Optical Angular Scatterometry: In-line Approach for Roll-2-Roll and Nano-Imprint Fabrication Systems

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OPTICAL ANGULAR SCATTEROMETRY: IN-LINE APPROACH FOR ROLL-2-ROLL AND NANO-IMPRINT FABRICATION SYSTEMS

by

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DISSERTATION

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Dedication

To those who forgive. To those who believe. To those who teach.

A los que perdonan. A los que creen. A los que enseñan.
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Abstract

As critical dimensions continue to shrink and structures become more complex, metrology processes are challenging to implement during in-line nanomanufacturing. Non-destructive, non-contact, and high-speed conditions are required to achieve proper metrology processes during in-line manufacturing. Optical scatterometry is a nanoscale metrology tool widely used in integrated circuit manufacturing for characterization and quality control. However, most applications of optical scatterometry operate off-line. A high-speed, in-line, non-contact, non-destructive scatterometry angular system has been demonstrated in this work
to scan pattern surfaces during real-time nano-fabrication.

Our system has demonstrated scanning capabilities using flat, 1D and 2D complex structures. The flat surface samples consist (commercially and grown) of thin film native oxide, grown oxide, and alumina. The 1D samples were made by using interferometric lithography with a thin deposited layer (~85 nm) of aluminum. The 2D complex samples are hollow silicon tubes fabricated using nano-imprint lithography, atomic layer deposition (ALD) and reactive ion etching (RIE). The inside diameter, outside diameter, and the period of the hollow pillars are respectively ~100 nm, ~135 nm and ~200 nm. All samples were fabricated on silicon substrates. These are test structures to establish the metrology capabilities. The applicability of the tool is not restricted to these samples.

Our current in-line scatterometer uses 45° off-axis parabolic mirrors which allows us to have an angular scan of the angle of incidence of ~50°. The system uses a high-speed scanner at 8 kHz to vary the angle of incident of the beam at the focal spot on the moving web. The system uses a 405 nm collimated diode laser with a beam profile of 1.8×3.5 mm². The beam is focused at the resonant scanner to vary the incident angle at the focal spot on the moving web. The number of resolvable points during the scan is ~313 set by the optical components that reduce the spot size to desire dimensions. The focal spot varies as a function of incident angle. At 45° incident angle, the focal spot is ~125×120 μm². At 19° incident angle, the focal spot is 85×70 μm². At 67° incident angle, the focal spot is 200×190 μm². Our scan period is 125 μs which will allow us to accumulate 20-30 reflectance
measurements before the web moves a distance comparable to the focal spot. A biased silicon detector is used to collect the high-speed reflection signal. The rise time of the detector is 14 ns. The data collected is averaged with a digital scope and further processed on the computer for analysis.

Our current system can be integrated with nano-imprint and other R2R real-time fabrication techniques. The goal is to improve quality control and monitor real-time high-speed nano fabrication processes. The angular range can be improved (up to 79°) by varying the focal length and the curvature of the parabolic mirrors. The scanning time can be reduced by increasing the frequency of the resonant scanner. Evidently, in-line angular scatterometry offers solutions to the future of R2R semiconductor nanomanufacturing.
Contents

Dedication ........................................................................................................................................ iv

Acknowledgements ............................................................................................................................. v

Optical Angular Scatterometry: In-line Approach for Roll-2-roll and Nano-imprint Fabrication Systems .......................................................................................................................... vi

Abstract ........................................................................................................................................... vi

Contents ........................................................................................................................................... ix

List of Figures .................................................................................................................................... xii

List of Tables ..................................................................................................................................... xvii

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

1.1. Introduction to metrology ........................................................................................................... 2

1.2 Metrology Technologies in Manufacturing .................................................................................. 3

1.2.1 Atomic Force Microscope ...................................................................................................... 4

1.2.2 Scanning Electron Microscopy ............................................................................................... 6

1.2.3 Scatterometry ........................................................................................................................... 8

1.2.3.1 Ellipsometric Scatterometry ............................................................................................... 8

1.2.3.2 Angular Scatterometry ......................................................................................................... 10

1.2.3.2.1 Introduction to RCWA Code .............................................................................................. 15

1.4 Outline of the Dissertation ......................................................................................................... 16
2 In-line Angular 2.5 kHz Scatterometry ................................................................. 18
  2.1 Design Overview .................................................................................................. 18
  2.2 High Speed Detection ......................................................................................... 20
  2.3 Calibration .......................................................................................................... 21
  2.4 Beam Profile ...................................................................................................... 24
  3.5 Angular Limits .................................................................................................... 26

3 In-line Angular Scatterometry for R2R and Nano-imprint fabrication ............ 35
  3.1 Design Overview .................................................................................................. 36
  3.2 High Speed Detection ......................................................................................... 39
  3.3 Beam Profile ...................................................................................................... 40
  3.4 Calibration .......................................................................................................... 41
  3.5 Angular Limits .................................................................................................... 44
  3.6 Full Design and Custom Parts ............................................................................ 47

4. Sample Preparation .................................................................................................. 50
  4.1 Thin Film Samples ............................................................................................... 50
    4.1.1 Silicon Wafers with Native Oxide and ~100 nm SiO₂ Overlayer .................. 51
  4.2 1D Undercut Nanoscale Al Lines on Silicon Wafer ............................................ 51
    4.2.1 Introduction to Interferometric Lithography (IL) .......................................... 51
    4.2.2 Fabrication Process ....................................................................................... 53
  4.3 2D Silicon Nanotubes on Silicon Wafer .............................................................. 54
## Contents

4.3.1 Introduction to Nano Imprint Lithography (NIL) ................................................. 55

4.2.2 Fabrication Process ................................................................................................. 56

5 Experiments and Results ............................................................................................... 59

5.1 Thin Film Samples ....................................................................................................... 59

5.1.1 Silicon Wafer with Native Oxide ............................................................................ 60

5.1.2 Silicon Wafer with ~100 nm SiO$_2$ Overlayer ......................................................... 65

5.2 1D Undercut Nanoscale Al Lines on Silicon Wafer .................................................... 69

5.3 2D Silicon Nanotubes on Silicon Wafer ....................................................................... 72

6. Conclusion and Future Work ......................................................................................... 75

6.1 Conclusion .................................................................................................................... 75

6.2 Future Work .................................................................................................................. 80

6.2.1 Multi-point In-line Angular Scatterometry Designs ............................................. 81

Appendix A: List of Parts for In-line System .................................................................... 90

Appendix B: Custom Parts .................................................................................................. 93

Appendix C: MATLAB Multiparameter Fitting User Interface using RCWA Code 97

References .......................................................................................................................... 100
List of Figures

Figure 1 Description of the principle operation of AFM ........................................ 4
Figure 2 Basic Schematic AFM with Laser source and micro-cantilever .............. 5
Figure 3 Schematic of a SEM ............................................................................. 7
Figure 4 Schematic of an Ellipsometric Scatterometer ....................................... 9
Figure 5 Schematic of an angular Scatterometer. ............................................... 10
Figure 6 Structure definition for WGP ............................................................... 13
Figure 7 Structure definition for the resist grating .......................................... 13
Figure 8 WGP Fitting results for 405 nm measurements: (a) TM polarization with vertical grating, (b) TE polarization with horizontal grating. ....................... 15
Figure 9 Resist grating fitting results of resist grating for 405 nm measurements: (a) TM polarization with horizontal grating, (b) TE polarization with vertical grating. .................................................................................................................. 15
Figure 10 Schematic of one leg angular in-line Scatterometer ......................... 19
Figure 11 Reverse Bias Silicon Detector ............................................................. 21
Figure 12 Calibration Coefficient vs incident angle for TE and TM Polarization .... 23
Figure 13 the in-line and the off-line angular scatterometer with respected incident and reflected beams used in equation 5 ......................................................... 24
Figure 14 Beam profile from laser source through all optical components. Lenses not
List of Figures

to scale. ............................................................................................................. 26

Figure 15 Schematic of two legs angular in-line Scatterometer. ..................... 27

Figure 16 2” parabolic mirrors comparison with different focal length. .......... 28

Figure 17 3” parabolic mirrors comparison with different focal length. ........... 28

Figure 18 4” parabolic mirrors comparison with different focal length. .......... 29

Figure 19 Tilting 5° and 10° symmetrically the parabolic mirrors to control $\theta_i$ and $\theta_f$. ............................................................................................................. 31

Figure 20 Custom 2” parabolic mirror. Focal length of 5.61 cm and off-axis angle of 80°. ............................................................................................................. 32

Figure 21 Custom 3” parabolic mirror. Focal length of 8.78 cm and off-axis angle of 80°. ............................................................................................................. 34

Figure 22 New in-line angular scatterometer using 45° off-axis parabolic mirrors. . 36

Figure 23 a) top view b) side view of new in-line angular scatterometer using 45° off-axis parabolic mirrors. ............................................................................................................. 37

Figure 24 Experimental in-line angular scatterometer setup using 45° off-axis parabolic. mirrors ............................................................................................................. 39

Figure 25 a) top view b) side view of new in-line angular scatterometer using 45° off-axis parabolic mirrors. ............................................................................................................. 41

Figure 26 Calibration Coefficient vs incident angle for TE and TM Polarization..... 44

Figure 27 Two-leg in-line angular scatterometry system using 45° off-axis ......... 45
Figure 28 Top view of two-leg in-line angular scatterometry system using 45° off-axis parabolas. .......................................................... 46

Figure 29 Custom made 45° off-axis parabolic mirror with an angular range of 70°. ............................................................................................................................................ 47

Figure 30 one-leg system design with all independent stages for each optical component. .......................................................................................................................................................... 48

Figure 31 two-leg system design with all independent stages for each optical component. .......................................................................................................................................................... 49

Figure 32 IL scheme. Interferometer geometries for IL .................................................................................................................................................. 52

Figure 33 J-FIL Lithography Fabrication Steps.......................................................................................................................................................... 56

Figure 34 J-FIL Lithography Fabrication Steps.......................................................................................................................................................... 57

Figure 35 The 4” (~100 mm) silicon wafer with 2D hollow nanotubes. ............... 58

Figure 36 (a) Side view and (b) top view diagram of the 2D nanotubes with approximate dimensions. .................................................................................................................................................. 58

Figure 37 TE off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE=8.039×10⁻³. Off-line scatterometer fitted is 1.9 nm. Ellipsometry fitted to 1.36 nm. ................................. 61

Figure 38 TM off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE=6.582×10⁻³. Off-line scatterometer fitted is 2.2 nm. Ellipsometry fitted to 1.36 nm. ................................. 62
Figure 39 TE reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation. .......................................................... 63

Figure 40 TM reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation. .......................................................... 63

Figure 41 TE off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE=3.908x10^{-3}. Off-line scatterometer fit is 114.0 nm. Ellipsometry fitted to 113.98 nm................. 65

Figure 42 TM off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE= 6.693x10^{-3}. Off-line scatterometer fit is 114.0 nm. Ellipsometry fitted to 113.98 nm................. 66

Figure 43 TE reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation. .......................................................... 67

Figure 44 TM reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation. .......................................................... 68

Figure 45 SEM side view of the 1D undercut Al lines .................................................. 70

Figure 46 TE Reflectivity curve vs. incident angle for 1D undercut Al lines. ........ 71

Figure 47 TM Reflectivity curve vs. incident angle for 1D undercut Al lines. ........ 71

Figure 48 SEM side view of the 2D nanotube................................................................. 72

Figure 49 Reflectivity versus incident angle for TE polarization of 2D nano-tubes off-line, 2.5 kHz in-line, and 8.0 kHz in-line scatterometer. ............................ 73
Figure 50 Reflectivity versus incident angle for TM polarization of 2D nano-tubes off-line, 2.5 kHz in-line, and 8.0 kHz in-line scatterometer. ........................................... 74

Figure 51 Custom-made central flat mirror holder angled, side and top view. ........ 93

Figure 52 Custom-made side flat mirror holder angled, side and top view. ........... 94

Figure 53 Custom-made parabolic mirror holder #1. Connects parabolic mirrors to rotation stage........................................................................................................................................ 94

Figure 54 Custom-made parabolic mirror holder #2. Connects parabolic mirrors rotation stage to X, Y, Z translation stage. ................................................................. 95

Figure 55 Custom-made stage for 4” collimating and focusing lenses holder, and flat side mirrors. Connects tilt stage to X, Y, Z translation stage. ............................ 95

Figure 56 Custom-made stage for resonant scanner. Connects scanner to tilt stage. 96

Figure 57 Custom-made stage 1” mirror. Connects mirror holder to translation stage. ................................................................................................................................. 96
List of Tables

Table 1 focal length, working distance, and angular range for 2” 90° parabolic mirrors. .......................................................... 28

Table 2 focal length, working distance, and angular range for 3” 90° parabolic mirrors. .......................................................... 29

Table 3 focal length, working distance, and angular range for 4” 90° parabolic mirrors .......................................................... 29

Table 4 angular range, clearance, and focal length for 3” symmetrically tilted. ........ 31

Table 5 Comparison table of all system fitted results and RMSE for TE Polarization. .......................................................................................................................... 63

Table 6 Comparison table of all system fitted results and RMSE for TM Polarization. .......................................................................................................................... 64

Table 7 Comparison table of all system fitted results and RMSE for TE Polarization. .......................................................................................................................... 68

Table 8 Comparison table of all system fitted results and RMSE for TM Polarization. .......................................................................................................................... 68


1. Introduction

Metrology is a fundamental aspect of any manufacturing system. New complex three dimensional structures are being fabricated in volume nano-manufacturing. The semiconductor device dimensions are down to 5 nm featuring complex structures such as field-effect transistors (FinFET)\(^1\)-\(^2\). Current devices are fabricated with 3D topologies which clearly increase the complexity of the semiconductor devices. The complexity of new semiconductor circuits has increased the needs of metrology tools for manufacturing\(^3\). The need for new metrology systems is a current challenge in manufacturing to ensure quality control and monitoring\(^4\). However, most metrology tools used in the integrated circuit industry today are off-line and at-line and monitor the processes statistically; limiting their capabilities during high-speed fabrication processes\(^5\)-\(^7\). New fabrication techniques, such as Litho-Etch-Litho-Etch (LELE), have been developed to decrease the node sizes\(^8\); however, more steps are added to the fabrication sequence, requiring additional metrology steps. Currently at wafer-scale, Samsung electronics produces multi-level cells flash memories at 10 nm node size. This increase in the number of fabrication steps for a single lithography step at wafer-scale has turned metrology into a time-consuming and expensive task\(^9\).

In the other hand, Roll-to-roll (R2R) is a fabrication alternative technique that is used to fabricate nano-scale pattern structures. Both R2R and NIL are low-cost, high-resolution,
and high-throughput fabrication techniques. For instance, wire-grid-polarizers (WGP), metal-mesh-grids (MMG), and metamaterials are being fabricated at large areas with R2R and NIL systems which is another emerging area for metrology$^{10-12}$. R2R and NIL consist on creating pattern structures by applying mechanical pressure on resist. Clearly, there is an urgent need to develop metrology systems to satisfy new manufacturing technologies including R2R and NIL. Meanwhile wafer-scale fabrication techniques are clearly defined and more mature; R2R and NIL requires metrology systems while fabrication. R2R nanofabrication adds additional requirements due to the mechanical motion and to stretching/deformation of the web.

1.1. Introduction to metrology

Metrology is defined as the science of measurement. Metrology comes from the Greek word “metron” which means measurement and “logos” which means proportions. Optical Metrology, science concerning measurements using light, dates to ancient times but more formal when the telescope was first developed by astronomers Galileo Galilei and Johannes Kepler to study astronomy$^{13}$. Since then, many other metrology systems have been developed and used to explore micro and macro scientific phenomena. Currently, metrology systems are widely used for research and industrial application to explore new boundaries at atomic scale sizes. Some of the most common current metrology systems in
nano-manufacturing are: SEM, AFM, and Scatterometry. However, there are many off-line metrology systems that are being used in industrial manufacturing. Fourier Transform Infrared Spectroscopy, STM, x-ray and elemental analyses, etc. Another way to monitor fabrication processes (off-line) is by tracking large area transmission and reflection and polarization properties. The fabricated substrate is illuminated and with a high-resolution camera defects can be imaged which is defined as functional metrology. Systems such AFM, SEM, scatterometer will be covered in this dissertation, as well as, the transition to real-time and in-line technologies.

1.2 Metrology Technologies in Manufacturing

Metrology systems are widely used for industrial and research applications. AFM, SEM, and Scatterometer are the three mostly used metrology systems these days. In this sub chapter, we will cover briefly the history, fundamental operation and applications for each them and their industrial application on nanomanufacturing.
1.2.1 Atomic Force Microscope

Atomic force microscopy (AFM) is a metrology tool used to characterize high-resolution structures at the nanometer scale. AFM was first developed early 1980s by IBM scientist Gerd Binnig, Heinrich Rohrer, and Christoph Gerber. The AFM images are obtained by measurement of the force on the sharp tip (mounted on a cantilever) created by proximity to the surface of the sample. The translation of the surface allows the tip to move across the surface tracing the surface contour. By early 2000s AFM was considered one of most popular metrology tools on the market and promised great future for high-speed measurements. Since the first development of the AFM, it has become an important metrology tool in industry to characterize pattern structures at the nanoscale. Figure 2 represent a basic AFM operation using a laser source and schematic of most current AFM

Figure 1 Description of the principle operation of STM [Reference 18]
AFM operates under two main modes: contact modes and non-contact modes. During the contact mode as previously described, the force between the tip and the surface causes deflection of the cantilever which is monitored by position sensing using a laser source and a quadrant diode detector. AFM allow user to scan X, Y, and Z directions creating a topographical picture of the surface. However, the problem with AFM is that it is considered destructive due to the contact mode between the tip and the surface while operation. Contact metrology is not ideal for manufacturing due to the damage that can create to the surface. Also, if the pattern structure has high aspect ratio profile, the triangular tip needs to be longer to allow a full scan. Depending on the tip characteristics,


the AFM provides its limits of how deep the aspect ratio can be to obtain good results. Most tips are triangular, but the triangular shape limits how deep the scan can be depending on the feature size of the surface. A solution to this problem is fabricating GaN tips with high-aspect ratios to increase the depth of the scan and increase mechanical properties of the tip\textsuperscript{18-19}. Even though AFM is a great tool for characterization of nano scale surfaces, it is not the ideal for high throughput nanomanufacturing due to destructive contact while scanning. Also, its resolution it is limited by the speed at which the characterization process is occurring reducing its resolution at high speed. AFM does not offer large coverage across the length of the web and it is not stable due with vibration while fabrication.

1.2.2 Scanning Electron Microscopy

Scanning Electron Microscope (SEM) is a metrology tool that scans a focused electron beam over a surface to create an image\textsuperscript{20}. Scanning electron microscope was first unveiled in 1926 when Hans Busch demonstrated that charged particles can be bent in a magnetic field as glass lenses bend visible light\textsuperscript{21}. The first scanning electron microscope was developed by Manfred Von Ardenne in 1938 with a resolution of 8,000X with beam diameter of \( \sim 10 \) nm\textsuperscript{21}. Figure 3 represents the structure of a SEM\textsuperscript{22}. 


Differently than AFM, SEM is considered a non-destructive metrology tool. However, if side-view image is desired, cleaving the surface is required which is considered destructive to the sample. SEM allows user to see real-time cross section view of the surface given more freedom to analyze the sample faster than AFM. Due to the need of vacuum conditions, SEM cannot be implemented on real-time fabrication which makes it a great tool for characterization, but not suitable for R2R and nano-imprint nanomanufacturing.

Figure 3 Schematic of a SEM [Reference 25]
1.2.3 Scatterometry

Scatterometry is an optical metrology tool used for characterization on periodically patterned nanostructures. Scatterometry collects 0th order reflection as a function of angular range or wavelength. There are two different types of scatterometer: angular and ellipsometric. Both types are based on diffraction from periodic structures. Scatterometry is a new technology having its first appearance in 1995 when Dr. Raymond et al. at The University of New Mexico using a He-Ne laser proved to measure sub-500 nm periodic structures by angular variation of reflectance. In July 1999, Dr. Naqvi et. al. measured sub-250 nm pattern structures using 632 nm He-Ne laser; the results were analyzed and compared with SEM demonstrating the capabilities of off-line scatterometry. Scatterometry is one of the most effective solution for nano-manufacturing of photonics components and offers metrology solutions to the current 10 nm node fabrication size.

1.2.3.1 Ellipsometric Scatterometry

Ellipsometric Scatterometry is non-destructive characterization tool that measures reflection as function of wavelength at a fixed angle. For ellipsometric scatterometry, the angle is usually around ~65° degrees and the wavelength is varied using an incoherent source. However, ellipsometric scatterometry requires a more detailed understanding of the optical properties of the surface scanned than optical angular scatterometry. Also, it requires longer period scanning time for measurements to be completed due to power
density and spot size variation due to wavelength dependence. Ellipsometric Scatterometry has demonstrated capabilities to measure 1D, 2D, and 3D periodic structures. Figure 4 represents the scheme of an ellipsometric scatterometer at a fixed angle of 70°. The Polarizer State Generator (PSG) consist of a linear polarizer, two ferroelectric liquid crystal devices (FLC1/2) and quartz retardation plate (QWP); similarly, the Polarizer State Analyzer (PSA) consist of a linear polarizer, two ferroelectric liquid crystal devices (FLC3/4) and quartz retardation plate (QWP). The wavelength variation is from 425 nm to 850 nm with four different polarization states.

Ellipsometric Scatterometry is a great tool for at-line application where the fabrication stage stops and provides static conditions for the scan. Even though it is more sensitive than angular scatterometry, it cannot be implemented on-line on a high-speed fabrication

Figure 4 Schematic of an Ellipsometric Scatterometer. [Reference 29]
system due to the scanning time delay and it requires a full stop of the web to complete the measurement. Also, it requires long period of time to characterize a full wafer.

1.2.3.2 Angular Scatterometry

Angular Scatterometry is non-destructive characterization tool that measures $0^{th}$ order reflection as function of angle$^{32}$. The system consists of two rotation stages where the speeds of the stages are adjusted such the $0^{th}$ order reflection stays focused at the detector as the angle of incidence is varied. Angular scatterometry uses a single wavelength laser source. The angular range varies from $8^\circ$ to $80^\circ$ and it takes >1 minutes for the full scan to be completed. The smallest angle that can detected (reflection) without blocking the beam path with the detector is $8^\circ$. At angle larger than $85^\circ$, the reflectivity of any material structure approaches 1 which is not useful for information. The polarization (TE or TM) is

Figure 5 Schematic of an angular Scatterometer. [Reference 34]
selected depending on the sample to be measured. For high reflectivity samples such as wire-grid-polarizer (WGP), the E-field polarization direction and the grating lines are perpendicular to each other; in the other hand, for low reflection samples such as photoresist, the polarization and the grating are parallel. Figure 5 represent the scheme of the angular scatterometer.

Angular Scatterometry is a functional tool for at-line application where the sample stage does not move during the scanning time of the surface. The benefit of angular scatterometry is a faster response than ellipsometric scatterometry since it uses a coherent laser source which offers higher brightness. Angular scatterometry only requires knowledge of the optical properties of the surface at one wavelength which makes the data processing simpler and more reliable. Even though it is less sensitive than ellipsometric scatterometry, it can be better implemented for at-line fabrication systems.

For the off-line angular approach studies by Dr. Zhu that was the precursor to this work, two main samples were used to demonstrate the capabilities. An aluminum Wire-grid-polarizer (WGP) and a resist grating on a polycarbonate substrate made by roll-to-roll (R2R) nano-imprint lithography (NIL). The samples were simulated using rigorous-wave analysis (RCWA). The WGP simulation was completed by using 7 parameters: Pitch ($P$), Bottom Width ($BW$), Top Width ($TW$), Al height ($Al$), Fused Silica undercut ($FS$), Horizontal rounding ($HR$) and Vertical rounding ($VR$) and an Al$_2$O$_3$ layer that forms over the Al on exposure to air ($AlO$) (see Figure 6). Meanwhile, the resist structures were
simulated using 5 parameters: Pitch ($P$), Bottom Width ($BW$), Top Width ($TW$), Resist Height ($H$) and Residual layer Thickness ($RT$) (see Figure 7). An automatic fitting process was run to find the minimum RMSE between the measurement and the simulation to obtain the best fitting results.

Four different laser sources were used: 244 nm (doubled Ar-ion laser); 405 nm (multimode diode laser); 633 nm (He-Ne laser), and 982 nm (diode laser). The angles measured ranged from $8^\circ$ to $80^\circ$ for the two perpendicular conditions, as mentioned above (TM polarization with vertical grating and TE polarization with horizontal grating)\textsuperscript{44}.
Figure 8 and 9 represent the fitting results of 405 nm TE and TM for the WGP and resist grating structures. Clearly, off-line angular scatterometry was very capable of

Figure 6 Structure definition for the resist grating. [Reference 34].

Figure 7 Structure definition for WGP. [Reference 34].
characterizing metal and resist structures. WGP are highly refractive when the polarization direction is parallel to the metal wires and highly transmissive when the polarization direction is perpendicular to the metal wires; about 90% of the energy is reflected when the polarization is perpendicular to the grating structures\textsuperscript{44}. Therefore, all WGP measurements were performed by having the polarization perpendicular to the grating structures. When the grating directions were perpendicular to the polarization direction for transparent resist grating, strong Fabry-Perot effects were observed in reflectivity measurements. Therefore, for transparent substrate resist grating, measurements were obtained by having polarization direction parallel to the grating directions.

The system offered good fitting and great angular range. The results of off-line angular scatterometry are comparable to AFM and SEM. The angular range was significantly high ($\sim 80^\circ$). Off-line angular scatterometry provides information on the thin layers under the patterned structures for which SEM and AFM are not suitable. However, a scan for off-line tool takes approximately 2 minutes. The rotation of the sample during scanning makes the off-line system incapable scan during real-time fabrication; therefore, it cannot be implemented on nano-manufacturing systems.
Introduction

Figure 8 WGP Fitting results for 405 nm measurements: (a) TM polarization with vertical grating, (b) TE polarization with horizontal grating [Reference 87].

Figure 9 Resist grating fitting results of resist grating for 405 nm measurements: (a) TM polarization with horizontal grating, (b) TE polarization with vertical grating [Reference 87].

1.2.3.2.1 Introduction to RCWA Code

The simulation method used for this research is Rigorous Coupled-Wave Analysis (RCWA). RCWA was first introduced by Moharam and Gaylord in 1981\textsuperscript{34}. RCWA provides a direct solution for Maxwell’s equation for the reflection and diffraction of a grating structure. It has two fields with many different orders above and below a
homogeneous layer or grating that can be described by a Floquet expansion\textsuperscript{44}.

The Fourier expansion of a unit cell of the thin layer can be described with the following equation: 
\[ F(K) = \int_{c_1}^{c_2} \varepsilon_1 e^{-iKx} dx + \int_{c_2}^{c_1} \varepsilon_2 e^{-iKx} dx + \int_{c_2}^{p} \varepsilon_1 e^{-iKx} dx \]

\( \varepsilon_1 \) and \( \varepsilon_2 \) are the permittivity of the grating material and the medium, \( p \) is the pitch of the grating structure; \( K \) is a continuous variable for a periodic structure evaluate at \( n \frac{2\pi}{p} \) (\( n \) is from 0 to m-1 where m is the number of modes need to be considered in RCWA). As it is very clear that \( p = c_1 + c_2 \), the expansion in (3.1) can be simplified to 
\[ F = \sum_{n=0}^{m-1} F(n) = \frac{i(\varepsilon_1 - \varepsilon_2)}{2\pi n} (e^{Kc_1} - e^{Kc_2}). \]

RCWA solves the eigenvalue problems using the Fourier expansion for each thin layer and can obtain the solution in a matrix form. From there, the total reflection, \( R \), and total transmission, \( T \), can be calculated, and the absorption is equal to \( 1-R-T \)\textsuperscript{44}.

\section*{1.4 Outline of the Dissertation}

This dissertation consists of 6 chapters. Chapter 1 is an introduction to the fundamental metrology and manufacturing metrology systems including: AFM, SEM and Scatterometry. In chapter one includes the comparison of all metrology tools; as well as, pros and cons within those systems.

Chapter 2 describes the first in-line set up system used to prove the high-speed scanning concept. 90° off-axis parabolic mirrors were used to demonstrate an in-line design that proved the concept of high-speed scanning for R2R and Nano-imprint fabrication systems. Calibration, high-speed detection and beam profile are discussed. Limits of the
90° off-axis parabolic mirrors and possible configurations to increase angular range are discussed in this chapter.

Chapter 3 describes an in-line scatterometer design that can be implemented on a R2R and nano-imprint fabrication system. We show the use of 45° off-axis parabolic mirrors to increase the scanning angular range. We discuss the increase of resonant frequency to reduce the scanning time. We cover the angular limitations of 45° parabolic mirrors. Last, this chapter covers the beam profile across the scatterometry system.

Chapter 4 describes the fabrication of all samples used to demonstrate the in-line scatterometer. This chapter covers the fabrication of the flat thin film, 1D undercut, and 2D silicon tube samples. Interferometric lithography and nano-imprint lithography are introduced to explain the fabrication process of 1D and 2D pattern structures.

Chapter 5 presents the results and comparison of different metrology tools. For flat surfaces, we compare ellipsometry, off-line scatterometry, in-line scatterometry, and thin layer simulation. For 1D undercut aluminum wall and 2D silicon nanotubes, we compare off-line angular scatterometry and in-line angular scatterometry (2.5 kHz and 8 kHz) with SEM imaging.

Chapter 6 summarizes the previous 5 chapters and describes future work.
2 In-line Angular 2.5 kHz Scatterometry

This chapter will cover the transition between off-line angular scatterometry to in-line angular scatterometry. As mentioned in chapter 1 there is an urgent need for metrology tools that can handle high-speed, non-contact, non-destructive conditions during real-time nanofabrication. The idea behind angular scatterometry is to collect the $0^{th}$ order reflection as a function of angle. Current off-line metrology system can operate by moving the sample, but those designs cannot be implemented during R2R and Nano-imprint fabrication processes. Rather than moving the sample stage, an optical system has been designed to vary the incident angle by moving the incoming beam with optics. In this chapter, we will show an angular high-speed scatterometry design that varies the incident angle by using optics rather a moving the sample stage.

2.1 Design Overview

This design shown in this chapter allows high-speed, non-destructive, non-contact metrology during real-time R2R and Nano-imprint fabrication processes\(^\text{35}\). However, this design is not convenient for large-area nanomanufacturing and needs some improvements for better in-line capabilities (shown on chapter 3). The system collects $0^{th}$ order reflection at 2.5 kHz scanning speed. Figure 10 represents the design of the optical angular scatterometry system. The red and green beam path on figure 10 represent the limits of the angular scan.
The system consists of a 405 nm diode laser, linear polarizer, lenses, parabolic, and flat mirrors. The class 3 diode laser is single transverse mode with an operating voltage of \(~5\) V. The output power is 4.5 mW at an operating current of 29 mA. The beam profile of the laser is elliptical with a total area of \(1.8 \times 3.5\) mm\(^2\). The laser beam is polarized and focused at the resonant scanner using a plano-convex lens with a focal length of 50 cm. The resonant scanner oscillates at a frequency of 2.5 kHz. A second lens collimates the beam before the parabolic mirrors. The parabolic mirrors focus and collect the beam at the moving web. The reflection from the web is collected using a biased silicon blue enhanced photodiode. The 90° off-axis parabolas have a focal length of 10.16 cm which gives a total angular range of the system of \(~30°\) with an initial angle \((\theta_i)\) of \(~29°\) and final angle \((\theta_f)\) of
In-line Angular 2.5 kHz Scatterometry

\[ \sim 59^\circ. \]

The scan speed was design for a web speed of 10 cm/sec. For the resonant scanner at 2.5 kHz, a scan period is 400 \( \mu \)sec. Considering scanning occurs only in one direction of the beam swipe the scan time is 200 \( \mu \)sec which allows us to average up to 5-10 reflectance curves before the web moves a distance comparable to the focal diameter.

The effective NA of the beam is (defined as the ratio of the beam NA to the total optical system NA) \( 8.67 \times 10^{-3} \) with an angular resolution of \( \sim 0.23^\circ \). The number of resolvable points of the system is \( \sim 130 \). A photograph experimental in-line angular 2.5 kHz scatterometer representation is shown on figure 13.

### 2.2 High Speed Detection

A blue enhanced silicon photodiode under reversed biased conditions was used to accomplish the detection. The voltage used to reverse bias the detector is 15V. The active area of the detector is \( 0.81 \times 0.53 \) cm\(^2\). Figure 11 represent the circuit layout of the detector.

The total capacitance \( (C_{\text{total}}) \) was calculated based on the size of the coaxial cables, the internal junction capacitance of the detector, and the capacitance of the oscilloscope. The detector has junction capacitance of \( \sim 100 \) pF at 15 Volts. The coaxial cables were \( \sim 7 \) feet long and the capacitance of the cable \( (C_{\text{coaxial}}) \) is 31 pF/foot. The oscilloscope internal capacitance \( (C_{\text{osc}}) \) is 20 pF. The junction internal capacitance of the photodetector \( (C_{\text{detector}}) \) is \( \sim 100 \) pF.
The total capacitance \( C_{\text{total}} \) of the circuit was calculated to be \( \approx 330 \) pF. The load resistance \( R_{\text{load}} \) is 300 Ω. The bandwidth \( B \) calculated for the detector is 2.05 MHz and a rise time \( \tau \) of 190 nsec (sufficiently fast for the \( \approx 200 \) µsec one reflectivity pulse).

Equation 1 to 3 shows all the calculation done to obtain the rise time needed to detect the reflection signal from the moving web at high-speed.

### 2.3 Calibration

One of the challenges with this design is the number of optical parts which each of them adds losses. Due to the number of optical parts in the setup, a calibration curve is
required\textsuperscript{35}. The collimating lens and the focusing lenses used on the system have a transmission range of \~92-98\% for 405 nm. The polarizer has a transmittance of \~15-22\%.

The reason why the polarizer transmittance is low is because the laser polarization source is oriented at 45° and the linear polarizer is only allowing TE and TM polarization from the laser source. A solution to the low transmission of the polarizer is to use a half-wave plate in order to better control the maximum output power of the laser. The parabolic mirrors have a reflectance range of 96-98\% at 405 nm which is non-negligible angle-dependence reflectance variation. The resonant scanner uses aluminum and dielectric layer as coating to increase reflection, but the reflectance is dependent on the incident angle with a range of \~80-91\%. 
In order to complete the calibration, we used the off-line angular scatterometry system. For off-line angular scatterometry the sample stages rotate. Since the sample stage rotates, all the optical components are all fixed to the movement of the beam. Using the off-line scatterometry system we were able to obtain a calibration constant. A well-defined flat surface was used to calculate the calibration constant. A silicon substrate was cleaned using HF to remove all native oxide and Piranha to remove all organic contamination. Then a 4.9 nm thick layer of alumina was deposited on the silicon wafer. The surface was characterized by using ellipsometry. Equation 4 shows how the calibration constant as a function of angle was calculated.

Figure 12 Calibration Coefficient vs incident angle for TE and TM Polarization.
In-line Angular 2.5 kHz Scatterometry

\[
\frac{I_{\text{off}}}{R_{\text{off}}} (\theta) = C(\theta) \times \frac{I_{\text{in}}}{R_{\text{in}}} (\theta) \quad \text{(Equation 4)}
\]

Figure 13 the in-line and the off-line angular scatterometer with respected incident and reflected beams used in equation 5 [Reference 37].

Figure 12 presents the calibration curves as a function of incident angle for TE and TM polarization. Due to the optical parts on the in-line system, after calculating the calibration curve, the TE and TM in-line experimental signal needs to be multiplied by ~21. Clearly the reflections/transmissions of the optical parts are angular dependent which affect the calibration coefficient. Figure 13 presents a photograph of the in-line and the off-line angular scatterometer with incident and reflected beams used in equation 5.

2.4 Beam Profile

The 405 nm laser beam has an elliptical beam profile of 3.8×1.8 mm² and divergence of 0.8 mrad. The spot size focus at the moving web is in the magnitude of ~220×200 µm².
The focal spot is angular dependent; e.g., the focal spot varies when the beam incident the web at different angles. At 28°, the spot size is $\sim160\times150 \ \mu\text{m}^2$. At 59°, the spot size is $\sim300\times290 \ \mu\text{m}^2$. A Gaussian beam propagation calculation was performed to calculate the spot size. The diode laser has a divergence of 0.8 mRad. The system consists of three plano-convex lenses and two parabolic mirrors. The first lens has a focal length of 50 cm. The following collimating and focusing lenses have a focal length of 15 cm. The Parabolic mirrors have a focal length of 10.16 cm at 45°. Figure 14 represent the beam profile through all the optical components. The focal spot at the moving web is $\sim220\times200 \ \mu\text{m}^2$. The number of resolvable angles is $\sim130$ points (the total system NA divided by the angular beam NA resolution). Spot size was designed to cover many order of the pattern structures. At 200 microns the spot size was able to cover many orders of periodic period when the pitch is around 100 nm. The effective NA is given by the ratio of the beam NA to the overall NA of the optical system. The effective NA of the beam is $8.67\times10^{-3}$ with an angular resolution of $\sim0.26°$. 
Figure 14 Beam profile from laser source through all optical components. Lenses not to scale.

### 3.5 Angular Limits

The limitations of the system are determined by multiple factors. The clearance (distance from reflecting mirror to the moving web) determines how close the system can be located from the moving web without interfering with the fabrication process. The system requires two legs in order to scan TE and TM polarization on high or low reflection surfaces. For example, for wire-grid-polarizers the polarization direction and the grating directions need to be perpendicular from each other. For transparent samples, the polarization and the grating directions need to be parallel from each other. Since two legs are required, the space needs are a challenge which is one of the cons of this design. Figure 15 represent the two-leg angular in-line scatterometry system.
The angular scanning range is dependent on the focal length, off-axis angle, and curvature of the parabolic mirrors. 90° off-axis parabolas angular range can be modified by varying their focal length/curvature, and off-axis angle. The higher the angular range the more points we can extract from the reflection curve (more accurate). For that reason, it is important to increase the angular range as much as possible. However, our system is limited by the clearance (shown on Figure 10). Commercially, there are 2”, 3”, and 4” parabolic mirrors available. What determines the angular range of the system is the focal length of the parabolas. The NA is directly dependent on the curvature, but the greater the curvature

Figure 15 Schematic of two legs angular in-line Scatterometer.
Figure 16 2” parabolic mirrors comparison with different focal length.

Table 1 focal length, working distance, and angular range for 2” 90° parabolic mirrors.

<table>
<thead>
<tr>
<th>Dia. Parabola (“)</th>
<th>Focal length (mm)</th>
<th>Working D. (mm)</th>
<th>$\theta_i$ (°)</th>
<th>$\theta_f$ (°)</th>
<th>$\Delta \theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>50.8</td>
<td>31.8</td>
<td>~9</td>
<td>~67</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>76.2</td>
<td>49.1</td>
<td>~25</td>
<td>~62</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>101.6</td>
<td>68.8</td>
<td>~29</td>
<td>~58</td>
</tr>
</tbody>
</table>

shorter focal depth will be. Figure 16, 17, and 18 represent comparison of 90° of axis parabolas with different focal length for 2”, 3”, and 4” parabolic mirrors. Table 1, 2, 3 show the focal length, clearance, angular range for 2”, 3”, and 4” parabolic mirrors.

Figure 17 3” parabolic mirrors comparison with different focal length.
Table 2 focal length, working distance, and angular range for 3” 90° parabolic mirrors.

<table>
<thead>
<tr>
<th>Dia. Parabola (&quot;)</th>
<th>Focal length (mm)</th>
<th>Working D. (mm)</th>
<th>$\theta_i$ (°)</th>
<th>$\theta_f$ (°)</th>
<th>$\Delta \theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>50.8</td>
<td>25.5</td>
<td>~17</td>
<td>~76</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>76.2</td>
<td>46.5</td>
<td>~8</td>
<td>~68</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>101.6</td>
<td>64.4</td>
<td>~21</td>
<td>~64</td>
</tr>
</tbody>
</table>

Figure 18 4” parabolic mirrors comparison with different focal length.

Table 3 focal length, working distance, and angular range for 4” 90° parabolic mirrors

<table>
<thead>
<tr>
<th>Dia. Parabola (&quot;)</th>
<th>Focal length (mm)</th>
<th>Working D. (mm)</th>
<th>$\theta_i$ (°)</th>
<th>$\theta_f$ (°)</th>
<th>$\Delta \theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4</td>
<td>101.6</td>
<td>61.8</td>
<td>~8</td>
<td>~68</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>152.4</td>
<td>97.8</td>
<td>~24</td>
<td>~62</td>
</tr>
</tbody>
</table>

Even though a large angular range can obtain using 90° off-axis parabolic mirrors, the system will not have enough room to have a clear beam path without interfering the
fabrication process. The parabolas might have large angular ranges but not all of them can be implemented due to the clearance of the system. The minimum clearance allowed is 5 mm. The web has a vertical displacement which limits how close the mirrors can be from it. However, the symmetry of both parabolic mirrors to the focal spot will determine the initial and the final angle. Therefore, we can vary the incident angle and utilize the full angular range of the parabolas. Figure 19 demonstrates how by varying the symmetry of the parabolic mirrors to the focal spot vary the initial and final angle.

Therefore, the small angles are controlled by how close the two parabolas are to each other and the large angles are controlled by how close the parabolas are located from the web. The initial contact angle and the final contact angle can be tailored as desired by symmetrically tilting both parabolic mirrors shown in figure 19. In order to increase the angular range, it is recommended to increase the size of the parabolic mirrors. However, the shorter the focal length, the greater the curvature will be and the shorter the focal depth will be respectively. Table 4 represent the initial, final, angular range, clearance and focal length as a function of tilting angle.
Figure 19 Tilting 5° and 10° symmetrically the parabolic mirrors to control $\theta_i$ and $\theta_f$.

Table 4 angular range, clearance, and focal length for 3” symmetrically tilted.

<table>
<thead>
<tr>
<th>Tilt (°)</th>
<th>Focal length (mm)</th>
<th>Clearance (mm)</th>
<th>$\theta_i$ (°)</th>
<th>$\theta_f$ (°)</th>
<th>$\Delta \theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>76.2</td>
<td>5</td>
<td>~36</td>
<td>~66</td>
<td>~30</td>
</tr>
<tr>
<td>5</td>
<td>76.2</td>
<td>5</td>
<td>~13</td>
<td>~63</td>
<td>~50</td>
</tr>
<tr>
<td>10</td>
<td>76.2</td>
<td>5</td>
<td>~2</td>
<td>~58</td>
<td>~56</td>
</tr>
</tbody>
</table>

The off-axis angle, the size and the focal length of the parabola can be adjusted to increase the angular range of the system, but the problem is that those parabolas are custom made which increases the price exponentially. Figure 20 represent a custom-made parabola with shorter focal (5.61 cm) length and different off-axis angle (80°). The angular range
In-line Angular 2.5 kHz Scatterometry

achieve with this configuration is 55° with an $\theta_i = 5^\circ$ and $\theta_f = 60^\circ$. Another example of a custom-made parabola is presented on figure 21 where the diameter of the parabola is 3” with an off-axis angle of 80° and focal length of 8.78 cm. The angular range achieve with this configuration is 60° with an $\theta_i = 2.5^\circ$ and $\theta_f = 62.5^\circ$. For both figure 20 and 21, the parabolas will need to be cut so they can be physically located next to each other without overlapping.

![Figure 20 Custom 2” parabolic mirror. Focal length of 5.61 cm and off-axis angle of 80°. Overlap area in between the parabolic mirror need to be custom cut to ensure that they don’t interfere with each other.](image)

In conclusion, an angular scatterometer can be designed using 90° off-axis parabolic mirrors. The angular range of the scan can be adjusted by modifying the focal length. The
clearance can be adjusted by varying the off-axis degree of the parabolic mirror. The angular range achieved using 2” parabolas was ~30°, but it can be expanded up to ~60° with the mentioned modifications. Even though this system can be implemented on a moving web, it is not ideal due to all the constraints mentioned on this chapter. The first in-line design was more appropriate to prove the concept of real-time angular scatterometry using parabolic mirrors and resonant scanner. For research application was ideal, but it has many conditions to satisfy to properly apply it during real-time R2R and Nano-imprint nanofabrication. Therefore, a better approach can be implemented on in-line R2R and Nano-imprint fabrication by using different parabolic mirror. Instead of bringing the beam from the bottom of the parabola, we can use 45° off-axis parabolic mirrors which will allow the beam path to come from the side. In the next chapter, we will be discussing a new approach using ~45° parabolic mirrors that avoids the clearance issue between the moving web and the mirrors.
Figure 21 Custom 3” parabolic mirror. Focal length of 8.78 cm and off-axis angle of 80°.
3 In-line Angular Scatterometry for R2R and Nano-imprint fabrication

A 45° off-axis parabolic mirror can offer greater angular range and simplify the system configuration for metrology scanning during real-time nanofabrication systems. This chapter focuses on an alternative design that solves the problem of the clearance shown in the previous chapter by using 4” (commercially available) parabolic mirrors. The optical path has been modified to reduce clearance issues. Larger optical parts have been purchased to increase the angular range. The new in-line scatterometer is suspended on top of the moving web. The new design allows the scatterometer to move across the web to scan multiple points across the web. The speed of the system has been improved by increasing the resonant frequency to 8 kHz. New design ensures the freedom of multi-axis movement for all optical parts. All optical parts will have tilt, tip, rotation, and translation stages for ensuring precision during the alignment. Since the system is suspended on top of the moving web, over 20 custom made machined parts have been fabricated to ensure the positioning of all optical parts. The new design also saves space by having both legs parallel to each other everywhere except at the web. This chapter will focus on explaining the new in-line angular scatterometry design including the necessary engineering compromises.
3 In-line Angular Scatterometry for R2R and Nano-imprint fabrication

3.1 Design Overview

The design shown in this chapter is an improvement of the previous in-line angular scatterometer. Using 45° off-axis parabolic mirrors the in-line angular scatterometer can be better suited to R2R and Nano-imprint real-time fabrication. Fundamentally, the new in-line scatterometer has the same optical approach. The 0th order reflection is collected as a function of incident angle. Figure 22 represent the new approach using 45° off-axis parabolic mirrors.

Figure 22 New in-line angular scatterometer using 45° off-axis parabolic mirrors.

The system uses a 405 nm diode laser (same as last chapter). The output power of the
laser is 4.5 mW, with an operating current of ~5 V. The low-cost diode laser is single transverse mode with a FWHM of is ~2.8 nm (characterized using a spectrometer). The polarizer is the same as used in the last chapter. The idea is to polarize the incoming laser (405 nm diode laser) beam to TE and TM polarization with respect of the pattern structures.

Figure 23 a) top view b) side view of new in-line angular scatterometer using 45° off-axis parabolic mirrors.

All lenses have been modified since the optical system required a larger scanning angle
and within a limited space. The current scatterometer presented on this chapter is planned to be implemented on a nano-imprint fabrication system design by Emerson & Renwick. The tool will be located at the University of Texas – Austin as part of the NASCENT center.

The first lens with 40 cm focal length focuses the incoming laser beam (3.8×1.8 mm^2) to the moving resonant scanner. The new 8 kHz scanner has an angular span of ~20° degrees. In order to fully use the swipe of the beam from the scanner, we use a 100 mm collimating lens with focal length of 30 cm. The beam is collimated by the second and is routed to the parabolic mirror using a set of flat mirrors.

Figure 23 represent a) top and b) side view of the new in-line angular scatterometry system using 45° off-axis parabolic mirrors. The parabolas are 101.6 mm in diameter and have a focal length of 11.9 cm with an angular range of ~50° from $\theta_i = -17^\circ$ to $\theta_f = -67^\circ$. At 45 degrees, the focal spot at the moving web is $\sim 125 \times 120$ µm^2. Similarly, the focal spot size at the web is dependent on the incident angle. At 17°, The focal spot size is $\sim 85 \times 70$ µm^2. At 67°, The focal spot size is $\sim 200 \times 190$ µm^2.
The reflected beam is monitored by a silicon PIN photodiode. The scan period is 125 µs, which will allow us to scan 20-30 reflectance measurements before the web moves cm/sec before the web moves a distance comparable to the focal spot. Figure 24 represents the actual setup mounted on the optical table.

### 3.2 High Speed Detection

A commercial SD-244-44 low-cost silicon detector photodiode is used for the detection of the reflected signal. The silicon detector is sensitive from 350 nm to 1100 nm wavelength range\textsuperscript{36}. The photodiode is reversed bias with a 10 V battery. The active area
3 In-line Angular Scatterometry for R2R and Nano-imprint fabrication

is 13 mm$^2$. The responsivity of the detector at 405 nm is \(\sim 0.12 \, \text{A/W}\). The scope trace is shown in the figure 25. Demonstrating the high-speed detection. Each section of this trace corresponds to a full \((19^\circ \text{ to } 68^\circ)\); the two sections correspond to a full oscillation of the mirror.

![Figure 25 Scope Ray tracing demonstrating detection speed.](image)

3.3 Beam Profile

In this chapter, we cover the beam profile of the system. The 405 nm diode laser is identical to the laser source of the previous system. The beam profile is elliptical with 3.8×1.8 mm$^2$ and divergence of 0.8 mrad. The first lens \((f=40 \, \text{cm})\) focuses the incoming beam to the surface of the resonant scanner mirror. The second lens has a focal length of 30 cm and collimates the reflected beam from the resonant scanner.
The parabolic mirrors have a focal length of 11.9 cm. The beam goes through a system of flat mirrors before impacting on the parabolic mirrors. Figure 25 presents the beam profile through all optical parts. The beam is reduced from 3.8×1.8 mm² to 0.319×0.317 mm² at the resonant scanner. The number of resolvable angles is ~330 given by the ratio of the beam NA to the overall NA of the optical system. The effective NA of the beam is $3.14 \times 10^{-3}$ with an angular resolution of ~0.16°.

![Figure 25 a) top view b) side view of new in-line angular scatterometer using 45° off-axis parabolic mirrors.](image)

**3.4 Calibration**

The in-line 8.0 kHz scatterometer requires a calibration curve due to the optical losses in the various optical components. Due to the addition of more optical components compared to the last 2.5 kHz scatterometer, the calibration curve is going to experience
greater losses. The laser source is located at 45°-degree angle. The polarizer has a low transmission since the position of the laser source. However, a half-wave plate can be added to use the full intensity of the laser and increase the beam power. The flat mirrors used to control the beam path have reflectance greater than 90% for all of them. All flat mirrors are coated with an aluminum thin layer. The flat mirror #1 has a reflectance of 91.24% experimentally (nominal reflectance at 405 nm is 92.4%). The flat mirror #2 has a reflectance of 97.93% experimentally (nominal reflectance at 405 nm is >90%). Flat mirror #3 has a reflectance of 93.31% experimentally (nominal reflectance at 405 nm is >90%).

For flat mirror #1, the incident angle is ~67.5° which for both TE and TM polarization represent a greater reflection. Flat mirror #2 has an incident angle of ~22.5° which is slightly lower reflectance. For static system, this reflectance difference can be negligible, but for our in-line scatterometer it will modify the calibration coefficient curve affecting the calibration process.

The optical system includes of three lenses. The first lens (f=400.0 mm) focuses the beam to moving resonant scanner. The transmittance of the first lens 84.90% at 405 nm experimentally (nominal transmittance at 580 nm is >90%). Also, the system uses a set of two identical lenses (f=300.0 mm) to collimate and focus the beam to the detector. These lenses have a transmittance of 90.63% experimentally (nominal transmittance at 580 nm is 97%). Finally, the parabolic mirrors have a reflectance range of 85-90% experimentally (nominal reflectance at 405 nm >85%). Considering all the losses of all the optical design,
we measured the calibration coefficient.

In order to evaluate the calibration, we used the off-line angular scatterometry system. For off-line angular scatterometry the sample stages rotate. Since the sample stage rotates, all the optical components are all fixed to the movement of the beam. Using the off-line scatterometry system we were able to obtain a calibration constant. A well-defined flat surface was used to calculate the calibration constant. A silicon substrate was cleaned using HF to remove all native oxide and Piranha to remove all organic contamination. Then a 4.9 nm thick layer of alumina was deposited on the silicon wafer. The surface was characterized by using ellipsometry\textsuperscript{35}. Equation 6 shows how the calibration constant as a function of angle was calculated.

\[
\frac{I_{\text{off}}}{R_{\text{off}}} (\theta) = C(\theta) \times \frac{I_{\text{in}}}{R_{\text{in}}} (\theta) \quad \text{(Equation 5)}
\]
Figure 26 present the calibration curve as a function of incident angle for TE and TM polarization. A calibration curve for TE and TM was calculated to calibrate the experimental results of the in-line angular 8.0 kHz scatterometer. The TE and TM in-line experimental signal needs to be multiplied by ~400. Clearly the reflection is dependent on the incident angle \(^{35}\). The peaks can be related to contamination on the optics.

### 3.5 Angular Limits

The limits of the system are determined by how close the parabolic mirrors are from the moving web. The 45° off-axis parabolic mirrors facilitate having the beam path come
3 In-line Angular Scatterometry for R2R and Nano-imprint fabrication

from the side of the parabolic mirrors eliminating the flat mirrors near the web in the previous design. The new in-line angular design allows us to position both legs parallel to each other which helps to reduce the space usage. Figure 27 presents the two-leg system design. Figure 28 presents the top view of the two-leg in-line scatterometer.

Figure 27 Two-leg in-line angular scatterometry system using 45° off-axis

The angular range of the system can be increased by decreasing the focal length of the parabolic mirrors. However, the smaller the focal length of the parabolic mirror, the closer the system will be located to the moving web (fabrication process). The angular range of the 45° off-axis parabolic mirrors can be expanded up to ~70° with $\theta_i = \sim10^\circ$ to $\theta_f = \sim80^\circ$. Figure 29 presents a 45° off-axis custom-made parabolic mirror with a focal length of 7.9 cm.
The distance from the parabolic mirrors and moving web is 5 mm. During a web operation, the typical vertical web movement due to vibration is specified as <1 mm. Also, the initial and the final angle can be varied by symmetrically tilting both parabolas. Another factor that limits the increase of the angular range of the parabolas are the center flat mirrors. The current set up uses 3 mm wide aluminum coated flat mirrors. If the custom-made parabolas are used, the space between to redirect the beam reduces. Therefore, smaller flat mirrors are needed due to the reduction of the space. The width of the flat mirror for the custom-made parabolas with 70° angular range will need to be ~1 mm due to the space constraints. As importantly the mirrors arrangement becomes more difficult to accommodate.
Figure 29 a) commercially available (currently used on system) and b) Custom-made 45° off-axis parabolic mirror with an angular range of 50° and 70°, respectively.

3.6 Full Design and Custom Parts

Tip, tilt, translation and rotation stages have been added to each optical component to allow alignment of the overall system (see appendix A for details). Since the system is not allowed to interfere with the moving web, many challenges have been part of the overall design. The space constraints was the number one concern when designing the in-line scatterometer. In order to combine different independent stages to each individual optical part, custom-made aluminum stages were machined to allow proper alignment of the overall scatterometer. The custom-made stages were black anodized to avoid reflection from the aluminum 6061. Aluminum is a great material for opto-mechanical components; it is light in weight and easy to customize, but it has a much larger thermal expansion than...
steel. Even though aluminum is more expensive than steel, it is better for custom machining and it is lighter. The less zinc it contains, the softer and easier the aluminum is to work during machining. Aluminum 6061 was selected since it offers superior welding and workability, yet it offers high strength and stress resistance. Figure 30 presents the overall one-leg system design including all independent stages for each optical component. Figure 31 presents the overall two-leg system design including all independent stages for each optical component. The length, width and height of the system are respectively ~1 m, 0.4 m, and 0.9 m. The total volume required for the system to suspend over the moving web is ~0.36 m³. A dual optical breadboard floor system is needed to hold all optical components.

Figure 30 one-leg system design with all independent stages for each optical component.
In conclusion, this chapter covered the in-line angular scatterometry design using 45° off-axis parabolic mirrors. The angular scan of the system is ~50° with the possibility of future expansion to ~70°. The 8 kHz resonant scanner allows us to obtain the reflectivity curve when the moving web at 125 µsec period. The elliptical laser profiles (3.8×1.8 mm²) gets focused at the moving web. The system has multiple custom-made aluminum stages to ensure proper alignment. The volume of the full system is ~0.36 m³. Clearly, this new design is an improved concept from the chapter 2 design. It allows us to obtain a greater angular range with less room to interfere the moving fabrication web. However, the usage of bigger optical components reduces the focal depth requiring a more precise alignment.
4. Sample Preparation

Total of 4 samples were used to demonstrate the in-line angular scatterometry capabilities. All sample were silicon wafers with thin films on Silicon wafers, 1-dimensional pattern structures (1D), and 2-dimensional (2D) complex pattern structures. All samples were used on off-line and both in-line scatterometers. The samples were fabricated by using thermal oxidation, interferometric lithography (IL), and Nano-imprint lithography (NIL). Thin films were fabricated and characterized using ellipsometry. Also, a thin film calculation was used to compare with our experimental off-line, and in-line results. The experimental results and the simulation were fitted for the lowest Root Mean Square Error (RMSE). All patterned structures were compared by using SEM characterization, off-line angular scatterometry, in-line 2.5 kHz scatterometer, and in-line 8.0 kHz scatterometer.

4.1 Thin Film Samples

In-line metrology is a great area of interest for thin film printing. For instance, thin film transistors (TFT) are currently being printed by using a combination of Roll-to-roll (R2R) gravure and inkjet. There is interest in high volume R2R manufacturing at the nanoscale for emerging nano applications. Therefore, our in-line scatterometer is a solution for monitoring and quality control during real-time R2R thin film fabrication. In order to demonstrate the capabilities of our in-line scatterometer on flat surfaces, we
characterized two thin film samples.

4.1.1 Silicon Wafers with Native Oxide and ~100 nm SiO₂ Overlayer

One of the samples was a silicon substrate with a thin layer ~0.5 nm of native oxide. The other sample was a (commercially available) J.A. Woollam silicon wafer with ~115 nm SiO₂ layer. Both samples were analyzed and characterized by using ellipsometry. Native and thermally grown oxide optical properties were used accordingly for proper simulation. Then compared to our off-line and in-line fitted results.

4.2 1D Undercut Nanoscale Al Lines on Silicon Wafer

Like thin film R2R gravure fabrication, there is an evident interest on in-line metrology for R2R and NIL manufacturing during real-time fabrication. For example, Wire-grid-polarizers (WGP) are fabricated by using NIL systems. WGP are widely used in many optical applications including LCD displays. Also, flexible substrate sub-100 nm patterned structures are being fabricated using R2R systems. Both structures fabricated by NIL and R2R are 1D structures; therefore, we use 1D patterned undercut nanoscale aluminum lines to demonstrate the measurements capabilities of our scanning system.

4.2.1 Introduction to Interferometric Lithography (IL)

Our 1D undercut nanoscale Al lines were fabricated by using interferometric lithography. Interferometric lithography is fast, low-cost (inexpensive), with large area
4. Sample Preparation

capabilities, simple, and powerful technique to fabricated periodic patterned structures\textsuperscript{42-43}. The use of two coherent light beams interfere with each other at the interference plane where a photoresist spin-coated sample (photoresist sensitive to the wavelength of the coherent beam) is located. The periodic patterned smallest feature size \((p)\) can be calculated by \(p=\lambda/2\), and \(\lambda\) is the coherent wavelength laser source. The smaller the laser beam the smaller the fabrication limits. Figure 32 represent IL interferometer arrangement.

![Image](image)

Figure 32 IL scheme. Interferometer geometries for IL [Reference 89]

IL is simple, inexpensive, and flexible fabrication approach that can fabricate 1D, 2D, and 3D periodic patterned structures. Compared to e-beam lithography and ion-lithography, IL offer a greater fabrication area at dramatically decrease the cost and increase the fabrication area. The fabrication resolution of the system can be reduced by either varying the wavelength of coherent laser source or increasing the index of refection of the medium in on top of the photoresist\textsuperscript{44}. The technique is called immersion Interferometric
Lithography (IIL). Water, for example at 193 nm, has an index of 1.44 allowing to accomplish smaller period fabrication. For IL, the grating structures are formed by the standing waves with sine square functions. The intensities, to achieve best results, need to have equal amplitudes. The representation of the intensity at the planes of incident is $I(x) = 4I_0 \cos^2(ksin(\theta)x)$ where k is the photon wave vector, $\theta$ is the incident angle, and x is the position of the sample. $n\lambda = 2p \sin \theta$ can be used to calculate the incident contact angle as a function pitch.

Our IL system uses a 355-nm frequency tripled YAG Laser (Coherent Model Infinity 40-100) to fabricate periodic structures. Due to the medium (air n=1) and the wavelength (355 nm). The smallest feature size that can be accomplished is $p=\sim177$ nm. Same system was used to fabricate our 1D undercut nanoscale aluminum lines.

4.2.2.2 Fabrication Process

The 1D undercut nanoscale Al lines on silicon were fabricated by the following procedure. The substrate is silicon which was cleaned by using acetone, methanol, and isopropyl. A layer of antireflective coating (BARC), and a layer negative of photoresist is deposit by spinning. The BARC ICON 16 layer was spin at 3000 rpm for 30 seconds. The BARC layer was baked at 190 °C for 60 seconds which resulted on a thickness of $\sim160$ nm. A similar process was done for the negative photoresist (NR7-500). The photoresist layer was spin at 3000 rpm for 30 seconds with a soft bake of 150 °C for 60 seconds to obtain a layer $\sim500$ nm thick. The sample was exposed to 355-nm frequency tripled YAG
coherent laser for 8 seconds to obtain a sample period of ~500 nm. The total exposure dose was ~115 mJ/cm$^3$. The sample was developed using MF-321 developer for a total time of 20 seconds.

The photoresist patterned sample (after IL) was subject to a metallization by evaporating aluminum on the top of the surface. An ~85 nm layer of aluminum was deposited on the photoresist patterned sample at a chamber pressure of 2×10$^{-6}$ Torr, followed by a lift-off process. The sample was etched to remove the exposed BARC ICON 16 layer with O$_2$ plasma reactive ion etching (RIE). The etching time was 90 seconds. The roughing pressure, RF power level, plasma power, and gas flow rate at 15 mT, 100 W, 300 W, and 21 sccm, respectively. The pitch was ~500 nm, the Aluminum wall are ~344 nm wide, the BARC ICON 16 layer is 150 nm, the thickness of the aluminum is 91 nm, and the undercut BARC ICON 16-layer is 140 nm wide. Samples were fabricated in collaboration with Vineeth Sasidharan.

4.3 2D Silicon Nanotubes on Silicon Wafer

The semiconductor industry is approaching the 5-nm node size. Features such as FinFET are three dimensional and complex requiring knowledge of multiple structural parameters. The complexity of the semiconductor circuits keeps increasing, creating more challenges during the monitoring and metrology of these processes. 3D complexed multi-layer structures are the future of the semiconductor industry. Therefore, it is
4. Sample Preparation

important to test our in-line scatterometry system with complex structures. The final sample used to show the scan capabilities of our system are 2D silicon nanotubes (donuts) on a silicon wafer. The structures were fabricated using nano-imprint lithography with a sub-500 nm pitch.

4.3.1 Introduction to Nano Imprint Lithography (NIL)

Nano-imprint lithography is a nano-scale method of fabrication. It is low-cost, high resolution, and high-throughput. The process consists of creating pattern structures by deformation of resist. The photoresist is cured by using UV light through a transparent silicon mask. The idea of nano-imprint lithography was first introduced during mid-1990s\textsuperscript{47}. There are different types of NIL fabrication processes. The most common are thermal nano-imprint and UV curing nano-imprint. Nano-imprint is a commonly fabrication technique used these days in the semiconductor industry\textsuperscript{48-49}. One of the main advantages of NIL is large-area fabrication. The throughput of NIL is much higher than electron-beam lithography, and ion-beam lithography. The system is capable since the mask is what determine the resolution. The features can be from simple 1D structures to 3D complex multi-layer pattern structures\textsuperscript{50}. NIL has challenges involving: overlay, defects, template patterning, template wear, and mechanical damage\textsuperscript{51-53}. One proposed solution to the challenges is to combine lithography fabrication techniques\textsuperscript{54}.
4. Sample Preparation

The Imprint Imprio-1100 tool (J-FIL) and a serious of fabrication processes were used to fabricate the 2D hollow nanotubes. Figure 33 represent the Jet and flash imprint lithography process [Reference 53]. First, a low viscosity resist is deposited in the substrate with a dispenser. Then the mask template is lowered onto the surface, so the relief patterns are filled by capillary action. While the mask compressing the resist, UV radiation is applied to cure the resist. The final step is to remove the mask leaving the desired patterned structures.

Figure 33 J-FIL Lithography Fabrication Steps [Reference 91].

4.2.2 Fabrication Process

The 2D silicon nanotubes on silicon were fabricated using a series of processes including: NIL, atomic layer deposition (ALD), and reactive-ion etching (RIE). Figure 34 presents the fabrication process flow for the 2D hollow silicon nanotubes. The silicon wafer is 4 inches in diameter (~100 mm). Figure 35 shows the final product silicon wafer with the nanotubes. The first step consists of nano-imprinting the photoresist pillars on the silicon wafer. Then, an ALD low temperature of SiO₂ was used to form the side walls. Following this growth, RIE was implemented on the surface to remove the cap and the SiO₂ acted as
4. Sample Preparation

a mask while the silicon was etch away forming the nanotubes \(^{35}\). If silicon nanotubes are desired without the SiO\(_2\) mask, the sample can be dip in buffered oxide etch and piranha for 5 and 20 second respectively to remove the top part of the tubes.

Figure 34 J-FIL Lithography Fabrication Steps [Reference 37].

The pillars are ~200 nm pitch. The SiO\(_2\) layer, the resist layer, and the Si layer are ~30 nm, 35 nm, and 75 nm height, respectively. The outside and inside diameter of the tubes are ~135 nm and ~100 nm\(^{35}\). Figure 36 represents the side view and the top view of the 2D nanopillars with approximate dimensions. All 2D complex nano-tubes were fabricated in by group of Dr. S.V. Sreenivasan at the University of Texas-Austin NASCENT Center.
4. Sample Preparation

Figure 35 The 4” (~100 mm) silicon wafer with 2D hollow nanotubes.

Figure 36 (a) Side view and (b) top view diagram of the 2D nanotubes with approximate dimensions. [Reference 37]
5 Experiments and Results

In this chapter we will cover the sample results from both the 2.5 kHz the 8.0 kHz in-line scatterometers. The samples are thin films, 1-dimensional pattern structures (1D), and 2-dimensional (2D) complex pattern structures. For thin layer samples, ellipsometry was used to characterize the thin layer thickness and compared to the fitted curves from the scatterometer. The experimental results and the simulation were fitted for the lowest Root Mean Square Error (RMSE)\textsuperscript{35}. All patterned structures were compared by using SEM characterization, off-line angular scatterometry\textsuperscript{32}, in-line 2.5 kHz scatterometer\textsuperscript{35}, and in-line 8.0 kHz scatterometer.

5.1 Thin Film Samples

Two silicon substrate samples used. One of them was a standard silicon wafer with a native oxide. The second sample is provided by J.A. Woollam with a thin nominal thermal silicon dioxide layer of \(~116\) nm. Both samples were characterized using multiple metrology systems. First, the samples were characterized by using a J.A. Woollam ellipsometer. The sample was exposed to set of wavelengths from 250 nm to 950 nm at 55\(^\circ\)-75\(^\circ\) angles. The variable angle spectroscopic ellipsometric experimental data was reverse fitted to a B-spline model finding the lowest RMSE. The index of refraction for native and thermally grown oxide was obtain from previous work done by Henzinger et. al.\textsuperscript{38} An off-line scatterometer was also used to characterize the thin films structures.
Scanning from 8° to 80° angle with a 405 nm diode laser source, an experimental TE and TM reflection curves were obtained. The reflection curve was normalized to the input power for later reverse fitting to thin layer calculation using RCWA. In-line 2.5 kHz and 8.0 kHz systems were used to also compared the thin layer samples. The source of the in-line system was a 405 nm diode laser. The normalized TE and TM reflection curves were also reverse fitted to a thin layer calculation. All results were finally compared in a single plot to demonstrate the consistency of the new 2.5 kHz and 8.0 kHz in-line scatterometers.

### 5.1.1 Silicon Wafer with Native Oxide

The thickness of the native oxide on the silicon wafer was unknown. In order to characterize the sample, ellipsometry was used to determine the thickness of the oxide layer. Also, the results from ellipsometer were compared with off-line scatterometry to confirm the oxide layer. Figure 37 and 38 represent the comparison of the ellipsometry results with the TE and TM off-line scatterometer fit. The RMSE calculated from the off-line scatterometer was $8.039 \times 10^{-3}$ for TE and $6.582 \times 10^{-3}$ for TM. For the model on the thin layer calculation using the RCWA, the index of refraction for silicon substrate was $n=5.475$ and $k=-0.36$ at 405 nm wavelength. The index of refraction used for the SiO$_2$ was $n=1.49$ and $k=0$. The thickness calculated by the ellipsometry was 1.36 nm. Meanwhile the thickness calculated by off-line scatterometer for TE is 1.9 nm and TM is 2.2 nm. Both TE and TM experimental reflectivity fitted curves show similar trends with the simulation with the RCWA simulation. Also, the RMSE for both are significantly equal; demonstrating that
off-line results are consistent. The reason why the ellipsometry and the off-line results are slightly different could be due to the result obtain in different spot on the sample showing a slight variation on the thickness. The difference between 1.36 nm and 1.9 nm fit are less than ~1 atom layer.

Figure 37 TE off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE=8.039×10^{-3}. Off-line scatterometer fitted is
1.9 nm. Ellipsometry fitted to 1.36 nm.

Figure 38 TM off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE=6.582×10⁻³. Off-line scatterometer fitted is 2.2 nm. Ellipsometry fitted to 1.36 nm.

The results of the off-line scatterometer and ellipsometer were used to compare with in-line 2.5 kHz and 8.0 kHz scatterometer. For the in-line 2.5 kHz scatterometer, a 405 nm diode laser was used as a source. The angular range of the 2.5 kHz scatterometer is ~27°. For the 2.5 kHz system, the \( \theta_i = -31° \) and the \( \theta_f = -56° \). For 8.0 kHz scatterometer, the same 405 nm diode laser was used as a source. The size of the parabolas are 2 inches bigger; therefore, the angular range is larger. For the 8.0 kHz system, the \( \theta_i = -20° \) and the \( \theta_f = -66° \). For both systems, there is a loss of ~3.5° due to the rise time of the detector. Figure 39 and 40 represent the TE and TM reflectivity for the in-line 2.5 kHz and 8.0 kHz systems; as well as, the simulation of TE and TM reflectivity curves.
**5 Experiments and Results**

Figure 39 TE reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation.

Figure 40 TM reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation.

Table 5 Comparison table of all system fitted results and RMSE for TE Polarization.

<table>
<thead>
<tr>
<th>System</th>
<th>RMSE TE</th>
<th>SiO₂ Fitted Values TE (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipsometer</td>
<td>$5.34 \times 10^{-3}$</td>
<td>1.36 nm</td>
</tr>
</tbody>
</table>
5 Experiments and Results

<table>
<thead>
<tr>
<th>System</th>
<th>RMSE TM</th>
<th>SiO₂ Fitted Values TM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-line Scatterometer</td>
<td>8.04×10⁻³</td>
<td>1.9 nm</td>
</tr>
<tr>
<td>2.5 kHz In-line Scatterometer</td>
<td>2.259×10⁻³</td>
<td>1.35 nm</td>
</tr>
<tr>
<td>8.0 kHz In-line Scatterometer</td>
<td>1.29×10⁻²</td>
<td>1.35 nm</td>
</tr>
</tbody>
</table>

For 2.5 kHz in-line scatterometer, the RMSE = 2.259×10⁻³ for TE and 1.177×10⁻² and the fitted native oxide thickness were ~1.35 nm for TE and 1.30 nm for TM. The ellipsometry fitted value was ~1.36 nm. For the 8.0 kHz in-line scatterometer, the RMSE = 1.29×10⁻² for TE and 1.27×10⁻² and the fitted native oxide thickness were ~1.35 nm for TE and 1.31 nm for TM. Clearly, the results for off-line, and in-line systems are consistent and equal to the ellipsometer measurements. Table 5 and 6 represent all results obtain from all the systems for TE and TM polarization respectably.

Table 6 Comparison table of all system fitted results and RMSE for TM Polarization.

<table>
<thead>
<tr>
<th>System</th>
<th>RMSE TM</th>
<th>SiO₂ Fitted Values TM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipsometer</td>
<td>5.34×10⁻³</td>
<td>1.36 nm</td>
</tr>
<tr>
<td>Off-line Scatterometer</td>
<td>6.58×10⁻³</td>
<td>2.2 nm</td>
</tr>
<tr>
<td>2.5 kHz In-line Scatterometer</td>
<td>1.18×10⁻²</td>
<td>1.30 nm</td>
</tr>
<tr>
<td>8.0 kHz In-line Scatterometer</td>
<td>1.27×10⁻²</td>
<td>1.31 nm</td>
</tr>
</tbody>
</table>
5 Experiments and Results

5.1.2 Silicon Wafer with ~100 nm SiO$_2$ Overlayer

The second thin layer sample used was a commercially available silicon wafer with a thermally grown SiO$_2$ layer. The nominal thermal oxide layer is ~115.8 nm. The nominal value was compared with ellipsometry, off-line scatterometry, in-line scatterometry, and simulation. The simulation was done by a thin layer calculation using RCWA code.

Figure 41 TE off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE=3.908×10$^{-3}$. Off-line scatterometer fit is 114.0 nm. Ellipsometry fitted to 113.98 nm.
Figure 42 TM off-line scatterometry reflectivity curves vs. incident angle from 8° to 80° with thin layer calculation fit. Off-line RMSE= 6.693×10^{-3}. Off-line scatterometer fit is 114.0 nm. Ellipsometry fitted to 113.98 nm.

Figure 41 and 42 represent the TE and TM reflectivity curves vs. incident angle for off-line scatterometry. The thin layer calculation was done by using the RCWA, the index of refraction for silicon substrate was $n=5.475$ and $k=-0.36$ at 405 nm wavelength. The index of refraction used for the thermally grown SiO$_2$ was $n=1.459$ and $k=0$. The thickness calculated by the ellipsometry was 113.98 nm. Meanwhile the thickness calculated by off-line scatterometer for TE is 114.0 nm and TM is 114.0 nm. Both TE and TM fitted values are significantly equal. Also, the RMSE for both are significantly equal; demonstrating that off-line results are consistent.

Figure 43 and 44 represent the TE and TM reflectivity curves for both inline systems: 2.5 kHz and 8.0 kHz and RCWA simulation. For the in-line 2.5 kHz scatterometer, a 405
nm diode laser was used as a source. For 2.5 kHz in-line scatterometer, the RMSE = 3.129×10^{-3} for TE and 3.896×10^{-3} and the fitted native oxide thickness were ~114.4 nm for TE and 113.9 nm for TM. The ellipsometry fitted value was ~113.98 nm. For the 8.0 kHz in-line scatterometer, the RMSE = 8.142×10^{-3} for TE and 6.612×10^{-3} and the fitted native oxide thickness were ~114.8 nm for TE and 114.2 nm for TM. Clearly, the results for off-line, and in-line systems are consistent and equal to the ellipsometer measurements. Table 7 and 8 represent all results obtain from all the systems for TE and TM polarization.

Figure 43 TE reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation.
5 Experiments and Results

Figure 44 TM reflectivity curves vs. incident angle for In-line scatterometer: 2.5 kHz and 8.0 kHz, and simulation.

Table 7 Comparison table of all system fitted results and RMSE for TE Polarization.

<table>
<thead>
<tr>
<th>System</th>
<th>RMSE TE</th>
<th>SiO₂ Fitted Values TE (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipsometer</td>
<td>1.45×10⁻³</td>
<td>114.0 nm</td>
</tr>
<tr>
<td>Off-line Scatterometer</td>
<td>3.91×10⁻³</td>
<td>114.0 nm</td>
</tr>
<tr>
<td>2.5 kHz In-line Scatterometer</td>
<td>3.129×10⁻³</td>
<td>114.4 nm</td>
</tr>
<tr>
<td>8.0 kHz In-line Scatterometer</td>
<td>8.14×10⁻²</td>
<td>114.8 nm</td>
</tr>
</tbody>
</table>

Table 8 Comparison table of all system fitted results and RMSE for TM Polarization.

<table>
<thead>
<tr>
<th>System</th>
<th>RMSE TM</th>
<th>SiO₂ Fitted Values TM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipsometer</td>
<td>1.45×10⁻³</td>
<td>114.0 nm</td>
</tr>
</tbody>
</table>
5 Experiments and Results

<table>
<thead>
<tr>
<th>Off-line Scatterometer</th>
<th>6.69×10⁻³</th>
<th>114.0 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 kHz In-line Scatterometer</td>
<td>3.90×10⁻³</td>
<td>113.9 nm</td>
</tr>
<tr>
<td>8.0 kHz In-line Scatterometer</td>
<td>6.61×10⁻³</td>
<td>114.2 nm</td>
</tr>
</tbody>
</table>

5.2 1D Undercut Nanoscale Al Lines on Silicon Wafer

The third sample used was fabricated by using IL. The substrate is silicon and sample consist of Al lines. The undercut 1D nanoscale Al structures (mushroom) structure is due to the extended reactive ion etching of ICON under the aluminum lines. The structure was used due to its 1D complex mushroom structures to challenge our system. Figure 45 represent the SEM image 40° side view of the undercut 1D Al structure. The thickness of the ICON is ~150 nm high, the width of the ICON is ~140 nm. The period of the pattern structure is ~500 nm with an aluminum layer of ~350 nm width and 90 nm high on top of the ICON.

For this sample, off-line and in-line experimental results were compared. The off-line scatterometer measures a total angular range of 80°. The two in-line systems: 2.5 kHz with an angular range of ~30° and 8.0 kHz with and angular range of ~50°. Figure 46 and 47 represent the TE and TM reflectivity curves versus incident angle. The calibration process for this structure were using the same calibration curves for each 2.5 kHz and 8.0 kHz systems respectively shown previously. Clearly, all experimental curves shown similar
trends demonstrating the high-speed capabilities of the in-line system. For the 8.0 kHz reflectivity curves, there is a slight deviation of the reflectivity at the lower angular range of the angles. There are many reasons why this might occurs: 1) the calibration curve is not properly measured since there is a slight variation on the angle while using the parabolic mirrors, 2) the 4 inches parabolic mirrors add conical diffraction during the measuring process, 3) the polarization orientation is not parallel nor perpendicular from the sample direction, 4) the alignment needs some work, 5) nonuniformities on the pattern structures. Even thought, there is deviation at the two ends of the 8.0 kHz reflectivity curves, the trends are similar and clearly show the high-speed scanning capabilities.

Figure 45 SEM side view of the 1D undercut Al lines [Reference 37]
Figure 46 TE Reflectivity curve vs. incident angle for 1D undercut Al lines.

Figure 47 TM Reflectivity curve vs. incident angle for 1D undercut Al lines.
5.3 2D Silicon Nanotubes on Silicon Wafer

The last sample used was a complex 2D nanotube pattern on a silicon wafer. The reason why this sample was selected is because WGP and MMG are complex metalized structures. The objective of the high-speed system is to scan and characterize WGP and MMG during R2R nano-fabrication. The 2D silicon nanotubes also are sub-200 nm (period). The sample was fabricated with nano-imprint lithography, atomic layer deposition coating, and reactive ion etching (more details in the fabrication chapter). The multi-layer nano-imprinted pattern structures have pillars with a ~30 nm SiO₂, ~35 nm resist layer, and ~75 nm silicon. The 2D tube structure also have a outside diameter of ~135 nm and inside diameter of ~100 nm. Figure 48 represent the SEM side view of the 2D nanotube. The sample was gold flashed to facilitate the SEM characterization. The three layers (SiO₂, photoresist, and etched Si) are clearly identified on the SEM picture.

Figure 48 SEM side view of the 2D nanotube. [Reference 37]
Figure 49 presents the measured reflectivity versus incident angle for TE polarization of 2D nano-tubes off-line, 2.5 kHz in-line, and 8.0 kHz in-line scatterometer. Figure 50 shows the measured reflectivities versus incident angle for TM polarization of 2D nano-tubes off-line, 2.5 kHz in-line, 8.0 kHz inline scatterometer. Clearly, this samples shows more non-uniformities on the surface affecting the reflectivity curve for the 2.5 kHz measurements. The high-speed capabilities have been demonstrated and experimentally proven by using moving resonant scanner. More optimization is required to improve the system, but the non-contact, high-speed, non-destructive scanning capabilities have been demonstrated on this dissertation.

Figure 49 Reflectivity versus incident angle for TE polarization of 2D nano-tubes off-line, 2.5 kHz in-line, and 8.0 kHz in-line scatterometer.
Figure 50 Reflectivity versus incident angle for TM polarization of 2D nano-tubes off-line, 2.5 kHz in-line, and 8.0 kHz in-line scatterometer.
6. Conclusion and Future Work

In this chapter, a summary of all the accomplishments and conclusions are summarized. Also, all future goals and plans are described including short, medium, and long objectives to be completed.

6.1 Conclusion

From chapter 1 to chapter 5, we have explained all the accomplishments during the research process of in-line optical angular scatterometry. Two in-line angular scatterometers have been constructed. Experiment and simulation have shown the in-line, high-speed, non-contact, non-destructive capabilities of our system. Sub-200 nm samples have been measured and characterized. Flat thin layer, 1D mushroom structures, 2D complex structures have been scanned using both in-line scatterometers with comparable results to an at-line scatterometer and to ellipsometer. Clearly, our system promises can characterize thin layers and 1D/2D pattern structures in the real-time nano-manufacturing. Our system also competes with state-of-the-art metrology tools since it can scan real-time, high speed fabrication process. Our current systems have a lot of future providing many options to optimize the all scanning process. Overall we have demonstrated the following points:

- This is the in-line angular scatterometer using an inexpensive diode 405 nm laser. The 405 nm diode laser has elliptical beam profile and offers linear
polarization which allows easy scanning without complex configuration and small space usage. Photoresist and metalize samples have been fully scanned and characterized by using 405 nm wavelength laser source. Differently than ellipsometric scatterometry, our system offers easy modeling using RCWA without varying the optical properties and simplifying the simulation process.

- It has been demonstrated that optical angular scatterometry has enough sensitivity to monitor smaller feature sizes. Previous investigation on the limitation and critical dimensions of optical angular scatterometry have shown promising capabilities to characterize down to 10 nm node structures.

- We also have demonstrated an angular in-line scatterometer that can be used during real-time fabrication. The systems use a 2.5 kHz resonant scanner for high-speed scanning capabilities. We demonstrated a $\Delta \theta = -30^\circ$ with and $\theta_i = -29^\circ$ and $\theta_f = -59^\circ$ and high-speed detection. The system used two inches 90° off-axis parabolic mirrors to optically vary the incident angle instead of moving the sample (moving sample cannot be implemented on real-time fabrication).

- We have demonstrated scanning capabilities with our 2.5 kHz system to obtain and average 5-10 waveforms during the real-time fabrication at a web speed of 10 cm/sec.

- We also have demonstrated the angular limitations of the first scatterometer. We have shown the expansion of the angular range of the 90° off-axis parabolic
mimics by changing the focal length and curvature of the parabolic mirrors. Also, we have discussed the trade-off when using 90° off-axis parabolic mirrors (clearance as the main limitation to achieve scanning across the web). We have shown how to tailor the angular range by symmetrically changing the parabolic mirrors position. Also, we showed the angular and space limitations of the 90° off-axis parabolic mirrors which led us to explore 45° off-axis parabolic mirrors.

- We have demonstrated the calibration and design of the in-line angular scatterometer at 2.5 kHz beam scanning speed over the fabrication process. We fully characterized thin layer, 1D and 2D samples with the first system.
- We demonstrated the Gaussian beam calculation to obtain a focal spot of ~200×220 µm² at the moving web. The optical design, dimensions and position of each part is shown for the first angular 2.5 kHz optical in-line scatterometer.
- For 2.5 kHz scanner, we have demonstrated a scan period of 0.4 msec which can scan fabrication processes with a web speed of 10 cm/sec. Considering scanning occurs only in one direction of the beam swipe the scan time is 0.2 msec which allows us to average up to 5-10 reflectance curves before the web moves a distance comparable of the spot size.
- We have demonstrated an effective NA of the beam ~8.67×10⁻³ with an angular resolution of ~0.23° for the 2.5 kHz in-line scatterometer. The total # of
6. Conclusion and Future Work

resolvable points for the 2.5 kHz system is ~130 points.

- We have demonstrated a second in-line angular optical scatterometer that can
be implemented in real-time nano-manufacturing by using 45° off-axis
parabolic mirrors. The second in-line system uses an 8.0 kHz resonant scanner
with a NA=0.25. Also uses larger (4 inches) parabolic mirrors with higher NA
that allow to increase the angular range from ~30° to ~50°.

- We demonstrated a focal spot at the moving web of ~125×120 µm². The focal
spot size at the web is dependent on the incident angle. At 17°, The focal spot
size is ~85×70 µm². At 67°, the focal spot size is ~185×190 µm².

- We have demonstrated capabilities to scan a moving web at 10 cm/sec during
real-time fabrication. Our scan period is 125 µs which will allow us to obtain
20-30 reflectance measurements before the web moves a distance comparable
to the focal spot. Current fabrication speed is only 10 cm/min.

- We have shown an effective NA of the beam is 3.14×10⁻³ with an angular
resolution of ~0.16° for the 8.0 kHz in-line scatterometer. The total # of
resolvable points for the 8.0 kHz system is ~330 points.

- We have shown the full design with all optical parts including: commercial and
custom-made stages, lenses, laser source, polarizer, parabolic mirrors,
d Detectors, and stage holding. We provided the components required to custom-
made stages and provided a full explanation of all optical mounts to accomplish
6. Conclusion and Future Work

the scanning process.

- We have demonstrated the calibration and design of the in-line angular scatterometer at 8.0 kHz beam scanning speed over the fabrication process. We fully characterized thin layer, 1D and 2D samples with the second system.

- We have demonstrated the angular limitations of the second scatterometer. We have shown the expansion of the angular range of the 45° off-axis parabolic mirrors by changing the focal length and curvature of the parabolic mirrors. Also, we have shown the space limitation with our second system. We have shown how to tailor the angular range by symmetrically changing the parabolic mirror positions.

- We showed the future angular range expansion by changing the size and the focal length of our 45° off-axis parabolic mirrors. The hypothetical angular range that we can expand is up ~79°, but space will be a limiting factor requiring the reduction of the number of stages used through the system.

- The combination of our system with fully developed library will allow the data processing to be fast enough to scan real-time fabrication without the need of stopping the web. This can reduce fabrication cost, yield, and increase the throughput of the manufacturing process.
6. Conclusion and Future Work

6.2 Future Work

This research project is promising for the future of R2R manufacturing of nano scale features, the number of possibilities to expand this research are promising. For instance, the following steps to optimize and further carectirize the system are described on the following points:

1. Collect experimental data while vertical movement is happening on the moving web to identify how the vibration of the web will affect the fabrication process.

2. Install current system on R2R real-time fabrication process at UT-Austin.

3. Develop a market analysis and commercialization plan for manufacturing capabilities.

4. Reduce the number of optical stages and holder to decrease the space usage of the system and cost.

5. Control the polarization by using a queater-wave plate which will allow us to fully utilize the power of the laser.

6. Design a vibration isolation stage that will hold the system on top of the moving web to properly scan during fabrication process.

7. Study in more detail the optical limitations and improve the critical dimensions of the system.
8. Design and write a fully operational code that can use a library to fit and
   monitor the fabrication process (improve user-interface).

9. Design a moving stage that will vary the scanning position at the moving web
   without varying the alignment of the optical system.

10. Study the effect of reflection from the R2R metallic rollers and design a cage
    that can isolate the detection to avoid external reflection at the detector.

11. Conical diffraction reflection phenomenon to allow a multi-point inspection
    system.

12. Design a multi-point scatterometer that can scan the full area of the web.

### 6.2.1 Multi-point In-line Angular Scatterometry Designs

After successfully proven the in-line 2.5 kHz and 8.0 kHz angular scatterometry
systems, one of the future directions of this project is to complete a system that can scan
multiple points at the moving web. For a multipoint scatterometer, the main challenge is
the space constraints to extract experimental data across the moving web. There are three
main designs that can be explored: dual resonant scanner with cylindrical mirrors, one
resonant scanner with diffraction orders with cylindrical mirrors, and 45° grating multi-
point inspection system. All three systems tradeoffs are going to be discussed during this
future work sub-chapter.

The first multi-point inspection system design consists of using two resonant scanners
6. Conclusion and Future Work

to scan the beam in 2 directions across the web. Figure 51 (side view) and 52 (top view) present the dual resonant scanner using cylindrical mirrors to scan a ray of points across the moving web. The two scanners are perpendicular from each other to allow scanning on both directions across the web. The cylindrical mirrors will be 90° off-axis. The angular range of the system will be dependent of the curvature of the mirror.

Figure 51 Side view of the dual resonant scanner system to extract multi-point experimental data from a moving web.
The advantages of this system are:

- Continuous ray of points scanned during the fabrication process on a moving web.

- The angular scan across the web can be easily expanded by decreasing the frequency speed of the first resonator allowing large scanning area across the web.

- The systems use less optical components than the other multi-point inspection systems.
The Disadvantages of this system are:

- At high web speed, the system will not be able to extract all points across the web.
- The optical lenses will be large which translate to more expensive optical components.
- The system will require 90° off-axis cylindrical mirrors which will require the usage of flat mirrors close to the position of the web (clearance).
- Since only one leg is shown on the design, further work needs to be done to have both legs operating simultaneously.

The second multi-point design that will be explore is using one resonant scanner and a patterned structure to create diffraction orders. Figure 53 (side view) and 54 (top view) present the multi-point scatterometer using one resonator, one pattern structure to create diffraction orders, and cylindrical mirrors. The system will use a pattern structure to create diffraction orders. The diffraction orders will be refocused by using a plano-convex lens that will focus all diffraction orders at the resonator. The resonant scanner movement will be perpendicular from the direction of the diffraction orders to ensure a ray of scanning points at the moving web. The cylindrical mirrors will focus the collimated beams to the moving web and further obtain by individual detectors across the web.
6. Conclusion and Future Work

Figure 53 Side view of the multi-point angular scatterometer with one resonant scanner, one patterned structure, and cylindrical mirrors.

The advantages of this system are:

- Continuous ray of points scanned during the fabrication process on a moving web.
- The angular scan across the web can be easily expanded by optically designing a patterned structure to extract diffraction orders all simultaneously.
- The systems scanned points can be processed simultaneously.
6. Conclusion and Future Work

Figure 54 Top view of the multi-point angular scatterometer with one resonant scanner, one patterned structure, and cylindrical mirrors.

The Disadvantages of this system are:

- The system will only extract the number of points at the web that the diffraction orders are obtain by the pattern structure.
- The system large optical components and multi-detecting system simultaneously.
- The system will require 90° off-axis cylindrical mirrors which will require the usage of flat mirrors close to the position of the web (clearance).
- Since only one leg is shown on the design, further work needs to be done to have both legs operating simultaneously.
6. Conclusion and Future Work

The third system design to be explore is 45° grating multi-point system. This system consists of scanning multiple points at the moving web using parabolic mirrors. The system will be position 45° from the moving web. The systems using a single resonant scanner per leg, and it can extract multiple points from the moving web simultaneously.

Figure 55 and 56 of the multi-point scatterometer using parabolic mirrors.

Figure 55 Side view #1 multi-point scatterometer position at 45° from the moving web.
6. Conclusion and Future Work

The advantages of this system are:

- Continuous ray of points scanned during the fabrication process on a moving web.
- The system will not require further work since the TE and TM polarization will be extracted at 45° from the direction of the web (conical diffraction).
- The systems scanned points can be processed simultaneously.
- The system uses 45° off-axis parabolic mirrors reducing space limitation and clearance problems with the moving web.

Figure 56 Side view #2 multi-point scatterometer position at 45° from the moving web.
The Disadvantages of this system are:

- The system will require a lot of optical components which will increase the costs.
- The system will cover less points due to all the optical components needed.
Appendix A: List of Parts for In-line System

In this section we will show all the optical parts required to assemble the 8.0 kHz in-line optical scatterometry shown in section 4. The following list consist of all optical parts required to complete the optical assembly:

8. Thorlabs, “Aluminum Breadboard 304.8 mm × 304.8 mm × 12.7 mm.” MB12 (2018).
10. Thorlabs, “Aluminum Breadboard 609.6 mm × 609.6 mm × 12.7 mm.” MB2424 (2018).
11. Thorlabs, “Aluminum Breadboard 304.8 mm × 101.6 mm × 12.7 mm.” MB412 (2018).
Appendix A: List of Parts for In-line System


18. Edmund Optics, “Ø101.6 mm × 119.03 mm EFL 45° OPA Protected Aluminum Mirror 100Å.” 35628.


26. Edmund Optics, “70 mm English Micrometer Tilt Stage” 66549.


31. Edmund Optics, “0.75 in. Travel Fine screw, Thru-hole Ball Bearing Stage.” 37983

Appendix A: List of Parts for In-line System

33. Edmund Optics, “110 mm Bar-type Lens/Filter Holder.” 03666.

34. Edmund Optics, “100 mm Diameter × 200 mm Focal Length, PCX Condenser Lens.” 27501.

35. Edmund Optics, “38 × 109 mm, 4-6 λ Mirror.” 32442.


37. Edmund Optics, “30 mm English Micrometer Tilt Stage” 66541.


42. Electro-Optical Products Corp, “Automatic Gain Control Driver.” AGC.
Appendix B: Custom Parts

A total of 9 optical components required custom-made aluminum stages to ensure proper alignment of the scatterometer. A total of 7 custom-made aluminum stages were machined to hold: flat sides and center mirrors, resonant scanner, collimating and focusing lenses, and parabolic mirrors. Figure 51 to figure 57 all custom-made stages for each of the previously mention optical components.

Figure 57 Custom-made central flat mirror holder angled, side and top view.
Appendix B: Custom Parts

Figure 58 Custom-made side flat mirror holder angled, side and top view.

Figure 59 Custom-made parabolic mirror holder #1. Connects parabolic mirrors to rotation stage
Figure 60 Custom-made parabolic mirror holder #2. Connects parabolic mirrors rotation stage to X, Y, Z translation stage.

Figure 61 Custom-made stage for 4” collimating and focusing lenses holder, and flat side mirrors. Connects tilt stage to X, Y, Z translation stage.
Appendix B: Custom Parts

Figure 62 Custom-made stage for resonant scanner. Connects scanner to tilt stage.

Figure 63 Custom-made stage 1” mirror. Connects mirror holder to translation stage.
Appendix C: MATLAB Multiparameter Fitting User Interface using RCWA Code

RCWA code was used to reverse fit the experimental curves obtain from the in-line 2.5 kHz, 8.0 kHz and off-line scatterometers. Also, it was used to explore the critical limitations of the off-line scatterometer. The RCWA code was essential to understand the optical properties of the samples used. Our code was ran using MATLAB. Due to the easy access to MATLAB at UNM, a user interface with multi-fit parameter capabilities was created. In this appendix, we will show the user interface created.

One common application of the off-line angular scatterometry is to characterize unknown patterned samples with reverse RCWA fitting. The fitting time is depending on the number of unknown characteristics of the sample. The more information from the sample the faster the fitting process will occur. Clearly, RCWA reverse fitting will not work for metrology during nano-manufacturing due to the time delay during the scanning and fitting process. For in-line application, a library of reflectivities curves is needed to ensure fast processing time.

However, RCWA code fitting can be useful for research and academic purposes. If done correctly, RCWA code can also fit known and unknown patterned samples considerably fast (<1 min). Our user interface consists of multi-variable fitting process. The parameters shown on our interface were only an example of how the user interface
works, but any parameters can be used on our interface. The user interface allows the scatterometry user to easy export experimental (reflection) excel data to MATLAB to further fitting process. The multi-variable fitting process occurs with a series of for loops to find the lowest RMSE between the simulation and experimental curves for all parameters. Also, the interface helps non-optical operators to navigate through the fitting process without deep understanding on the optical properties of the samples. Figure 64 presents the user interface with the multi-variable fitting parameters.

Figure 64 User interface of the RCWA multi-parameter using MATLAB
Figure 65 presents the TE (top) and TM (bottom) fits using the user interface. The fit for the photoresist thickness was ~550 nm; the fit for the wavelength of the laser source was 407 nm; and the fit for phi angle (angle between the sample grating and polarization) was 44.3°. Delta represent the changes of the fitted parameter. The smaller the delta, the slower the fitting process will take.

Figure 65 (top) TE and (bottom) TM experimental reflectivity curve vs. simulation
References


9 Liddle, J.A; Gallatin, G.M. “Lithography, Metrology, and Nanomanufacturing.”


12 S. V. Sreenivasan. “Nanoscale Manufacturing enabled by Imprint Lithography.”


References


References


37 Homenick, C.M. “Fully Printed and Encapsulated SWCNT- Based Thin Film
References


References


