variations) described in many other resources too. The process involves a laser being directed through a chopper and a polariser. Then the beam is directed through a series of lenses and mirrors before it is reflected off the sample onto a detector. The receiver is then moved to various angles relative to the normal plane of the sample, and then the reflected beam is measured, shown in Figure 6. The intensities are measured and are used to create a Bidirectional Reflectance Distribution Function (BRDF), a function commonly used to describe the scattering properties of a surface. It is Bidirectional because it considers the direction of both the radiated beam and the irradiated beam. This function is essentially a measure of the normalised intensity of the beam at various measured angles. This method is also called Angle Resolved Scattering, as will be used throughout this paper. The detector used is highly dependent on what results are required, for example LeQuime (2009) uses a Charge Coupled Device (CCD) to measure the intensity, a device used in most modern photographic equipment. Something as simple as a single silicon detector (as was used in our tests described later) can be used.
There are a few major advantages to the Angle Resolved Scattering approach, the first being the simplicity and flexibility. Most of the components and equipment required were readily available and used in the UWA optics laboratory for the previously described reflectivity tests. Furthermore, there is no specific requirements that must be followed. The laser’s intensity or wavelength is not specified, the sample could be placed at any reasonable angle to the laser and detector providing polarisation is considered. This meant that the current setup in the optics laboratory would need minimal modification and no expensive new equipment was required. The major disadvantage is described in Germer’s article (1999), and was later encountered during the testing of this method; the detector is not efficient at measuring the reflected beam at any angle. The detector will measure the intensity, but will also measure any beams reflected off other surfaces. Germer suggests that painting all surrounding surfaces black would help this inaccuracy, but would not eliminate it entirely.

2.7 Coblentz Spheres

An approach similar to ARS scattering is presented by Gliech (2002) as a Coblentz sphere is introduced to the setup, shown in Figure 7. The laser is once again directed through a chopper and then through a series of attenuators before a mirror directs the beam onto the sample. The major difference is that surrounding the sample is a Coblentz sphere, with a small 7° opening that allows the incident and reflected beams to enter and leave the sphere. The detector used is a CCD detector, and it can be moved in a three dimensional space the smaller sphere in Gliech’s setup. Ronnow (1994) provides more detailed information about Coblentz spheres, although he does position the detector in the centre of the sphere, not in its own adjustable sphere attached to the Colbentz apparatus. The
Colentz sphere is made of Pyrex glass and its internal surface is coated with highly reflective Aluminium.

The use of a Coblentz sphere can increase the accuracy of the measurements taken. In Goniometric scattering, there can be difficulty in measuring intensities at small angles, and the use of a Coblentz sphere helps to give such measurements. If an appropriate CCD or photodiode was used in Ronnow’s Coblentz method, the number of measurements required fall to a small number as the one detector captures the entire array of the scattered beam. Gliech’s moveable detector has the advantage of being able to easily measure intensities in three dimensions, another measurement that can be difficult in an ARS setup. However, the Coblentz sphere must be manufactured to near-perfect specifications to ensure correct focusing of the beams, and there must be minimal imperfections to the inner area that could affect the directions of the beam adversely. As such, given the early stages of scattering that this project is investigating, it is not worth the added expense for the extra accuracy that will be attained. Furthermore, the Coblentz sphere will not be easily integrated with the other tests that are performed in the Optics laboratory.

2.8 In-Situ Scattering Measurements

Volk (2005) describes a process called ‘In-Situ’ scattering which was another commonly encountered method, that can be seen in Figure 8. This process was essentially the submerging of a sample of porous silicon into a volume of etchant; hydrofluoric acid and ethanol were used in Volk’s experiments. A laser beam would then be directed into the solution and onto the face of the sample, at some predetermined angle. The reflected beam is then captured by a detector (a CCD system in Volk) and the results are analysed. Foss (2005) explains that the reflected beam’s amplitude is affected by the transmission and reflection coefficients the mediums, and any boundary it encounters.
By calculating the RMS value of the reflected beam, the RMS roughness of the boundary between the porous silicon and the silicon can be readily calculated. Furthermore, by performing a short term Fourier transform on the reflected beam and analysing the frequency components, the etching rate and porosity at the porous silicon and substrate boundary can be calculated. It is clear that the major advantage of an in-situ experiment is the amount of useful information that can be attained; etching rate, roughness and porosity. It is not possible to measure the etching rate in the other scattering methods that have been described here. However, it is also clear that an integral part of the experiment is submerging the silicon sample into the substrate, a setup that would require equipment not readily available in the optics laboratory, and extensive changes to the current experimental setup.

2.9 Choosing a Measurement Method

After thorough research of these three methods of scattering measurement, it was decided that an ARS approach would be the most appropriate. Almost all the apparatus required was already available in the optics laboratory, while the setup could easily be achieved with little to no modification of the reflectivity tests being performed in the same laboratory. A Coblentz sphere, while adding another level of accuracy was deemed inappropriate for this project. The added expense was an important factor that came into the decision process. This project is only the beginning of a much larger investigation of the scattering properties of porous silicon, and it would be inappropriate to spend a not-insignificant amount of money on an investigation that had yet to even prove that the ARS measuring system would be successful. As this investigation of the scattering properties continues, it is foreseeable that an added level of accuracy would become desired, and it is only at this time that a Coblentz sphere might be considered. The ease with which it could be implemented in an ARS experiment would be an advantage, but this is not within the scope of this particular project. An in-situ experiment also has the advantage of being able to provide extra information regarding the etching rate of the material. However, this would be extremely difficult to integrate with the reflectivity tests, and would probably need to be done in a different testing environment. As such, an ARS scattering experiment was chosen as the most appropriate given the conditions and stage of the investigation of scattering.
2.10 Components of Angle Resolved Scattering

After deciding upon the Angle Resolved Scattering approach, the research became more specific and detailed, exploring the specific elements more thoroughly. Most of the components in the system are self-explanatory and require little to no reasoning. As will be explained later, the laser and mirrors were already present in the laboratory and as this project focused on the proof of concept, the specific details of these components were not needed to be optimised so were not thoroughly researched. However, the detector that would provide the readings is an integral component of the system. Throughout the investigation concerning the scattering method to be employed, it became evident that two types of detector were commonly used; silicon sensors and charge-coupled devices (CCD). Both were relatively easily acquired, so both were investigated to see which would be most appropriate for the experiments. It did become apparent though, that CCDs were used in spectroscopy experiments and were not usually used in scattering testing. While Goniometric spectroscopy shares many similar features to Angle Resolved Scattering, a CCD would provide an array of intensities not required in these tests. While a CCD could be used, a single-silicon sensor would provide an appropriate output to an accurate level. The specific detector that was decided upon (a single-silicon detector BPW34) is extremely effective in the visible and near-infrared ranges of radiation, ideal given a visible red laser was being used (Bayhan 2007).

2.11 Introduction to MATLAB Code

A series of MATLAB codes created by L. Tsang was used in the analysis of the results. The code named rsgeng.m (Appendix 9.4) generates a Gaussian surface, and rs1dg.m (Appendix 9.5) creates three separate simulations according to the Kirchhoff Approximation, Small Perturbation Approximation (SPA) and the Method of Moments Approximation. Due to the limited period of time given to complete this project, only the Method of Moments method was investigated, while the Kirchhoff and SPA simulations were not examined. These simulations were compared to the results that were measured in the experiments, as will be discussed later in this paper.
2.12 Generation of a Gaussian Surface

The first part of Tsang’s MATLAB code generates a Gaussian surface. A Gaussian surface is a semi-random surface that is a good approximation of a rough surface. The reason a Gaussian surface must be used, and a simple random surface is not sufficient is that an entirely random surface does not model a rough surface accurately. A real rough surface is a series of raised areas and troughs that are not entirely random. If one were to consider a series of points on a real rough surface, each point would have some relation to the previous point. The further away any point is from another, the lower the correlation would be between the two points.

Figure 9 is an entirely random surface generated by MATLAB with a mean height of 0 (Appendix 9.1). It is intuitive that this is not a real surface as there is no correlation between any of the points. When that surface is compared to a Gaussian Surface shown in Figure 10, it is once again intuitive that the Gaussian Surface is a better approximation of a rough surface.

The author attempted to understand the mathematics behind the complicated process of the creation of a Gaussian surface, as explained in Tsang’s Scattering of Electromagnetic Waves: Theories and Applications, however did not completely understand the concepts. The following is the author’s current understanding of the code, and the steps that were taken in order to create the Gaussian surface. Firstly, the MATLAB code requires several inputs;
the number of sample points \( N \), the length of the rough surface \( r_L \), the RMS height \( h \), the correlation length \( l_c \) and a seed for random number generation. Initially, a matrix of \( N \) random numbers is created using the \texttt{randn} function in MATLAB. This is followed by the generation of a series of Gaussian random variables. Equation 1 creates the first Gaussian variable in the series:

\[
b_0 = \sqrt{2\pi(rL)W(0)}r_\alpha \quad \text{(Equation 1)}
\]

Equation 2 creates the \( N/2 \)th variable in the series:

\[
b_{+N/2} = \sqrt{2\pi(rL)W(\pi N/rL)}r_\beta \quad \text{(Equation 2)}
\]

In the above two equations, \( r_\alpha \neq r_\beta \), and both represent one of the random numbers generated previously. Finally, equation 3 generates the remaining \( N-2 \) Gaussian random variables for \( n = -N/2 + 1, \ldots, -1 \):

\[
b_n = \sqrt{2\pi(rL)W(K_n)}\left\{\frac{1}{\sqrt{2}} \left( r_\sigma + ir_\epsilon \right) \right\} \quad \text{(Equation 3)}
\]

In Equation 3, \( r_\sigma \) and \( r_\epsilon \) represent two distinct values of the random number set \( N \), and:

\[
K_n = \frac{2\pi n}{L} \quad \text{(Equation 4)}
\]

Furthermore, \( W \) represents the Gaussian Spectral Function, described in equation 5:

\[
W(k) = k^2 (l_c) e^{-\frac{(k(lc)(0.5))^2}{2\sqrt{\pi}}} \quad \text{(Equation 5)}
\]

Equation 3 only calculates half of the Gaussian random variables though, so the remaining half must be calculated using the equation \( b_n = b^*_{-n} \). This can be done using equation 3.

The next step is to create a Fourier transform equal to \( b_n \), shown in equation 6:

\[
X(n) = b_n = \sum_{j=0}^{N-1} x(j)e^{-\frac{2\pi j}{N} k} \quad \text{(Equation 6)}
\]

Following the Fourier Transform, the following transformations are made:

\[
\tilde{X}(k+1) = X(k) \quad \text{(Equation 7)}
\]

\[
\tilde{x}(k) = \frac{1}{N} \sum_{k=1}^{N} \tilde{X}(k)e^{\frac{2\pi j}{N}(j-1)(k-1)} \quad \text{(Equation 8)}
\]
\[ \tilde{x}(j + 1) = x(j) \]  

(Equation 9)

The final equation is the Gaussian Surface, the height of a point as a function of the distance in the x direction, described in equation 10:

\[ f_m = \frac{N}{l} x(m) \]  

(Equation 10)

It is this function that approximates the Gaussian Surface, and this series of calculations that is used in Tsang’s code. An example of a Gaussian Surface generated in this way is shown previously in Figure 10.

2.13 Method of Moments Approximation

The second part of Tsang’s MATLAB code that was used was rsldg.m. This created the three scattering approximations; Kirchhoff, Small Perturbation, and the Method of Moments. As has been mentioned, the Method of Moments (MoM) was investigated in this project. Once more, the mathematics involved in MoM is quite challenging, and the following is a brief discussion of the author’s understanding of the concepts behind Tsang’s MATLAB Code. It should also be noted that the author did experience difficulty with the application of MoM to the MATLAB code, and this is something that could be investigated in the future.

Equation 11 is a one dimensional integral of Green’s function \( G(x,x') \) and a function \( f(x') \), and is the base of the MoM method:

\[ \int_{a}^{b} d x' G(x,x')f(x') = c(x) \]  

(Equation 11)

There are two additional functions that form the MoM method; the Basis Function and a Weighting Function. The basis function is formed by the previously determined set of Gaussian Random Variables \( b_n \). These do not need to be Gaussian in all Method of Moment approximations, however Tsang’s MATLAB code is determining the scattering from a Gaussian surface, so Gaussian Random Variables are used. This set of random variables is multiplied by a function \( f_n \) shown in equation 12. \( f_n \) is often a pulse or triangle function.

\[ f(x) = \sum_{n=1}^{N} b_n f_n(x) \]  

(Equation 12)
Substituting equation 12 into equation 11 yields equation 13, the first half of the MoM approximation:

$$ b_n \sum_{n=1}^{N} \int_{a}^{b} \ dx' \ G(x,x')f_n(x') = c(x) \quad \text{(Equation 13)} $$

A set of weighting functions is $w(x)$ is then created. A common choice is to simply set the weighting function equal to the basis function $w_m(x)=f_n(x)$. This weighting function is integrated on the rough surface length, and multiplied equation 13, yielding equation 14:

$$ b_n \sum_{n=1}^{N} \int_{a}^{b} \ dx w_m(x) \int_{a}^{b} \ dx' \ G(x,x')f_n(x') = \int_{a}^{b} \ dx w_m(x)c(x) \quad \text{(Equation 14)} $$

This creates a matrix equation, equation 15:

$$ \sum_{n=1}^{N} G_{mn} b_n = c_m \quad \text{(Equation 15)} $$

This leads to the matrix equation 16, which is the final Method of Moments equation, and $G_{mn}$ is the matrix

$$ G_{mn} = \int_{a}^{b} \ dx w_m(x) \int_{a}^{b} \ dx' \ G(x,x')f_n(x') = \langle w_m, G f_n \rangle $$

$G_{mn}$ is the MoM function that approximates the scattering properties of the sample. This is the approximation that was be used for the experimental results. For a more thorough description of the Method of Moments, refer to Chapter 2 of Tsang’s book.
Part 3: Manual Testing

3.1 Introduction to Procedure

The first step to creating a highly effective ARS system is to prove the concept, to show that the results shown in the researched sources can be replicated and that the method of Angle Resolved Scattering is feasible. This proof-of-concept was followed by the enhancement of the testing setup with the use of a small servo motor and microprocessor to increase accuracy and speed of testing, created by Dr Keating.

3.2 Manual Testing Procedure

In order to prove that Angle Resolved Scattering was a feasible method of measuring scattering, a simple test was created. A Helium-Neon laser was placed on a stand, and directed through a chopper. The purpose of this chopper is to eliminate any background noise so only the laser is being analysed. In essence, a chopper is a wheel with several large slits in it. This rotates at high speeds and through constantly blocking the laser source, the level of intensity of light in the room can be measured and isolated, leaving only the laser’s intensity to be analysed (ideally).

The light that passes through the chopper is directed onto a mirror, which then directs the beam onto the sample of porous silicon. The wafer of porous silicon is held in place by a circular ring which is screwed onto a backing plate, as can be seen in Figure 11. The wafer is placed between the ring and the plate as the ring is being tightened. Once the beam is being directed onto the laser, the beam’s position must be altered so it is at an angle of 90° to

![Porous Silicon Sample Holder](image)
the sample. If the beam approaches the sample at any angle other than 90°, the reflected light will be polarised and the results will be compromised unless the correct equipment is being used. In order to attain 90° in the simplest possible manner, remembering that this is a rudimentary test to prove a concept, the mirror and laser source were both adjusted until the beam was reflected back from the sample, onto the mirror and as close to the laser source as possible.

A single silicon sensor was glued onto a piece of plywood, and this was clamped onto a stand. The sensor was connected to a voltmeter which measured the intensity of the laser. In order to take readings relative to any angle, a basic 90° template with 5° increments was placed with its centre at the sample with the stand and sensor being moved to each increment for every reading. The entire process can be seen in Figure 12. While it is clear this is not an accurate way of measuring the intensity, it should be noted once again that this test was only to gain a basic understanding of the testing procedure and if it would produce results that resemble an expected scattering pattern. To attempt to have the sensor aimed directly at the sample, it was manipulated until a maximum intensity was attained.

3.3 Manual Testing Results

The results of the first manual test are perhaps the most important in this project. They hold such importance as they can either prove that Angle Resolved Scattering is an effective way to measure scattering, or could indicate that this method is inappropriate, or requires a different setup with a much higher level of accuracy. The results of this test can be seen in Figure 13 and in Appendix 9.2. The results were normalised with respect to 90mV, the incoming beam intensity that was measured during the testing. Figure 13 shows this data
compared to data published in Locher (1993). Locher is not the scattering behaviour of porous silicon, but is the result of Angle Resolved Scattering of a diamond film of an unknown rms height. What is initially obvious in the comparison between these two data sets is the large difference in normalised intensities. They both appear to have similar scattering profiles, yet the published results appear to have a higher intensity. The most likely reason for this is the distance from the detector to the sample. While this distance is not reported in Locher (1993), it is likely that it is smaller than the manual testing done in this project, which was measured to be 4.2cm. The further away the detector is from the sample, the area over which the beam’s intensity has been scattered is larger, resulting in a smaller reading of the intensity.

The most important observation to be made from Figure 13 is that the two scattering profiles share a similar form. Both exhibit a cubic relationship between the scattered angle and normalised intensity. This is the evidence that was required to prove that the manual testing was a success, as Locher’s results were measured by a similar ARS setup. As was stated in this section, the fact that the intensities exhibit a large difference is not specifically concerning due to the probable difference in distances between the two samples.
3.4 Inaccuracies in Manual Testing Results

There were many difficulties encountered in the manual test however. The first problem occurs with a lack of data between 75° and 90°. There is an extreme change in the intensity between these angles, and the inability to measure them due to the laser hitting the detector setup causes inaccuracy in the trend line. The ability to measure these angles would provide a more accurate scattering profile, however due to physical constraints and the rudimentary method by which the angles were measured using a template, they could not be accurately measured.

Another issue experienced with this experimental setup is the lack of ability to measure angles greater than 90°. Due to other immovable equipment in the laboratory, no measurements could be taken beyond 90°. Therefore, there was no way of measuring how symmetrical the scattered beam was, an important aspect of Angle Resolved Scattering and a key method to prove the success of the test. Another important difficulty was the beam striking the shield before or after reflection from the sample. One of the reasons why measurements could not be taken at angles larger than 75° was that the beam would strike the shield of the detector, scattering the light and rendering the results unusable as shown in Figure 14. Furthermore, the shield was not perfectly aimed at the sample, so some of the reflected light was deflected off the inside of the shield before it reached the detector. This explains the difference in intensities shown in Figure 15, displaying the shielded and unshielded results.
It is also important to describe inaccuracies that may not be evident from the above results. Firstly, moving the detector around a template and manipulating its rotation relative to the sample by hand will create a large level of error. Using this method, it is not possible to ensure the centre of the template is below where the laser strikes the sample, and the angles can only be measured to a very low level of accuracy. Furthermore, manipulating the angle of the detector relative to the sample is flawed once more due to the inaccuracies of the human hand.

Despite these difficulties and inaccuracies, this testing procedure was considered a success. Not only did the measured model match the expectations gained from previous research, the tests created a scattering profile that was proven to be similar to published results.

Figure 15: Shielded vs Unshielded Results
Part 4: Semi-Automated Testing

4.1 Semi-Automated Testing Procedure

Following the analysis of these tests, a semi-automated testing mechanism was created by Dr Keating. An arm was attached to a simple servo motor, and the sensor was attached to this arm. The model seen in Figure 16 was mounted onto a stand with the centre of the motor and arm directly beneath the sample. This ensured the measured or calculated angles would be correct, and that the sensor was always aimed directly at the sample. The motor was connected to a microprocessor, which was then linked to a computer in the laboratory. The microprocessor could then be programmed to change the position of the arm through an input manually typed into the computer. While the microprocessor had not been calibrated to degrees, by measuring the input when the arm was at 90° to the sample, and the input when it was at 0°, the angles could be calculated later. The sensor was once again connected to the voltmeter so intensity readings could be taken.
4.2 Semi-Automated Testing Results

The scattering results of the semi-automated testing procedure can be seen in Figure 17 and in Appendix 9.3.

![Semi-Automated Scattering](image1)

Figure 17: Semi-Automated Testing Results

As has been stated previously, a scattering pattern should be symmetrical about an axis normal to the sample. In order to assist in viewing the symmetry, Figure 18 has been reflected about 0º, to superimpose the intensities at angles less than 0º over those greater.

![Reflected Scattering Intensities](image2)

Figure 18: Reflected Semi-Automated Results
There are several important observations that must be considered. Firstly is a comparison to the manual tests, and whether these were more or less successful. The major difference between the two scattering profiles was the intensities measured. The range in intensities of the semi-automated scattering results is from approximately 0 to -4dB, while in the manual testing it was from 0 to -6dB. The reason for this is an error in normalisation. The detectors were a similar distance away from the sample in both tests, 4.2cm in the manual tests and 4.5cm in the semi-automated tests. If this was the cause of the difference, it would be expected that the semi-automated results would be smaller than the manual as it is slightly further away. The intensity of the incoming beam was measured in the manual procedure to be 90mV, however it was not measured in the semi-automated case. Therefore, this 90mV was assumed to be the intensity of the incoming beam in the semi-automated tests, an assumption that is possibly the cause for the difference. In all future tests, the incoming beam intensity must be measured to ensure correct normalisation.

Despite these errors, the test was not a failure. The graphs still hold significance as the error in normalisation is constant for all semi-automated measurements. From Figure 18 it is clear that the scattering test was sufficiently successful. While the two data sets do not line up exactly, there is a clear similarity between them. In an accurate scattering test however, a higher level of precision would be required. The inaccuracies in this test could come from the detector on the arm being slightly misaligned and not aimed directly at the sample. The centre of the arm could also be off centre and not directly below the sample. The centre of the arm would have to be directly below the point where the laser beam strikes the sample, a difficult task to achieve perfectly. Also, as was stated previously, ideally the beam should be at a 90° angle to the sample. While this was attempted by hand, it cannot be achieved perfectly through this manual method.
Part 5: Scattering Simulations

5.1 Testing of MATLAB Code

In order to be confident that Tsang’s MATLAB code is an accurate representation of scattering, some testing on the program must be conducted. The first test was to input an RMS Height of 0 and a large correlation length of 100. This is the minimum available, and should provide an output close to what a perfect surface would. This is expected to be a large maximum with the intensity dropping quickly on either side. The results of this test can be seen in Figure 19.

This simulation matches what was expected, and contributes towards confirmation of Tsang’s code. There are clear inaccuracies though. At an angle of 0°, the log of the normalised intensity should be almost equal to 0, and cannot be higher than 0. This is one of the clear inaccuracies of the approximation. The fact that the simulation does not represent a perfect mirror is due to the Gaussian surface. Despite an RMS value of 0, the surface is still random, and will still exhibit scattering.

The second test of Tsang’s code is to input a high value for RMS height, simulating an extremely rough surface. What is expected from this is a very small peak at 0°, and a smooth transition to lower intensities. The results of using an RMS value of 1 can be seen in Figure 20. As can be seen, the results are as expected. There is a small peak at 0°, and then a gradual decline in intensities. When compared to the intensities of Figure 19, the peak is lower in the rough simulation, yet at larger degrees the intensities are much higher, as
expected. Using these two tests, it appears that Tsang’s Code for scattering simulation is one which can be used to verify the experimental results in this project.

5.2 MATLAB Simulations

After the research and previous MATLAB simulations, it appears that the measured intensities match an expected intensity profile. However, to ensure that the results were reasonable, they were compared to Tsang’s MATLAB simulations. The laser had a wavelength of 600nm, so this was used in the simulation. Through manipulation of the RMS height and correlation length, values of 80nm and 0.1 were obtained respectively. The results of this simulation compared to the semi-automated results are shown in Figure 21. There are certain differences in the two graphs, however they follow the same trends. There are three major sources for these differences. The first is that the Method of Moments is only an approximation, as has been previously described. A second difference is caused by the fact that the Method of Moments measures pure scattering. The scattering from a porous silicon sample is affected by the layer of porous silicon before the boundary layer. This diffracts the light and alters the scattering characteristics of the sample. Finally, errors in the measurements taken could have caused the inaccuracies. However, despite these differences, there is a clear and similar trend between the two graphs, and this not only suggests that the tests were a success, but also has provided information about the samples RMS Height and correlation length.
Part 6: Improved Testing Design

Using these results, a new arm was designed that would provide more information for the scattering. The newly designed arm has several additions that will assist in the accuracy of the measurements. Firstly, a second detector has been added to the arm. At an angle of 90° to the sample, the light polarisation is not altered so there is no need to be concerned with polarisers. However, if the beam was directed at a different angle, the light’s polarisation would change, and the current testing setup would not be appropriate. By adding a second detector and placing a polariser in front of each of the two detectors (one in the p-direction, the other in the s-direction), the intensity of the two polarised orientations of the light can be measured. This would be a helpful addition as the reflected beam would no longer be disrupted by the detectors, so careful measurements could be taken at the angles where the intensity is at its peak. These two detectors can be seen in Figure 22.

Another addition to the arm was a third sensor, a silicon photodiode. This detector is placed at an angle of 30° to the centre between the two silicon detectors, and is faced in the opposite direction. This will measure the intensity of the incoming laser beam when the beam is directed at it, and therefore the intensities can be normalised and accurately compared to other results that used different beam intensities. It also enables the detecting assembly to be used with different beams, and different setups with a meaningful and comparable output. Furthermore, the dimensions of the arm have been altered so the distance between the detectors and the sample is minimised while ensuring the maximum range of angles can be achieved. The new dimensions also ensure the assembly can be moved to any height on the sample holder.
It is evident that these designs could be implemented to improve the accuracy of a scattering test. Further additions could be made to improve the accuracy too. A method to ensure the centre of the arm is directly below the point at which the beam strikes the sample would be advantageous. Furthermore, making the process fully automated would also produce much more accurate results. Devising a method by which the arm moves in a continuous motion, with the various intensity readings being taken by each of the sensors being automatically recorded would really enhance the accuracy. With such a setup, the number of data points recorded could be increased dramatically.
Part 7: Conclusion

This aim of this project was to create a strong foundation of research in the field of scattering of porous silicon. A design of a testing setup was to be created, with some basic testing to prove the methods being used. After thorough investigation of the many methods scattering can be measured, an Angle Resolved Scattering approach was decided upon. This method could be manipulated to fit into the current reflectivity tests in the Optics Laboratory, and required no new technological equipment. After proving that Angle Resolved Scattering was successful, a testing setup was designed that enabled semi-automated testing. This design was essentially a detector attached to an arm that was controlled by a motor. This setup enabled a higher accuracy of results and allowed a larger number of data points to be measured.

After analysing the results of the tests, it became clear that although there were sources of inaccuracy, the experiments were seen to be successful. As was stated though, this project was to provide a strong base for further research. There are many improvements that can be made to the current design, such as designing and testing a fully-automated detector system, and installing the detectors for polarisation and beam intensity. With these additions, highly accurate measurements would be possible, and many more data points could be measured.

After considering all the objectives that were desired to be completed for this project, it is clear that they have been met. There has been extensive research undertaken to create the best possible design given the constraints outlined in this paper. From this investigation, further research and design can be undertaken to create an effective and accurate method of measuring scattering properties.
Part 8: References


Baglio, S. (2008) Scaling Issues and Design of MEMs Wiley and Sons, Chichester


Part 9: Appendices

9.1 Generation of Random Surface

\[ y = (\text{rand}(1,100) - 1/2) \times 2; \]
\[ \text{plot}(y); \]
\[ \text{title}('\text{Random Surface}'); \]
\[ \text{xlabel}('x'); \]
\[ \text{ylabel}('\text{Random Number}'); \]

9.2 Manual Testing Results

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<th>Angle</th>
<th>Intensity</th>
<th>log(Norm. Intensity)</th>
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9.3 Semi-Automated Results

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<th>log(Norm. Intensity)</th>
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9.4 MATLAB Code for Generation of Gaussian Surfaces

RSGENG

```matlab
function [f,df,x]=rsgeng(N,rL,h,lc,seed);
%RSGENG generates 1D Gaussian random rough surfaces with Gaussian Spectrum.
% [f,df,x]=rsgeng(N,rL,h,lc,seed)
% INPUT:
% N=total number of sample points
% rL=rough surface length
% h=rms height
% lc=correlation length
% seed=seed of random number generator
% OUTPUT:
% f=rough surface profile
% df=df/dx
% x=sample points on the surface
% -- Part of the Electromagnetic Wave MATLAB Library (EWML) --
% <http://www.emwave.com/>


randn('seed',seed);
y=randn(N,1);
for n=1:(N/2-1);
    bh(n)=(y(2*n-1)+i*y(2*n))/sqrt(2);
end;

bhc=conj(bh);
bhf=fliplr(bhc);
bi=[bh y(N-1) bhf y(N)];
kx=2*pi*[-N/2+1:1:N/2]/rL;
yi=sqrt(wk(kx,h,lc));
```

Generation of random numbers

Generation of Gaussian Random Variables according to Equations 1, 2 and 3
\[ y = y_1 \sqrt{2 \pi r_L}; \]
\[ b = y \cdot b_i; \]
\[ x_s = \{ b (N/2+1:1:N) \ b(1:1:N/2) \}; \]
\[ x_t = \{ x_s(N), x_s(1:1:N-1) \}; \]
\[ f_t = \text{ifft}(x_t, N); \]
\[ f_t = f_t \cdot N/r_L; \]
\[ f_s = \{ f_t(2:1:N), f_t(1) \}; \]
\[ f = \{ f_s(N/2+1:1:N) \ f_s(1:1:N/2) \}; \]
\[ f = \text{real}(f); \]
\[ dx = r_L/N; \]
\[ x = [-N/2+1:1:N/2] \cdot dx; \]
\[ n = 2:N-1; \]
\[ d_f1 = (f(n+1) - f(n-1))/(2 \cdot dx); \]
\[ d_f = [(f(2) - f(N))/(2 \cdot dx), d_f1, (f(1) - f(N-1))/(2 \cdot dx)]; \]
\[ \% plot(x, y); \]
\[ plot(x, df); \]

---

**Generation of Gaussian Surface**

according to Equation 10

---

**Gaussian Spectral Density**

(Equation 5)

---

**9.5 MATLAB Code for Generating Scattering Simulations**

**RS1DG**

```matlab
function [tsd, sig, sigka, sigspm] = rs1dg(wave, nr, N, rL, h, lc, g, tid, nsa, seed)
% rs1dg computes the bistatic scattering coefficient for Gaussian rough surfaces
% with Gaussian spectrum.
% [tsd, sig, sigka, sigspm] = rs1dg(wave, nr, N, rL, h, lc, g, tid, nsa, seed)
% INPUT:
% wave=wavelength
% nr=total number of surface realizations
% N=total number of sample points
% rL=rough surface length
% h=rms height
% lc=correlation length
% g=tapering parameter for incident wave
% tid=incident angle in degree
% nsa=number of scattered angles from -90 deg to 90 deg
% seed=seed for random number generator
% OUTPUT:
% tsd=scattered angles in degree
% sig=bistatic scattering coef (MoM)
% sigka=bistatic scattering coef (KA)
% sigspm=bistatic scattering coef (SPM)
% REQUIRES: rsgeng.m for generation of Gaussian rough surfaces
% -- Part of the Electromagnetic Wave MATLAB Library (EWML) --
```

---
%  <http://www.emwave.com/>

% Original: L. Tsang, 1998

tai=tid*pi/180;
h2=h^2;
k=2*pi/wave;
ti=tan(tai);
cl=cos(tai);
denom=1+2*ti^2;
denom=denom/(2*(k*g*cl)^2);
denom=8*pi*k*g*sqrt(pi/2)*cl*(1-denum);

sig=zeros(nsa,1);
randn('seed',seed);
for ir=1:nr
    fprintf('Processing realization %i
',ir);
    [f,df,x]=rsgeng(N,rL,h,lc,seed);
    seed=randn('seed');
    b=incid(k,x,f,tai,g);
    dx=rL/N;
    [xm,xn]=meshgrid(x);
    [fm,fn]=meshgrid(f);
    arg=k*sqrt((xm-xn).^2+(fm-fn).^2);
    for m=1:N
        arg(m,m)=1;
    end
    A=dx*i*besselh(0,1,arg)/4;
euler=1.78107;
e=exp(1);
    for m=1:N
        dl=sqrt(1+df(m)*df(m))*dx;
        A(m,m)=(i/4)*dx*(1+(2*i/pi)*(log(euler*k*dl/4)-1));
    end
    b=b.';
    u=A\b;
    u=u.';

dan=180/(nsa+1);
for m=1:nsa
    tsd(m)=-90+m*dan;
tas=tsd(m)*pi/180;
    ss=sin(tas);
    cs=cos(tas);
    integ=exp(-i*k*(ss*x+f*cs));
    integ=integ.*u*dx;
    psis=sum(integ);
    sige=abs(psis)^2/denom;
    sig(m)=(sige+(ir-1)*sig(m))/ir;
end
%plot(sig,tsd);
Q=[-4.03E+01
   -3.97E+01
   -3.85E+01
   -3.75E+01
   -3.60E+01
   -3.38E+01
   -3.29E+01
   -3.10E+01
   -2.97E+01]
Experimental Scattering Results

R=[76.66667
72.22222
66.66667
61.11111
55.55556
50
44.44444
38.88889
33.33333
27.77778
22.22222
16.66667
11.11111
7.777778
6.666667
5.555556
4.444444
3.333333
2.222222
-1.11111
-2.22222
-3.33333
-4.44444
-5.55556
-11.1111
-16.6667
-22.2222
-27.7778
-33.3333];

P=log(sig);

plot(tsd,P-1.5,R,Q/10,'r:+');
legend('Method of Moments','Semi-Automated Results');
% Kirchhoff Approximation
for m=1:nsa;
    tas=tsd(m)*pi/180;
    ss=sin(tas);
    cs=cos(tas);
    csa(m)=cs^2;
    kxq=k*(ss-sin(tai));
    kx(m)=kxq;
    csum=ci+cs;
    fac=(1+cos(tai+tas))^2*k^3/ci*exp(-(k*h*csum)^2);
    p=0;
    arr=1/(k*csum)^2;
    for ma=1:20;
        term=lc/(2*sqrt(pi));
        term=term/sqrt(ma);
        term=term*exp(-(kxq*lc/2)^2/ma);
        arr=arr*(k*csum*h)^2/ma;
        term1=arr*term;
        p=p+term1;
    end
    sigka(m)=p*fac;
end;

% Small Perturbation Method
sigspm=csa.*wk(kx,h,lc)*4*k^3*cos(tai);

function b=incid(k,x,z,tai,g)
% generates the spatial tapered incident wave
    ti=tan(tai);
    ci=cos(tai);
    si=sin(tai);
    fac=((x+z*ti)/g).^2;
    kg=(k*g*ci)^2;
    w=(2*fac-1)/kg;
    b=exp(i*k*(x*si-z*ci).*(1+w)-fac);

function y=wk(kx,h,L)
% Gaussian spectral density
    y=h^2*L*exp(-((kx*L*0.5).^2)/(2*sqrt(pi)));
    plot(tsd,y);
Appendix 9.6 Design of Improved Arm and Base