FABRICATION OF MICROPOLARIZER AND NARROW BAND-PASS PIXEL FILTERS FOR FOCAL PLANE ARRAY

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FABRICATION OF MICROPOLARIZER AND NARROW BAND-PASS PIXEL FILTERS FOR FOCAL PLANE ARRAY

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ABSTRACT

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Pixel level optical filters such as micropolarizer arrays for polarimetric imaging and dielectric interference filters are rapidly becoming viable technologies for image enhancement for visible to near-IR wavelengths. The research in fabricating arrays of micropolarizer filters that has been done in the last decade focused on multiple different fabrication methods with various results in performance with respect to extinction ratio and TM transmission that generally follow the trend that they improve as the fabrication method and materials becomes increasingly complex. While the design and fabrication of multilayer metal-dielectric interference filters is more established, there are many unidentified pixel level implementations that offer several possibilities of multiple filter designs and types on the same imager array.
This work serves to address some of these complex fabrication issues and offers a rudimentary technique for fabricating micropolarizer arrays based on combination interference and contact lithography method with Damascene metallization of aluminum wire-grids with good possible performance in extinction ratio and TM transmission. This thesis also details a multilayer narrow band-pass filter design and offers discussion on practical implementation with an imaging system. Pixel level grating structures of three orientations are fabricated, polarizers are developed on glass for testing, multilayer filter designs are generated, and the feasibility of directly bonding these filters onto a CCD imager array is experimentally determined. The body of this work addresses the problems encountered with this novel wire-grid fabrication process and with multilayer filter design and calibration steps while presenting the solutions implemented to realize these filters on the pixel level.
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INTRODUCTION

The purpose of this thesis is to develop and refine a method for fabricating pixel micropolarizer filters for direct bonding application to a focal plane array. While some simulations based in optical theory are included to prove feasibility and provide target expected performance values of the filters, the majority of this work is presented from a fabrication standpoint, with a foundation from thin film technology and lithography principles cultivated from graduate coursework, topical literature review and experience working in the nanofabrication laboratory setting. The research done in this thesis work offers a novel process in the fabrication of pixel level micropolarizers and continues the progress of previous research in creating pixel level filters to bond directly onto an image sensor for real-time polarimetric imaging for visible to near-IR wavelengths.

Chapter 1 discusses the basics of optics, polarimetry and frequency filters as well as the importance of these filters in society today. Chapter 2 provides a literature overview examining various fabrication techniques employed to create wire-grid polarizers and discusses applications of both multilayer filters and micropolarizer arrays. Simulation and design of these filter devices are presented in Chapter 3. Chapter 4 details the essential steps in the novel fabrication process of the pixel level micropolarizer filters developed in this work with a focus on specific problems that
arose and solutions devised to meet them. The finalized results of this thesis work are reserved for Chapter 5, in order to isolate them from the previous iterations and trial samples made during the fabrication tuning process. The process of bonding these filters directly onto a charge-coupled device (CCD) image sensor is examined in Chapter 6. Finally, Chapter 7 wraps up with the significance of this work and suggestions for future directions to take this research.
CHAPTER I – POLARIMETRY AND OPTICAL FILTERS

The work in this thesis deals specifically with light in the range of deep ultraviolet (DUV) through visible to near infrared (IR), meaning wavelengths ranging from 200nm at DUV up to 1.5µm of near IR with visible nominally characterized as wavelengths from 400-900nm. Basic optical phenomenon such as polarization and interference are introduced throughout this thesis. Since the majority of this thesis is devoted to micropolarizers, the introduction for these devices is more in depth than the brief overview of multilayer optical filters.

Figure 1.1: Electromagnetic spectrum showing where UV to IR light resides (1).
A. Polarized Light and Brewster Angle

Light can be characterized as a transverse electromagnetic wave comprised of electric field components and magnetic field components orthogonal to each other. The cross product of these electromagnetic field components results in a third orthogonal vector, the Poynting vector, which describes waves of electromagnetic energy flux pointing in the direction that the light as travelling. The orthogonally of the electric field vector to its direction of travel allows the oscillating wave nature of the electric field vector to be further decomposed into components – oscillations parallel to and oscillations perpendicular to the plane of incidence (POI), which is the surface normal to the propagation direction.

This further decomposition is known as the polarization of light, which describes the intensity of the electric field of light oscillating in a certain direction compared to the total intensity of incident light. Polarized light parallel to the POI is sometimes called p-polarized light and polarized light perpendicular to the POI is called s-polarized light. Unpolarized light is light that, over a time average, exhibits no preference for p- or s-polarized light. When unpolarized light with electric field strength $E_0$ strikes a linear polarizer filter—a filter that allows light of one polarization direction to pass through—the intensity of the light is reduced by a cosine squared relationship with respect to the angle difference between the incident photon’s polarization and the filter direction. It is a squared relationship because the intensity is a power measurement where the electric field strength is voltage measurement. Since unpolarized light has no preference for
polarization, we observe a time average of the cosine squared function which equals a factor of 0.5.

![Diagram showing linear polarization of unpolarized light resulting in completely polarized light at half intensity.](image)

**Figure 1.2: Linear polarization of unpolarized light results in completely polarized light at half intensity.**

It is important to note that though the intensity is reduced by a factor of 0.5, the energy and therefore wavelength of light before and after polarization remains the same. Thus, a quantum mechanical approach to photons passing through the linear polarizer is preferred, even though both reach the same result, known as Malus’ law \(2\). Malus’ law describing intensity after linear polarization can be formally written as in Equation 1.1.

\[
I = I_0 \cos^2 \theta_i
\]  

(1.1)

While studying the physics of polarizer filters is useful for modeling and engineering purposes, it is necessary to understand how light becomes polarized in nature. One natural phenomenon that produces polarized light is polarization by reflection. To illustrate this idea, we consider a ray of light incident on a boundary of two media such as air and glass.
Figure 1.3: Light incident from air to glass surface with indices of refraction of \( n_1 \) and \( n_2 \) respectively. The polarization orientations are depicted in green, with p-polarized light coming out of the paper and s-polarized light parallel with the POI. Light is reflected off the surface and refracted through the glass medium, governed by Snell’s Law.

From the figure above, if we measure any difference in intensity from the reflected parallel and perpendicular components, we are observing polarization.

Therefore, to study polarization from reflection, we examine the strength of the electric field component of the reflected parallel beam. Following from Maxwell’s equations (2):

\[
E_{\text{refl},//} = E_{\text{inc},//} \frac{n_1 \cos(\theta_2) - n_2 \cos(\theta_1)}{n_1 \cos(\theta_2) + n_2 \cos(\theta_1)}
\]  

(1.2)

By using Snell’s law (1.3), we can simplify (1.2) to achieve (1.4).

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}
\]  

(1.3)

\[
E_{\text{refl},//} = -E_{\text{inc},//} \frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)}
\]  

(1.4)

In one special case of incident light, when \( \theta_1 + \theta_2 = 90 \) degrees, the denominator becomes infinitely large and the reflected parallel component of the electric field becomes zero. In this case, we end up with only p-polarized light which constitutes
100% polarization. Remembering that if $\theta_1 + \theta_2 = 90$ degrees, we can use the relationship of sine and cosine of these angles to transform Snell’s law into (1.5)

$$\tan(\theta_1) = \frac{n_2}{n_1}$$

where $\theta_1$ is known as the Brewster’s Angle (2). For our air to glass interface, the Brewster angle works out to be approximately 56 degrees.

Another important note to mention is that this reflection polarization phenomenon occurs only when light is reflected off a non-conductive material. This property allows image processing to differentiate man-made metallic objects from naturally occurring surfaces that may reflect polarized light.

**B. Polarized Light for Image Processing**

The human eye is sensitive to two parameters of light, intensity (brightness) and wavelength (color, in the visible spectrum). The polarization signature is imperceptible to our human senses, but exists nonetheless and can be captured, analyzed and modified with current image sensors and image processing techniques. This has significant applications in areas like surveillance, remote sensing, target tracking, and enhancing optical characterization in other scientific fields (3) (4) (5).

Polarizer filters are made from designs or materials that exhibit good electron conduction along one axis and poor electron conduction along the other. Devices such as periodic metal wire-grids show this property, as electrons conduct along the wire-grid but not from wire to wire. In this way, metal wire-grids appear as a conductor along the wire-grid direction and as a dielectric against the wire-grid direction, behaving
respectively to light polarized along and against the wire-grids. The period of these wire-grids must be smaller than the wavelength of light incident for polarization to be effective. If the period is close to the wavelength, the p-polarized light sees an aperture on the order of its wavelength and diffracts, significantly reducing its transmission. This is what happens for diffraction gratings, but is undesirable for polarimetric filtering applications.

The complete polarization signature of light is described by 4 Stokes parameters given in (1.6)

\[
\begin{align*}
S_0 &= I_0 + I_{90} \\
S_1 &= 2I_0 - S_0 \\
S_2 &= 2I_{45} - S_0 \\
S_3 &= I_R + I_L
\end{align*}
\]  

(1.6)

where \( I_0, I_{90}, \) and \( I_{45} \) are the intensity of polarized light along those respective angles and \( I_R \) and \( I_L \) describe the right and left hand polarization components (6). The parameter that details to what extend light is polarized is called the degree of polarization (DOP) and it represents the fraction of polarized light intensity out of total light intensity. For unpolarized light, the DOP is 0% and for completely polarized light, the DOP is 100%. The DOP can easily be determined once the Stokes parameters are known, using equation 1.7

\[
p = \sqrt{\frac{S_1^2 + S_2^2}{S_0}}
\]  

(1.7)

where \( p \) is the DOP parameter.
The first three Stokes parameters can be determined by measuring the intensity of linearly polarized light at those three angles from a common source (7). This means that three distinct polarizer orientations are needed to characterize the linear polarization signature of incident light.

In current practice, polarimetric imaging can be done by inserting different polarizers in the optical path of an image sensor, and capturing consecutive frames with different filter orientations. Due to the cumbersome mechanical insertion of multiple polarizer filters and the consecutive frame grabbing, this process is too slow to obtain real-time polarimetric image data. Another means of gathering polarized light signatures is by splitting the incident beam and using multiple polarizers and sensors to capture the Stokes parameters. While this method is fast enough to use for real-time polarimetric imaging, its main disadvantage of this technique is the need to maintain proper alignment for each sensor under all operating circumstance, leading to bulky implementation. By integrating the polarizer filters directly onto the surface of the image sensor chip, these problems can be circumvented.

Since the measurement of the last Stokes parameter mandates the use of a special optical component called a quarter waveplate, which presents a design complication, typically only the first three Stokes parameters are detected with real-time polarimetric imaging sensors. Circular polarization detection could be important for objects that exhibit chirality, but it is unclear whether that modality has any significance in remote sensing applications. The classic example of Nordin et al. (seen in
Figure 1.4) shows the potential significance of processing images with control of the first three Stokes parameters. The polarization signatures of various surface orientations are clearly visible when examining the roof, and man-made objects give distinct polarization signatures which also allow post processing techniques to differentiate them from natural, background noise.

As previously stated, at least three orientations of polarizer filters are needed to capture the Stokes parameters for linear polarization discrimination. For pixel array implementation, these orientations can be organized in a super pixel fashion (seen in figure 1.5), comparable to the way the red, green and blue Bayer color filters are organized on focal plane arrays. Since only three orientations are necessary, a fourth pixel area remains available for use. One could put a fourth micropolarizer orientation in this space to increase signal to noise ratio, or another option would be to incorporate another type of optical filter such as a narrow band-pass frequency filter tuned to a laser frequency for active illumination imaging—as in laser designators—discussed later in this chapter.
The figures of merit for a polarizer filter are the transmission of allowable polarizations, or $p$-polarized light—also called transverse magnetic (TM) transmitted light—and the extinction ratio which compares the intensity of $p$-polarized light transmitted to the intensity of $s$-polarized light transmitted. For good operation, it is desirable to have high $p$-polarized light transmission to attain good image strength and low $s$-polarized light to capture a strong polarization signature. These figures of merit are functions of the polarizer grating period, the type of metal used for the wire-grid, the thickness of the wire-grid, the duty cycle of the gratings and the substrate material.

C. Optical Frequency Filters

Optical filters which allow certain wavelengths to pass through while reflecting or absorbing others are devices that have been utilized and engineered for several decades. One of the most common uses for these filters is for image enhancement, whether for photography purposes, astronomy improvement or surveillance applications. These filters fall into two separate categories: absorptive filters and
dichroic filters. Absorptive filters work on the principle of absorption, where the material that makes up the filter will absorb certain wavelengths of light and transmit others. Dichroic filters, the type of filter presented in this work, utilize interference of light waves for their filter operation.

Dichroic filters are typically made of thin films deposited on a transparent substrate. Transparency is relative to the wavelength of light in question and the thickness of the thin film. At each interface of the film, incident light will be transmitted or reflected based on the Fresnel equations. These filters rely on thin-film interference where incident light reflected off the top and bottom surfaces of a thin film interfere with each other. The degree of interference, either constructive or destructive, depends on the phase difference between the two reflected light waves. This is the same principle that anti-reflective coatings are based upon.

![Figure 1.6: Anti-reflection coating with engineered thin film (8).](image-url)
To minimize the reflected light, anti-reflective coatings are designed to match the amplitude of both incident and reflected light and offset the phase to eliminate the reflected beam. By engineering the thicknesses of thin films with known refractive indexes, dichroic filters can be made.

Taking this same process a step further, multiple layers of materials with contrasting high and low refractive index can be introduced to selectively transmit certain bands of wavelengths while reflecting others. Important factors of these multilayer filters that determine their performance are refractive index contrast between each layer and the number of layers. By having a higher contrast of refractive index, greater design freedom can be achieved. The same is true with a higher number of layers. Thus, complex filter designs like a narrow band-pass filter—one that allows only a small band of frequencies to pass though—can be achieved by alternating high and low index thin films of specific thickness.
CHAPTER II – CURRENT MICROPOLARIZER FILTER ARRAYS AND APPLICATIONS

This chapter introduces selected work previously done with micropolarizers and provides some discussion for the application of both micropolarizers and multilayer filters. The techniques used to create filters as well as the reported performances are compared. The shortcomings of each of these methods are also addressed. Since the majority of this thesis work focuses on the fabrication of pixel micropolarizer arrays, the main topic of this chapter is other micropolarizer array implementations seen in literature.

A. Current Micropolarizer Filter Arrays

The work done by Nordin et al. is a good starting point, as it was the one of the first successful attempts at fabricating pixel level micropolarizers for use with an imager. They designed the micropolarizers for the mid-IR range of 3-5 µm wavelengths of operation and used molybdenum as the wire-grid metal. The technique utilized by Nordin et al. is similar to that presented in this work whereby interference lithography is the exposure mechanism used to achieve their gratings with a 475nm period. What is different is the pixel patterning technique: in the case of Nordin et al., an SiO₂ layer was
patterned to create the 16µm square pixels. Similarly, Nordin et al. used a super pixel configuration, though with the fourth pixel location, a redundant polarizer alignment was implemented. For 134nm thickness of molybdenum at 41% fill factor, extinction ratios of 13 were reported. This is rather low for practical purposes, though they claim to have since further developed the technique to achieve an extinction ratio of 200.

Guo and Brady reported micropolarizer arrays attaining extinction ratios of 330 for the visible regime (9). In this case, a polarizing thin film in a nematic state—a state between a liquid and solid state—was applied to a glass substrate by spin coating. The polarizing thin film has long chain molecules that were aligned by a weak electric field, and once aligned exhibited strong polarization filter effects. A necessary step to achieve this polarization effect was to condition the surface by constantly rubbing it one direction with a soft material. During operation, if the applied electric field was parallel with the rubbing direction, the polarizing effect was minimized; when the applied electric field was perpendicular to the rubbing direction, the polarization effect was strongest. The patterning of this polarizing film was done with standard UV lithography and RIE etching. To achieve the necessary polarization scheme to determine the Stokes parameters, the multiple orientations must be electrically isolated.

Figure 2.1: Two-state micropolarizer array, each layer electrically isolated (9). The black areas are the dichroic dye solution, followed by a transparent silicone polyimide. To achieve further isolation and planarization, a spin-on-glass material is next. After this, PECVD SiO₂ is deposited followed by the next layer of polarizer solution.
While it was a novel approach for achieving polarimetric filters for the visible regime, there are several drawbacks to this method including the fact that it uses an active filter and that separate polarizer orientations must be electrically isolated and are therefore non-planar. This fact could lead to resolution problems when considering diffraction effects of light around the polarizer pixels. Ideally, the filters should be in direct contact with the imaging pixels to reduce these effects.

A third micropolarizer array technique also used a thin film approach to polarization filtering. Gruev et al. implemented an iodine-doped polyvinyl alcohol (PVA) layer which, when mechanically stretched, created extremely thin wires (approximately 5nm) capable of achieving extinction ratios of 1000 for blue and green light and 100 for red light (10). These extinction ratios more closely match the performance of commercially available sheet polarizers. A super pixel approach was also pursued here, though only two orientations of polarizers were implemented: 45 degrees offset from each other, with the other two pixels measuring intensity without any filter. Gruev et al. only required two polarization orientations because they also created a custom made CMOS imager for use with the micropolarizer array that performed additional, complex real-time processing to extract the first three Stokes parameters. Due to the mechanical stretching used to create the micropolarizers, the second orientations had to be made on a separate tier.
Figure 2.2: Complete micropolarizer array imaging system from Gruev et al. (10).

While the extinction ratios reported by Gruev et al. are impressive, the fabrication process is extremely cumbersome and the operation requires a specially made CMOS imager, and additional image processing. These are issues that do not easily lend themselves to industry manufacturing.
B. Applications

Micropolarizer imaging has the potential for many future applications once the technology can be implemented in imaging systems for real-time polarimetry data capture. The added degree of information given by polarimetric filters can enhance images by suppressing overexposed areas, highlighting underexposed areas, differentiating surface orientation, and distinguishing man-made objects in a natural setting. This last application is valuable in conjunction with narrow band-pass filters for use in laser designator target tracking applications.

Laser designator systems are commonly used with laser guided munitions and are widely supported in defense and security applications to enhance targeting precision and reduce collateral damage. They operate by illuminating a target with a laser, the respected sparkle of which is detected by a specialized sensor on the bomb, which in turn adjusts the flight characteristics to strike the designated target (11). A major challenge with this system is ensuring the seeker finds and maintains vision on the laser sparkle throughout its time of flight. To help reduce the noise the seeker detects, a narrow band-pass filter that is selectively tuned to the laser frequency can be implemented in the imaging system. One issue with simply putting a blanket notch filter over the seeker’s image sensor is that it eliminates all background image and contrast which is important in order for the seeker to distinguish whether the laser sparkle is truly coming from the intended target and not from a secondary reflection.
To address these challenges, we propose that a multilayer narrow band-pass filter be implemented which only covers certain pixels of a seeker’s imager array. While the other pixels gather background imagery by staring, the filtered pixels are pulsed with the laser designator to further reduce noise and maintain image contrast. Furthermore, the micropolarizer filter arrays can also be implemented to enhance the background staring pixels’ capability of detecting man-made objects that emit characteristic polarization signatures. The result would look something like the super pixel from figure 1.5. The advantage of this filter implementation method is that no major changes to the seeker system are needed – only the bonding of these filters directly on the seeker’s imager and some adjustments to integration times and post processing of the laser designator pixel are required. These filters could greatly enhance the seeker’s capability to locate the designated mark and maintain tracking with certitude that it is the correct target, thereby reducing necessary payload and collateral damages associated with off-target munitions.
CHAPTER III – FILTER DESIGNS AND SIMULATIONS

Before beginning the fabrication process for any long-term project, it is important to model and simulate the expected responses to verify the theory behind the idea, and to determine if the endeavor of engineering the device is worthy of the resources it requires. The simulations of the polarizers are implemented with Matlab following the rigorous coupled-wave analysis (RCWA) for characterizing gratings, while the multilayer filter designs are modeled and designed with an optical filter software called OpenFilters.

A. RCWA for Micropolarizer Simulation

The simulation for wire-grid polarizers is done using the rigorous-coupled wave analysis technique developed by Wu (12). The simulated extinction ratios and TM transmissions are shown below with various metal thicknesses, grating periods for visible wavelengths, and fill factors.
Figure 3.1: Simulated extinction ratios for 270nm period gratings.
Figure 3.2: Simulated extinction ratios for 200nm period gratings.
These simulations show good promise for strong micropolarizer filter effects without losing too much transmission overall. With this knowledge, an attempt to fabricate aluminum micropolarizer arrays for use in the visible spectrum is justified.
B. Multilayer Filter Design

OpenFilters is a numerical filter design software based on the transfer matrix method for solving light propagating through various media with given complex indices of refraction. The transfer matrix method (TMM) solves Maxwell’s equations in conjunction with the constitutive relations and boundary continuity conditions in order to analyze the reflection and transmission at media interfaces and the absorption of light propagating through a material. One can define any arbitrary material, or redefine a known material based upon experimental observation, by providing the complex index of refraction as a function of wavelength. Various material layers and thicknesses can be input to the model, but the power of the software resides in its capability to numerically solve and converge the filter performance to a design target performance. The user can tell the software to refine layer thickness in order to achieve a desired transmission or reflection target window and the program iteratively adjust the layer thicknesses, converging toward a solution that gives a filter performance to match the transmission and reflection objectives. By increasing the number of layers present in the filter, more complex and designs with tighter tolerances can be achieved. This band-pass filter is designed for the laser frequency of 980nm.

To accurately design a multilayer narrow band-pass optical filter, a calibration step is required. Although the properties of crystalline silicon are well known, with physical vapor deposition (PVD) techniques, the resulting films are not crystalline and their properties need to be determined for each method of deposition. This calibration
serves a twofold purpose: to ensure the crystal monitor of thickness deposition is properly tuned and to test the deposited film’s refractive index and compare it to the accepted values for crystalline silicon’s refractive index of 3.45 (13). The refractive index is measured with a Filmetrics F10-VC thin film analyzer. Three methods for deposition are examined, CVD, evaporation and heated evaporation. The CVD silicon gave an index of refraction of around 2.55+0.12i for a 980nm wavelength. The evaporated silicon yielded a refractive index of 2.93+0.087i at 980nm. This result was unchanged after a 30 minute and 2 hour anneal step at 550°C. Finally, the silicon evaporated on a substrate heated to 350°C gave a refractive index of approximately 3.45 with a negligible imaginary component. Evaporated silicon at 350°C heated substrate gives the closest refractive index to accepted silicon values, and also the highest value which is good for contrasting with the low refractive index of 1.45 with SiO₂.

This empirically determined value of refractive index for silicon is entered into OpenFilters as a new material, and the multilayer narrow band-pass filter design is completed with three different total layer amounts – 9, 11 and 13. Initial estimates of film layer thickness are entered with alternating 150nm of SiO₂ and 50nm of Si based on one quarter of the effective wavelength for each material. OpenFilters numerical algorithm then converges on a local solution, matching the transmission targets of 5% with a 1% tolerance for all wavelengths from 400nm to 1000nm except a 10nm band from 975nm to 985nm where the target peaks at 97% centered on 980nm. These target transmissions are selected to be non-ideal so that the algorithm does not sacrifice
performance in one band to obtain perfect performance in another when attempting to match the targets. It is important to note that since this is an iterative numerical convergence and there may be many solutions to achieve the design target, the design given by OpenFilters may not necessarily be the best global solution to the design problem, but running multiple convergence tests with various initial film thicknesses helps to find the best solution.

While adding more layers increases the filter’s performance, it also introduces more deviation from the design due to imperfections in deposition. This may be problematic, as a slight deviation could shift this narrow band away from the intended wavelength, significantly hurting the performance. To circumvent these issues, the deposition should be done in steps of several layers at a time, with the performance tested and compared to the design. By catching these deviations in the middle of a design, we are able to further refine the remaining layers to readjust the band peak to the intended target.

![Figure 3.4: 9-layer narrow band-pass filter design performance.](image)
The performance of these filters gets better with the more added layers, as expected and shows the possibility to greatly reduce the noise a detector sees when seeking for laser sparkle at the 980nm wavelength.
CHAPTER IV – MICROPOLARIZER FABRICATION PROCESS

The methods of micropolarizer fabrication developed for this project with a focus on the goal of creating pixel micropolarizers are discussed in this chapter. The purpose of this chapter is to introduce the techniques and tools used in the fabrication process as well as detail the challenges and solutions that arise with these fabrication steps. Many of the scanning electron microscope (SEM) and optical microscope images show samples developed during the fine-tuning of this crafting process and are highlighted here to show what can go wrong during the process or to show the test trials used to optimize the process parameters and variables. A focus on the final benchmarks achieved during this fabrication process is reserved for the following chapter in order to distinguish the outcomes from the procedural development.

A. DUV-IL and Contact Lithography

The method used to create pixel micropolarizers uses a combination of both deep ultraviolet interference lithography (DUV-IL) and contact photolithography. The interference lithography is used to generate the small feature sizes of the gratings and the contact lithography is used to pattern the gratings into a pixel form. Since the interference lithography is done in the deep-UV range with a 266nm laser, the
photoresist used in the patterning process must be sensitive to this wavelength. This presents a problem when looking at typical photolithography processes which use h- and i-lines of a mercury-vapor lamp for exposure (405 nm and 365nm wavelengths respectively) and photoresist designed for these wavelength. In order to use a combination approach to create pixel micropolarizers, a single type of resist must be used throughout the process, but a resist sensitive to both deep UV and i-line exposure with predictable results is not available. To avoid this obstacle, a new exposure source wavelength must be used for either the DUV-IL or projection lithography. The lower limit of feature size in terms of grating period is directly proportional to the wavelength of light exposure. Thus, in order to maintain the potential for smaller grating periods, the deep-UV wavelength is chosen, and the deep-UV resist UVN-30 is employed for pattern transfer.

**B. DUV-IL Process**

The deep-UV interference lithography step enables small enough feature sizes for the micropolarizers to be operational from visible to near-IR wavelengths of light. It utilizes a negative tone resist sensitive to deep-UV wavelengths (below 300nm wavelength) and the interference phenomenon of light waves to achieve a controlled variation of periodic exposure dose on the sample. A negative tone resist means that exposed areas remain on the substrate and unexposed areas are dissolved away during development.
The controllable parameters of this process include photoresist thickness, interference pattern (and therefore grating period), exposure dose, post-exposure bake (PEB) temperature and time, and development time. By effectively controlling these parameters, a photoresist grating structure can be created with some degree of control over the grating period, grating thickness, duty cycle, and shape.
1. Substrate Preparation

The interference lithography step begins with sample wafer preparation of a prime grade Si <100> 3” wafer. The native oxide is removed in a buffered oxide etch (BOE) with 50:1 solvent to hydrofluoric (HF) acid ratio. After three minutes, the surface is oxide-free as evidenced by the hydrophobic nature after the deionized water rinse. In order to increase the UVN-30 resist adhesion to the silicon substrate, a vapor priming step with hexamethylidisilazane (HMDS) is next performed in a YES Vacuum Bake / Vapor Prime system. By pumping down the sample to milliTorr range and baking at 150°C, the sample is dehydrated before flooding of the chamber with HMDS vapor, resulting in a more effective adhesion treatment (14). After a three cycle pump and subsequent nitrogen purge to purify the chamber, HMDS vapor is introduced to prime the substrate for five minutes and then consequently pumped and nitrogen purged before venting. Upon completion of vapor priming, the sample is now ready for photoresist coating.

Figure 4.2: YES HMDS Vapor Prime System.
2. DUV Photoresist

UVN-30 deep-UV photoresist is applied to the primed sample by a spin coating procedure. The sample is vacuum-secured to a rotating chuck and spun at 3000rpm using the Laurell WS400-LITE Spin Coater.

The thickness of the resist after spin coating is a function of three controllable parameters: spin speed, spin time, and photo resist dilution percentage. After one minute of spinning, the resist thickness reaches a steady state. To keep sample processing consistent, the spin speed is set to 3000rpm and the spin time is set to one minute. At 60% dilution, the Shipley specification sheet for UVN30 shows the resist thickness versus spin speed (15).
The nominal photoresist thickness for 3000rpm is 6000 angstroms. The goal to achieve grating periods of 200nm necessitates that with photoresist thicknesses of 600nm, the aspect ratio for these gratings is 6:1. This is too high, and can cause collapse of the grating structure. So, to maintain grating integrity, the aspect ratio must be reduced, and a controllable way to do this is to dilute the photoresist. The UVN-30 photoresist is diluted with Shipley’s Thinner P at various dilution levels to find an adequate thickness, keeping spin speed and time constant. After spin coating and soft baking, a razor blade is used to scratch down to the Silicon surface, and the photoresist thickness is measured with a surface profiler.

Figure 4.4: UVN-30 photoresist thickness versus spin speed (15).
At dilution of 35%, the resist thickness is around 250nm so that for gratings with period 200nm and larger, the aspect ratio remains less than 2.5:1. This ensures that the gratings do not collapse after the development stage due to excessive capillary forces on the large surface area of the grating sides during evaporation of the developer solvent.

Figure 4.6: SEM Image of gratings collapse if aspect ratio is too large (4.5:1 in this case).
The UVN-30 photoresist is diluted 35% by mass with Thinner P and placed in an ultrasonic bath for ten minutes to homogenously mix the chemicals. After sonication is complete, the resist is spin coated onto an HMDS primed sample at 3000rpm for one minute. Next, a soft bake is performed in order to drive off the solvents in the photoresist. The soft bake is done at 140°C for 90 seconds for several different reasons. A higher soft bake temperature has the benefit of increasing the resist durability which serves a twofold purpose: durability prevents collapse of nano-scale photoresist gratings and sturdy gratings are more resistant to the dry etch processing in subsequent steps. A limit of 140°C was also chosen because the Thinner P solvent used to dilute the resist has a boiling point of 145.8°C and though the purpose of the soft bake is to drive this solvent out, if the solvent boils out too violently, it may disturb the homogeneity of the photo chemicals present in the photoresist (16). These soft bake parameters have also been found to be successful in other literature for UVN-30 (17). The Silicon <100> sample is now manually scribed and broken into several subsample pieces, approximately 1 in² each, that will fit onto the DUV-IL substrate holding platform. These samples are wrapped in aluminum foil to prevent stray UV light from exposing them and transported to the laser interference lithography lab for further processing.

3. Interference Lithography

The interference lithography system is set up at the Deep-UV Laser Interference Lithography Lab, as part of the Nanofabrication Laboratory.
Laboratory Configuration

In contact or projection lithography, diffraction effects limit the minimum achievable feature size, which at 365nm is approximately 500nm. This implies structures with periods smaller than 1µm cannot be made. Interference lithography does not suffer from diffraction or depth of focus issues, and is able to print features roughly half the wavelength size. The setup is equipped with a solid-state diode-pumped 532nm Coherent Verdi laser with a maximum output of 2 W. The green laser is then fed into a resonant frequency doubling unit, the MBD-266 producing a coherent deep-UV beam at 266nm with a maximum power of 200 mW. The beam is expanded and collimated, and the substrate holding fixture is capable of processing 3” wafers (18). The interference fixture mirror is on a motor-controlled rotating stage to precisely regulate the beam’s incident angle and, ultimately, the grating period. The interference process uses a Lloyd Mirror configuration for interference exposure.

Figure 4.7: TOP) Laser interference setup on a Newport Smart Table. LEFT) A 3” wafer held onto sample holder with vacuum. RIGHT) The interference mirror from laser’s perspective (18).
Experimental Parameters

The controllable parameters for the interference lithography step include rotating mirror angle, exposure dose, PEB dose, and development time. With a Lloyd’s mirror interference configuration, the resulting grating interference pattern period can be calculated using equation 4.1.

\[
\Lambda_{\text{grating}} = \frac{\lambda_{\text{laser}}}{2\cos\theta_{\text{mirror}}} \tag{4.1}
\]

By plotting equation 4.1, we can visually determine the optimal mirror angle to achieve the desired grating period. Initially, to ensure that grating collapse is not an issue when developing the pixel micropolarizers, a large grating period of 500nm is chosen. This means the resulting mirror angle is set to 15 degrees according to the plot.
Once the angle is set, several other parameters are controlled between each exposure in order to isolate variables present in the fabrication of the photoresist gratings. The PEB time and temperature are held constant at 40s and 140°C respectively, based upon previous literature success (17). A development time of 20s is found by trial and observation of exposed photoresist. Underdevelopment will leave a residual layer of unexposed negative tone photoresist behind on the substrate, and too much development time causes the developer to dissolve the exposed areas (19). With these parameters held constant, we vary the exposure dose until the optimal grating structures are produced. To do this, the laser power incident on the sample is measured with a power meter, and a corresponding exposure time is selected to achieve total
exposure dose, given that exposure time in seconds multiplied with laser power in milliwatts will give a total exposure dose measured in millijoules.

**Figure 4.10:** SEM Images of exposure dose test for optimal grating profile. Image a) is overexposed. Image f) and g) show evidence of a standing wave in the vertical direction of resist thickness.

Based on the results of the preliminary exposure dose tests, it is found that exposure doses between 5-7mJ/cm² yields gratings with approximately 50% duty cycle and flat sidewall profiles. At the lower exposure doses, an undesirable standing wave phenomenon is observed, created by the superposition of the incident beam and its reflection from the substrate. This causes ripples through the thickness of the film that
become less pronounced as the higher exposure doses begin to saturate the intended exposure areas.

With the photoresist grating structure fabricated, we now have a couple different options for completing the micropolarizers. An absorptive metal must be included in the grating structure, either by a metal deposition and photoresist liftoff process or by an etch down and metal deposit technique to enable an effective polarizing filter. This metal will maintain the grating structure and exhibit extinction of s-polarized light incident on the surface while allowing a portion p-polarized light to pass through. After attempting both liftoff and etch down techniques, the etching proves to be more reliable and cleaner between each subsequent step. More details of the etching process are discussed in a later section; for now, the challenge of generating pixel photoresist gratings is explored.

C. Contact Lithography Process

Successful grating fabrication using deep UV interference lithography is common practice at the time of writing (20) (21). However, implementation of these gratings as micropolarizers useful for real time imaging requires several more processing steps. In the pixel method pursued in this project, the fabrication process requires there to be photoresist gratings present in one of the four pixels making up the super pixel for the subsequent etch step. This is necessary because the grating direction is uniform during the deep UV interference lithography step, and we require multiple polarizer orientations. Thus, we must fabricate one micropolarizer pixel at a time while leaving
the rest of the substrate clean and unaffected between each exposure operation. Other areas of the substrate not intended for pixel patterning during the etch step must be protected in order to achieve this effect. Since the UVN-30 photoresist is negative tone, the more exposure it receives, the more photoresist will remain after development. Hence, by overexposing the areas outside of the intended pixel, the photoresist will be completely exposed, leaving the total thickness of photoresist behind after development. The photoresist thus masks three of the four pixels of each super-pixel from etching, allowing the etch to pattern the substrate through the normal gratings only in the intended pixel.

Figure 4.11: Overview of deep-UV interference lithography and pixel overexposure lithography process.
Figure 4.12: Top view of deep-UV interference lithography and pixel overexposure lithography process. 1) Cleaned, primed Si wafer. 2) Spin coat UVN-30 photoresist. 3) Deep-UV interference lithography. 4) Following DUV-IL, sample is not PEB / developed immediately. 5) Overexposure with through pixel mask. 6) Single pixel is left with gratings, others in super-pixel are overexposed. 7) Post exposure bake and develop down to silicon substrate.

The controllable parameters of the contact photolithography are photoresist type, photoresist thickness, soft bake temperature and time, exposure wavelength, exposure dose, post exposure bake temperature and time, and develop time. At this point in the combination lithography process the photoresist parameters and exposure
wavelengths are determined, leaving exposure dose, PEB and develop time as the controllable parameters. However, as the PEB and develop time are already constrained with the deep UV interference lithography step, we are left with only the exposure dose to vary.

1. Deep UV Contact Lithography

The contact lithography is performed with the assistance of a Karl Suss MA6 / BA6 Mask Aligner which provides hard contact between the mask and the substrate, wedge error compensation (WEC), and alignment capabilities, which all serve to increase the exposure quality. The lamp currently set up with the Suss MA6 is an i-line mercury lamp at a wavelength of 365nm, not suitable for the UVN-30 deep-UV resist. Instead, a handheld UV wand—typically used as a germicidal lamp—at a wavelength of 254nm is used in place of the mercury vapor lamp.

Figure 4.13: Hand held UV lamp at 254nm used with Suss MA6 for pixel overexposure.
Since the overexposure is performed on approximately 1” samples with relatively large feature sizes of 24µm square pixels, the lamp source doesn’t require the precise optics in the Suss mask aligner to ensure even distribution of lamp power or a collimated beam shape. As long as the beam intensity varies a negligible amount across the surface of the sample and the same lamp position is used from sample to sample, the possible negative effects of the handheld lamp without complex beam conditioning optics are sufficiently mitigated. However, using a deep-UV lamp source for photolithography with the Suss mask aligner means that the glass used must be non-absorptive at 254nm wavelength (quartz or fused silica will suffice) and the opaque areas of the mask must not allow deep-UV wavelengths to pass through. Therefore, a unique mask is produced on a 3” fused silica substrate and then taped to a 5” x 5” quartz mask blank so as to fit the form factor of the mask aligner.

2. **Contact Lithography Mask**

The mask is created on a 3” fused silica substrate that is prepared with a 10 minute piranha etch, followed by a 15 second BOE etch in HF acid at 1:50 dilution with deionized water. The mask used to create the pattern on the fused silica is a photo-plotted Mylar mask cut-out that is adhered to a blank borosilicate glass panel which fits in the mask aligner. The mask is opaque in one of the four pixels making up the super pixel, which is the same tone of pattern that is required for the final overexposure mask on the fused silica. To produce these opaque areas on the mask, a metal of sufficient thickness to prevent 254nm wavelength transmission is patterned by using a liftoff
technique to achieve the pixel pattern of molybdenum on the fused silica. A negative tone photoresist AZ-nLOF is diluted in a 3:2 ratio with PGMEA and is then exposed through the Mylar mask using standard i-line photolithography with the Suss mask aligner, thus leaving a blank area for the metal pixel.

![Photo plotted Mylar mask stuck to borosilicate 5" x 5" glass to fit in Suss mask aligner.](image)

Molybdenum is deposited at 500nm thickness using a Denton RF Magnetron Sputter system, and an acetone liftoff leaves metallized pixels on the custom mask in the same pattern as the Mylar mask. This custom mask is taped with the pixel side facing up onto a quartz mask blank to be integrated into the Suss mask aligner form.
Figure 4.15: Denton RF Magnetron Sputter System

Figure 4.16: Custom pixel mask for deep UV contact lithography on a quartz mask blank in the Suss mask aligner.
3. Contact Lithography Exposure

Several samples of UVN-30 photoresist on silicon substrates are exposed with the handheld deep-UV lamp setup while all other factors are held constant, in order to determine a proper exposure time to achieve adequate overexposure. Too much overexposure leads to a bleeding effect, where the negative tone photoresist underneath the edges of the mask pattern is also become exposed, making it insoluble in developer (19). This results in distorted pixel shapes which are undesirable when attempting to create a super-pixel that relies on consistent pattern transfer. Starting with an exposure time of 20s and, after realizing this bleeding effect of overexposure, decreasing in 5s intervals for each subsequent sample, we find that even an exposure time of 1s is too long. The handheld lamp is too powerful for this contact lithography process. In order to use this lamp for contact lithography, a reduced transmission filter at 254nm wavelength must be included between the lamp and the substrate.

Mask Transmission Filter

Using the optical filter software OpenFilters, an adequate filter is designed to significantly cut down the transmission at the 254nm wavelength. Choosing a metal with predictable sputter characteristics like copper increases the chance that the thin film deposition hits the design mark—in this case 5% transmission.
A calibration run of copper sputtering is performed to find the sputtering deposition rate of copper at 25W of RF sputter power. Then, as determined by OpenFilters, 35.7nm of copper is sputtered onto the backside of the fused silica custom mask with the Denton sputter chamber. Exposure testing for pixel overexposure can now begin.

**Exposure Tests**

Various doses of overexposure are tested to obtain pixels in the deep-UV resist with the contact lithography method. It may be tempting to assume that since we are overexposing the parts of the filter that we will later remove, we can use any amount of exposure dose as long as it is significant enough to completely cross-link the negative resist. However, too much overexposure can distort the pixel shape underneath the
opaque parts of the mask, leading to pixel shrinking and rounding, as the pixels’ corner definitions will be the first to be affected by the bleeding phenomenon. By contrast, too little overexposure will leave traces of the grating pattern in the areas outside of the intended pixel in a ripple pattern. Again, it is tempting to think this will not affect the process since we are ultimately etching through this resist and stripping it off. But if the resist layer is completely etched during the etching step, this ripple pattern will transfer into the substrate, leaving permanent gratings outside of the pixel. Since we will be utilizing the other pixel areas for different polarizer orientations, this pattern transfer of the first pixel onto the entire substrate is problematic. An optimal overexposure dose is sought to attain the balance between these possible issues.

Figure 4.18: Underexposure leaves a grating pattern in unintended areas. LEFT) Optical microscope image of grating ridges outside of pixel. RIGHT) Ripple pattern continues past the pixel boundary.
Figure 4.19: Overexposure begins to blur the pixel definition and shrink the pixel size. Overexposure increases in dose from 1-4. The checkerboard mask pattern is from a previous design no longer used in this project. The exposure times are 1s, 2s, 3s and 4s from 1-4 respectively.

Though the exposure test seen in figure 4.19 is performed before the copper filter is added to the mask, the characteristic effect of too much overexposure seen here still occurs with the reduced transmission filter, if exposure doses are high enough. Once the filter is added to the mask, more overexposure tests are done to narrow down an optimal exposure time. Four samples are tested with exposure times of 5s, 10s, 15s and 20s. With a 5s exposure time, the photoresist does not fully crosslink to the substrate, so development removes all of the photoresist. The exposure times of 10s, 15s and 20s give results as expected from previous tests, with longer exposure time reducing pixel size and exacerbating the rounding effect.
Figure 4.20: Overexposure tests continued after the addition of the copper reduced transmission filter. Exposure times are 10s, 15s and 20s for 1-3 respectively.

The exposure times of 10s and 15s produce the best results, while 20s diminishes the pixel quality too much. While 10s gives the most square looking pixel, further inspection after etching with an SEM shows that this exposure time is too little and leaves the ripple pattern over the entirety substrate area following overexposure.

Now that the issues with overexposure have been examined and the parameters have been varied to find the optimal ranges, we can move onto the next step in micropolarizer fabrication, which is to etch these pixel grating patterns into the substrate.
D. Etching and the Damascene Process

The novel aspect of micropolarizer fabrication presented in this work is the utilization of the Damascene process for metallization of the wire gratings. The Damascene process is a metallization technique commonly used in the CMOS industry for fabricating contacts through the thickness of a device on a planar surface. It involves a deposition step that overfills etched channels to establish electrical contact, and polishing away of the top layer to achieve a planar surface and to discretize the metal contacts made during the deposition. The Damascene process can be broken into two significant processing steps, the etch and the metal polish.

Figure 4.21: Damascene process for metallization in fabrication of wire grid polarizers.
1. Etching

There are three types of etching available to transfer the photoresist grating pattern into the substrate. One is a chemical wet etch and the other two are dry etches that use reactive-ion etching (RIE) processes, one with inductively coupled plasma (ICP) to enhance ion density and etch rate.

**Wet Etch**

The application of a wet etch is viable only if glass substrate is used. A transparent substrate such as fused silica is needed for visible applications, but for near-IR wavelengths and for testing the Damascene process, a silicon substrate can be used, in which case a wet etch is not feasible since a KOH wet etch propagates at approximately 54 degrees into the diamond silicon substrate. With glass such as fused silica, HF acid can be used to effectively etch the substrate at a high contrast to the photoresist. The difficulty with this technique arises when considering the isotropy of the etch with respect to the etch depth and grating period. When attempting to create micropolarizers with a grating period of 400nm or less, a downward etch of 200nm will also etch horizontally into the next grating channel, thus eliminating the wire grid pattern. To fabricate micropolarizers of sufficient thickness to yield high extinction ratios at a small enough period to be effective in the visible regime, extreme anisotropy during the etch is required.
**Reactive-Ion Etching**

RIE is capable of achieving the anisotropy necessary to transfer the resist grating pattern into the substrate and also of etching both silicon and fused silica substrates. This method uses an RF plasma in a vacuum chamber filled with an etchant gas precursor to etch a sample substrate with a combination of bombardment and reactivity. The RF plasma ionizes the gas, generating positive ions and neutral free radicals. The substrate is placed on the RF electrode, which acquires a negative potential determined by the chamber configuration and the secondary electron emission coefficient of the substrate. The positively charged ions are accelerated toward the negatively charged substrate and etch by colliding with the substrate—as occurs in a sputter system—and also break the chemical bonds of the substrate, allowing the free radicals to combine with freed bonds to create a byproduct that is pumped from the chamber. Because of the vertical nature of the striking reactive ion, the etching occurs anisotropically, favoring the vertical etching direction.

In addition to the reactive-ion etching system, an ICP RIE can obtain higher ion densities within the plasma generated by an RF powered magnetic field. It also increases the free radical concentrations while leaving the ion energy the same, which can be useful in engineering the sidewall profiles during the etch. One drawback of using ICP to enhance ion and free radical density is that the etching directionality becomes less vertical and therefore more isotropic.
Figure 4.22: Reactive-Ion Etching System

The controllable parameters of an RIE etch include operating pressure, operating gases, gas flow rates, RF power, ICP power, and etch time. The first etch trial includes both RIE power and ICP power to examine whether the increased etch rates allowed by the ICP make up for the decreased anisotropy.
Figure 4.23: ICP RIE trial – TOP) Photoresist gratings at 400nm period prior to etch. MIDDLE) After ICP RIE with 20sccm SF6, 5sccm O2, 5mT operating pressure, 50W RIE power, 250W ICP power, and 30s etch time. BOTTOM) After residual photoresist is stripped.

Upon inspection with the SEM, the isotropic nature of the ICP etch proves to yield unacceptable sidewall characteristics for use with the Damascene process. Thus, to achieve better etch directionality, the ICP power is eliminated and the RIE power is increased to 100W. Additionally, since organic photoresist is used as the sacrificial mask, the oxygen flow in the chamber is removed to decrease the mask etch rate. Another technique used to reduce the photoresist etch rate is hard baking of the samples at 120°C for an hour prior to etching. By holding the remaining parameters constant for each etch and only adjusting the etch time, an optimal time is found. The DUV-IL exposure test samples are used for these etch time trials.
Figure 4.24: RIE time trials with 20sccm SF6, 5mT operating pressure, and 100W RF power with various DUV-IL exposure doses.
Upon inspection of the SEM images after the etch trials, we first note that this method yields the anisotropic etch results necessary for the wire-grid polarizers. It is determined that with a 30 second etch time (figure 4.24b, c, e and f), a thin layer of resist still resides on the top of each etched channel. After 45 seconds of etch time (figure 4.24a, b, c, e) the resist is completely removed and the sidewalls begin to slope near the top of the channels. After 60 seconds (figure 4.24a, d), this sidewall profile change becomes even more pronounced and a widening of the etched channels starts to occur. By examining these etching trials, two important aspects can be noted: the etch rates seem fairly constant between each etch trial and the optimum etch time for this resist thickness is just over 30s. This duration etches the substrate enough to produce a good wire-grid depth after metallization while also preserving the binary pattern of the wire-grid.

2. Metallization and Polishing

Common metallization techniques used with many lithographic pattern transfer methods are metal etching and lift-off of metal deposition. For the small feature sizes with unity aspect ratios we are fabricating here, an isotropic metal etch is defunct because of the isotropic nature of the etch. Previously, a lift-off approach was attempted with no RIE etch step involved, however sidewall coating of the resist structure caused shadowing of the intended wire-grid structure, giving rounded wire-grids and eventually limiting our metal thickness. Initial attempts also showed issues with adhesion of metal deposition on the substrate and difficulty removing the deep-UV
resist without damaging the metal wire-grids. Finally, the total allowable metal thickness is less than the resist structure, as the resist-dissolving solution must be left open to achieve liftoff. To avoid these issues, the Damascene process for metallization is utilized, whereby the RIE etch trenches are overfilled with a soft metal and then polished down to a planar surface. With more surface area in contact with the substrate, the deposited metal’s adhesion is increased. Also, the planar result makes reprocessing for multiple pixels less complicated.

Based on the RCWA simulations presented in the previous chapter, aluminum is used as the metal-of-choice for the wire-grid micropolarizers. Using the Denton sputter system, aluminum is deposited to overfill the etched channels to a 250nm thickness. The sputter chamber is pumped down overnight to achieve a base pressure of approximately 5µT to ensure chamber purity. The sputtering is then done at 4mT of argon with 100W RF power applied to sputter the aluminum target.

Figure 4.25: Aluminum overfill on an etched sample for Damascene polish trial.
After the aluminum overfill, the only remaining step is to polish the surface of the sample to produce individual aluminum wire-grids that make up the polarizers. This is done using the Beuhler MPC 3000 backside thinning system. The sample is held on to the grinding chuck with a wax that is heated to seat the sample and cooled to secure the sample in place. While various lapping sheets can be used with the rotating polishing chuck, the Beuhler system is intended for thinning wafers, thus for this application we need the lapping sheet with the least surface roughness so as to not over-grind the wire-gratings. A sheet with 0.1 µm lapping roughness is used, rotating at initially at 50rpm and later at 80rpm. Polishing results show that the Beuhler backside thinner is capable of polishing the samples down to appropriate thickness, though the challenge of maintaining a uniform polish across the surface of the sample still remains.

Figure 4.26: Aluminum overfill on an etched sample for Damascene polish trial. LEFT) Tilted SEM view showing slight non-uniformity during polish. MID) Cross-sectional view showing Al filling wire-grid channels. RIGHT) Cross-sectional view showing wire-grid dimensions and planar surface after polish.
Adequate polishing time is determined via visual feedback by examining the surface of the sample for a strong, uniform diffraction pattern and by using an optical microscope to visually confirm the wire-grid pattern present under the aluminum film. It is vital not to apply too much pressure while polishing, lest the lapping sheet grind off the aluminum from within the channel depths. An aluminum film on a glass like fused silica is especially susceptible to over-grinding during the polishing stage due to weak adhesion between the film and the substrate.
The purpose of this chapter was to introduce, with initial trial examples and images, the process used to fabricate the pixel micropolarizer. The tools utilized to
accomplish the fabrication were introduced and the major challenges met during the fabrication process were detailed along with the solutions used to overcome them. The outcome of this experimental tuning process is presented in the next chapter, which focuses on the finalized micropolarizer results.
CHAPTER V – MICROPOLARIZER FABRICATION RESULTS

The final results for micropolarizer fabrication include various benchmarks achieved with different substrates and patterning steps, as follows:

- Three micropolarizer orientations etched in a pixel format on a silicon substrate demonstrates the capability of the micropolarizer fabrication process detailed above to withstand three iterative procedures and maintain substrate integrity. By demonstrating three separate orientations, at 0, 45 and 90 degrees, we show the capability to fabricate micropolarizers which can completely characterize the linear polarization signatures of incident light for integration on separate pixels. The etched grating period for these samples is 400nm, sufficiently small enough for use in near-IR applications, but not quite small enough for the visible regime.

- One orientation of pixel micropolarizers is etched into a silicon substrate at a 200nm grating period to validate the capability of this process to scale down features sizes of the micropolarizers for filtering in the visible spectrum.

- Blanket wire-grid polarizers are created on a fused silica substrate, verifying the proficiency of the Damascene process for metallization and planarization of the grating pattern on a softer, transparent substrate suitable for use with visible
light. These polarizers can also be tested for TM transmission and extinction ratio performance.

These benchmarks represent significant steps in the fabrication of pixel micropolarizers for use with focal plane arrays from visible to near IR wavelengths.

A. Three Pixel Micropolarizer Orientations

After the single pixel process is refined to yield good and repeatable results each time, the biggest obstacles in creating multiple pixels are the alignment during the overexposure step and etch consistency during the RIE steps. The alignment is critical because the fabricated pixel filters must fit together within a super pixel and directly above the CCD camera pixels. The etch consistency is important in achieving wire-grids of similar thicknesses for each orientation and to ensure that any defects in the photoresist pattern are not etched into the substrate. One notable attempt at creating multiple pixel micropolarizers shows the issue of over-etching a ripple pattern in photoresist that is a result of not enough overexposure during the pixel patterning, leaving the periodic grating structure in areas where the pixels are not intended. This periodic grating structure outside of the pixel definition, seen in figure 5.1, affects the future micropolarizer orientations due to its non-planar surface in the other pixel areas reserved for separate pixel micropolarizers.
Figure 5.1: Over-etch of undesirable grating pattern outside of pixel area. LEFT) Cross-sectional image showing slight modulation outside of pixel area. RIGHT) Tilted top view showing defined pixel area and etched grating structure inside and outside of pixel boundary.

Continuing on with the second pixel fabrication shows the undesirable effects of over-etching the defective photoresist pattern into substrate. The second pixel micropolarizer orientation is rotated 90 degrees to the previous first pixel and aligned in a checkerboard pattern with the first pixel. These etches are done for 35 seconds to fully utilize the resist thickness and to achieve a deeper etch so as to examine the effects of over-etching.

Figure 5.2: LEFT) Shows offset pixels at different orientations. RIGHT) Over-etching causes problems in other pixel areas. Cross-sectional view of second pixel etch and the lines left-right are ripple pattern from over-etching first pixel.
Due to this over-etching issue, the etch times must be slightly reduced to avoid transferring the photoresist ripple pattern into the substrate. The decreased etch time leaves a small layer of photoresist in-tact which must be removed with an ultrasonic acetone bath or a short oxygen plasma etch to expose the bare silicon etched gratings. This new procedure is then used to create another batch of sample pixel micropolarizers. The pixel etch is done for 25 seconds to ensure the pattern transfer is clean, and SEM inspection after the first pixel etch shows favorable results.

![Cross-sectional view of pixel boundary](image)

**Figure 5.3: Cross-sectional view of pixel boundary shows good pixel definition**

With the first pixel etch successful, the process is then reiterated for a second pixel etch. The sample is cleaned and primed with HMDS again before applying the deep-UV resist, followed by the subsequent exposure process with an additional
alignment step after DUV-IL and before pixel overexposure. The etch is done for 25 seconds again and the residual resist is stripped.

Figure 5.4: Second pixel alignment and etch. a) Top view showing two orthogonal orientations aligned in a checkerboard pattern. b) Cross-sectional view showing pixel polarizer boundary. c) Top view showing corner of pixels without pattern interference.
The pixel mask used for these patterns is exactly 24\(\mu\)m x 24\(\mu\)m which corresponds to the CCD camera pixel size. In retrospect, this is undesirable as the pixel mask should be made slightly smaller than the camera pixel size in order to more easily fit multiple orientations of the super pixel into the boundaries of the camera pixels without one pattern crossing over to another pixel area. Moving ahead regardless of this slight concern, a third pixel is patterned and etched in the same way as the first two. This time, alignment becomes more critical as the dimensions are constrained by the two large pixels.

Figure 5.5: Third pixel patterning and etch. a) Cross-sectional view showing etch depth. b) Tilted top view depicting the alignment of the three pixels. c) Top view showing a zoom image of b). d) Top view showing the array of micropolarizer pixels.
By completing the etch of three separate micropolarizer orientations, we demonstrate the functionality of the fabrication process presented in Chapter III—with a few minor adjustments such as pixel size and sharper pixel definition—in generating the necessary micropolarizer pixel structure for complete polarimetric filtering on the pixel level.

B. Pixel Micropolarizer for Visible Wavelength

Another goal of this project is to investigate the possibility of fabricating pixel micropolarizers that operate at visible wavelengths as well as near-IR wavelengths. Since the wire-grid period must be at least as small as a half-wavelength of operation, the grating period must be scaled down to 200nm to be operable at visible wavelengths starting nominally at 400nm and above. To achieve this, the rotating mirror fixture must be adjusted before the DUV-IL step to achieve a tighter grating pitch in the exposed DUV resist. Reference to the plot in figure 3.9 leads us to adjust the mirror from 19 degrees to 40 degrees. In turn, this will require us to adjust the necessary exposure dose to obtain gratings in the photoresist of approximately 50% fill factor.

There are two opposing factors that affect the new exposure dose: the higher angle means more light is reflected off the surface of the substrate, and by the nature of the Lloyd’s mirror configuration, the necessary exposure dose to saturate the photoresist decreases. Thus, to pinpoint the new optimal exposure dose, several samples are tested starting with an exposure dose of 5 mJ/cm² (an acceptable dose for previous gratings) and incrementally increasing until diffraction effects are observed. At
5 mJ/cm², all of the photoresist is developed away meaning the exposure was too low for the photoresist to cross-link to the surface. At 7 mJ/cm², photoresist remains, but the diffraction effect is weak suggesting the modulation in the resist is low because too much of the photoresist was cross-linked, signifying overexposure. By striking the difference and exposing with 6 mJ/cm², the diffraction effects appear stronger. The sample is then etched with the same procedure as before. SEM images of part of the sample are taken before and after the etch.

![SEM images of part of the sample before and after etch](image)

Figure 5.6: 200nm grating period pixel fabrication. TOP) Exposed and developed resist pattern before etch. LEFT) Cross-section showing transferred etch pattern. RIGHT) Tilted top view of pixel pattern after etch.
Ideally, the modulation should extend down to the surface of the substrate to produce a more binary grating pattern. This depicted sample had been overexposed during the DUV-IL step, but it still shows the ability to produce gratings on this scale. For further evidence of this capability, one can look at an older, previous micropolarizer sample from when a lift off technique was being pursued.

![Figure 5.7: 217nm grating period fabricated with the DUV-IL set up.](image)

By etching 200nm period gratings into pixels on a silicon substrate, we exhibit the potential for this fabrication process to generate micropolarizer filters for visible camera applications.

**C. Blanket Micropolarizer on Glass**

An important consideration for micropolarizer filters for visible wavelengths is the transparency of the substrate. To address this need, the micropolarizer fabrication technique are used to create wire-grid polarizers on a fused silica substrate. Generating
polarizers on a fused silica substrate serves two purposes: it investigates potential complications of using this technique on substrates other than silicon and also allows for testing of the polarizers with a broadband visible source. One issue with switching to a glass substrate is that the required exposure dose will increase. This is due to the reduced reflectivity of a glass substrate at 266nm wavelengths when compared to silicon (2% from glass compared to ~70% from silicon). Another common issue observed in thin film sciences that glass substrates is the problem of decreased adhesion. This can lead peeling of the gratings during the development stage after DUV-IL, as well as the aluminum being pulled out of the etched channels during the polish step.

The procedure is nevertheless tried first on a Pyrex substrate. As anticipated, we observe much difficulty in getting the photoresist gratings to remain firmly attached to the substrate, especially at exposure doses to adequately separate one grating line from the next. At high enough exposure doses, a bottom layer of photoresist remains continuous across the surface of the substrate and allows for the modulated gratings to adhere, but at exposure doses low enough to yield the stand-alone binary gratings, the majority of the photoresist grating lines are simply washed away during development.
Figure 5.8: Low modulation gratings capable of sticking to Pyrex substrate. Achieving a binary grating structure on Pyrex remains elusive due to poor adhesion.

Since Pyrex remains troublesome, we switch to using a fused silica substrate—a glass with fewer impurities—with hopes that this may increase adhesion. This switch proves to be fortuitous as successful polarizer gratings are fabricated on the fused silica substrate. The required exposure dose is increased from the 5.5 mJ/cm² previously used with silicon substrates to 7 mJ/cm² required for the fused silica substrate.

Figure 5.9: Deep-UV photoresist gratings on fused silica substrate.
Another complication in the change of substrates from silicon to fused silica is that the RIE etch rate decreases. With silicon substrates and hard baked photoresist, the etch ratio of mask to substrate was 1:1, meaning the depth of the etch can potentially reach the thickness of the photoresist while preserving the planar quality of the substrate after the etch. Moving to fused silica using the same etch parameters reduces the etch contrast to 1:2. This means that in order to achieve the same grating depth, and therefore performance quality, with a fused silica substrate, the photoresist grating aspect ratio must be doubled. At current fabrication parameters for gratings on fused silica, the period is 400nm and the resist thickness is 200nm giving an aspect ratio of 1 before the etch and 0.5 after the etch. By moving to 200nm grating periods as suggested, the aspect ratio is doubled and the effective extinction ratio performance will increase. Regardless of the aspect ratio achieved, the process is continued with aluminum overfill and polish steps.

Figure 5.10: Aluminum overfill in etched grating structure in fused silica before and after polishing step.
By utilizing this procedure to fabricate wire-grid polarizers on a transparent substrate, we demonstrate the plausibility of making micropolarizers for the visible regime.

**D. Conclusion**

With these accomplished benchmarks, we present a successful fabrication process for developing three vital aspects of pixel micropolarizer filters for visible to near IR wavelengths. By constructing the three necessary orientations of micropolarizers in pixel array form, we show the efficacy of this combination DUV-IL and contact lithography overexposure to completely characterize the linear polarization signature of incident light. With the creation of 200nm grating period pixels, we establish the ability to achieve the small feature sizes required to make micropolarizers operate at visible wavelengths. Furthermore, fabricating polarizers on a glass substrate gives feasibility to the idea of directly bonding these filters onto a camera for visible applications.
CHAPTER VI – BONDING AND TESTING

In an effort to examine the further challenges required to incorporate these micropolarizer arrays into a practical device, attempts to align and bond 24µm x 24µm pixels on a CCD image sensor with 24µm square pixels were made using transparent ultraviolet cured bonding adhesive. This chapter addresses the complications with using the Suss Mask Aligner for aligning and exposing the UV cured adhesive.

A. Custom Bonding Accessories

Other bonding methods such as flip chip bonding were considered before determining that slightly modifying the Suss Mask Aligner was the best approach. The strength of the flip chip bonder lies in its ability to package opaque semiconductor devices that require application of solder bumps to achieve electrical connectivity. Since we are dealing with optically transparent filters with no need for solder application, the mask aligner offers a simpler, effective method for our bonding purposes. The ubiquity of optically transparent UV cured adhesives makes using the mask aligner’s precise alignment and exposure capability the best method for bonding the filters to the imager.
Given that the CCD image sensor is prepackaged in a chip to work with the Kodak daughter board, the size of the image sensor is considerably thicker than the typical wafer used with the Suss Mask Aligner MA6. Simply placing the chip on the chuck would risk bending the pin leads, so a small piece of aluminum is machined to house the sensor leads such that the substrate rests flat on the aluminum block.

![Sensor in aluminum holding block](image)

**Figure 6.1: Sensor in aluminum holding block**

Furthermore, the height of the sensor is too tall to fit into the Suss Mask Aligner even without the aluminum block sensor holder. A custom wafer sample plate for the Suss MA6 is machined in order to allow the necessary gap required to fit the sensor into the mask aligner body. This special bonding plate fixture must be machined to fit the form factor of the mask aligner’s sample chuck. Design of the bonding plate is done with a three-dimensional sketching and design software. With these custom bonding accessories, the Kodak CCD image sensor can be used with Suss Mask Aligner for UV adhesive bonding at 365nm wavelength.
Figure 6.2: Bonding plate dimensions.

Figure 6.3: Curing setup using the bonding plate with the aluminum holding block in the mask aligner. LEFT) Using normal plate, sensor does not fit. RIGHT) With custom plate and aluminum holding block, sensor snugly fits within mask aligner.
Finally, a mechanism for securing the filter substrate above the image array is required. Furthermore, this mechanism must fit within the mask holding chuck on the mask aligner and be optically transparent for visible and i-line (365nm) light so as to accommodate an optical microscope for alignment inspection and the mercury lamp for UV curing. To solve this problem, a 1/8” hole is drilled into the center of two glass plates, one 5” x 5” and the other 1” x 1”. The plates are aligned such that the holes match up, and are taped together. A 1/8” outer diameter hose is stuck into the hole and glued into place such that the small glass side is on the bottom and the tube comes out from the top. Then, the tube is connected to a vacuum and the filter is placed flush on the 1” glass piece, filter side facing down toward the image array. The vacuum is engaged to hold the filter steady during alignment, during which the chuck holding the image array is shifted and rotated beneath the filter apparatus as guided by the topside microscope viewing capability. The indentation glass piece on the bottom allows for the filter to fit onto the focal plane array that is slightly recessed in the packaged imaging chip.

Figure 6.4: Indented filter vacuum holder.
With these unique adjustments to the mask aligner, we are able to utilize its precise alignment functionality and i-line ultraviolet exposure in order to align and bond the micropolarizer filter array to an image sensor for implementation of real-time polarimetry imaging.

B. Alignment and Bonding onto Image Sensor

An optically clear UV cured adhesive with low viscosity is tested to examine the feasibility of bonding micropolarizer and multilayer filters directly to a focal plane array. The adhesive is EMI’s OPTOCAST 3718 which has a refractive index near glass (1.473) and a low enough viscosity (50 kg/s-m) to spin coat directly on the filter surface (22). After spin coating at 4000rpm for one minute, a dummy filter made of pixel-patterned molybdenum is placed on the indented filter vacuum apparatus, which is in turn placed into the mask holder chuck in the mask aligner. Then, a non-functional CCD imager array is taped down onto the aluminum bonding plate fixture with double sided tape. This ensures the imager and filter do not stick together during alignment. The alignment is done by top side alignment (TSA) and an optical microscope at 20x power. Since the pixel sizes are 24µm, the alignment is not difficult, and a 20 second hard contact exposure follows once the two components are set. The UV curing is successful, and the filter maintains its alignment through the bonding process.
Figure 6.5: CCD imager after pixels on glass are bonded with UV cured adhesive.

Figure 6.6: Alignment and bonding microscope images. Some areas contain trapped air bubbles, but most of the imager is free of these issues.

Though there are air bubbles present in some areas of the bonding interface, under further inspection with an optical microscope, they appear not to noticeably
affect the image quality. This bonding trial shows the viability of using the modified mask aligner tool for precise alignment and bonding of filters directly on the face of an imager array.

C. Micropolarizer Testing

Four micropolarizer samples on glass are created on fused silica substrate with the process from Chapter 4. One of the samples had been over-polished and the aluminum had been swept clean off the substrate in some areas. Another sample, in an attempt to get the aluminum to reflow into even metal wire-grids, was annealed at temperatures just above aluminum’s melting point of 660°C in a vacuum of a few milliTorr. The sample came out charred in certain areas and had lost its polarization effect. The remaining two samples appear fairly uniform after the polishing step and have their polarization effects tested with the Filmetrics thin film analyzer. This characterization tool uses a visible light source and detector that accurately determines reflection and transmission characteristics of light in the visible spectrum. Since the Filmetrics lamp is an unpolarized source, two linear polarizer films are also used with the samples to produce a linearly polarized light necessary to examine the fabricated polarizer response. However, the linear polarizers weak polarization effects toward the red and IR end of the spectrum. What follows is a series of plots showing the results of these initial micropolarizer fabrications. For reference in the plot captions, use the following abbreviations: linear polarizer (LP), micropolarizer (MP), parallel (//), and perpendicular (T).
Figure 6.7: TOP) Blue-LP1, Green-LP2, Purple-LP1 // LP2, Yellow-LP1 T LP2. BOTTOM) Blue-LP1 at 0 degrees, Green-LP1 at 45 degrees, Purple-LP1 at 90 degrees, Yellow-LP1 at 135 degrees.
Figure 6.8: TOP) Blue-LP1, Green-MP1, Purple-LP1 // MP1, Yellow-LP1 T MP1. BOTTOM) Blue-LP1, Green-MP2, Purple-LP1 // MP2, Yellow-LP1 T MP2.
Figure 6.9: TOP) Blue-MP1, Green-MP2, Purple-MP1 // MP2, Yellow-MP1 T MP2. BOTTOM) Another measurement of MP1 // MP2 and MP1 T MP2.
Figure 6.7 serves to show the shortcomings of this quick experimental set up. Not only do the linear polarizers exhibit poor polarization at wavelengths above 750nm, the lamp source also appears to have a polarization preference, as different orientations of a single linear polarizer can vary transmission by up to 10%. Figure 6.8 shows the two micropolarizer transmissions with respect to the linear polarizer, and depicts an extinction ratio of around 2 for the blue end of the spectrum, with inconclusive results for the red end of the spectrum due to the incapacity of the linear polarizer to effectively filter this light. Figure 6.9 depicts the two micropolarizer samples together with similar transmission ranges for the visible spectrum. An extinction ratio of about 2.5 is observed with blue light, but this extinction characteristic is significantly reduced toward the red light.

Particular issues with this setup include the lamp source polarization, which makes it difficult to distinguish whether measured polarizing effects are due to the filter or the lamp source itself. Another important factor is that the grating periods for these polarizers are 400nm, too large to exhibit significant polarization effects for light of that same wavelength, but in all measurements with the micropolarizers, the greatest extinction characteristics are observed near this wavelength.

Some possible explanations of these results are that the polishing step is not sufficient enough to isolate each wire-grid from the next, allowing electrons to travel in the direction perpendicular to the gratings which decreases the transmission of p-polarized light, and therefore polarization effect. Also, given the relatively shallow depth
of the wire-grids (100nm), the absorption of s-polarized light is low, again leading to decreased polarization effects. To address these issues, a short TMAH etch of aluminum could further isolate the wire-grids, or the prospect of reflowing the aluminum by annealing to isolate the wire-grids could be re-examined, with lower temperatures. To increase the etch depth, the etch parameters could be further optimized for fused silica substrates and the photoresist grating aspect ratio can be increased during DUV-IL. While the results seem inconclusive, they are not discouraging given the fact that these are the very first trials of micropolarizers by the Damascene process and there are numerous options to continue to refine the fabrication process to achieve extinction characteristics seen in the RCWA simulations.
CHAPTER VII – FURTHER RECOMMENDATIONS

The previous chapter showed how this novel, combination technique of DUV-IL, contact lithography, RIE and Damascene metallization can be employed to fabricate micropolarizer arrays for pixel level polarimetry imaging. While many of the shortcomings have been addressed, there is always room for improvement to bring these polarizers performance closer to commercially available sheet polarizers. A brief listing of suggestions is included as follows:

- Increase the photoresist thickness to increase aspect ratio and therefore metal thickness. This will increase extinction ratio performance and also adhesion since the surface area after the etch and metal overfill increases with aspect ratio. Further developments to stabilize the resist gratings and achieve high aspect ratios should be investigated. It had been determined that the grating collapse comes after the development stage during the drying, as surface tension forces of water on the nanoscale also greatly increase with surface area. Methods for critical point drying to achieve tension-free drying of high aspect ratio gratings are promising.

- The RIE etching of fused silica can be further refined, as the same etch process used with silicon is not necessarily the optimum this glass. To improve the etch
contrast into fused silica during RIE, a thin layer of RIE resistant metal, like chromium is suggested to be deposited on the fused silica substrate before the photoresist is added and patterned (23). This chromium layer must be thin enough that the wet etch isotropy does not affect neighboring gratings and the deep-UV exposure could be slightly increase leaving narrowing etch trenches that could help isolate the isotropic chromium etch.

- For the multilayer filter, the designs presented in this work should be fabricated and tested. In order to maintain the filter design stability, the deposition should be done in steps of several layers at a time to test for inconsistency and alter design as needed throughout the development. In this way, multilayer filters with many more layers are realizable.

- Materials other than Si and SiO$_2$ can be examined keeping in mind that a high contrast in refractive index and low absorption at the laser wavelength are desirable.

- Once these performance issues are addressed, the three micropolarizer orientations should be fabricated on a fused silica substrate. Then, a buffer layer of SiO$_2$ can be deposited and etched away over the fourth pixel, allowing for the multilayer band-pass filter to be implemented in the super pixel design.
WORKS CITED

http://www.kollewin.com/blog/electromagnetic-spectrum/.


http://refractiveindex.info/?group=CRYNSTALS&material=Si.


http://www.cnf.cornell.edu/cnf_process_photo_resists.html#hmds.


APPENDIX

A. RCWA Matlab Code

Derived from Wu (12) and developed by Yu Wang at the University of Dayton.

% metalgrid calculate the response of metal grid sub-wavelength grating
% Note: for this RCW model, lossy materials must have index with
% negative imaginary part
% this is different with the rayopt part

clear all
close all
clc

format long e

% Define setup for the
% gratings

% All length units is micron
% Lambda is wavelength
% perm1 and perm3 are permittivity of super- and substrate
% perm2 is permittivity of grating material
% X is the period of grating

para.X=0.2;
para.perm1=1.5^2; % Superstrate
para.perm3=1^2; % Substrate
para.Theta=0;
para.Phi=0;
para.Psi=pi/2; % for TE
para.Lambda=5;

fillfactor=0.7;

% tran gives the transition points of grating
para.tran=[0 fillfactor 1];

althick=0.3;
% Slabdepth gives depth of each layer
para.Slabdepth=althick;
% -rth to rth orders are kept
% total number of orders kept is s=2*r+1
para.r=100;

% Setting up polarization
PsiTM=0; % TM
PsiTE=pi/2; % TE

lambda=[0.750 0.660 0.633 0.532 0.488 0.442];
k=[4.60676 3.75051 3.41279 2.59313 2.52814 2.35593];
n=[0.23088 0.21442 0.24869 1.065 1.14156 1.17027];
% oxide dispersion--Al2o3
oxide=[1.76147 1.76507 1.76636 1.77225 1.77569 1.78025];

for ii=1:length(lambda)
    para.Lambda= lambda(ii);
    % perm2 gives the permittivity of each corresponding slab
    para.perm2= [(n(ii)-1j*k(ii))^2 oxide(ii)^2];
    out=rcwtek(para);
    Ts= out.DET;
    TsI(ii)= Ts(para.r+1);
    out=rcwtm(para);
    Tp= out.DET;
    TpI(ii)= Tp(para.r+1);
    ExtRatio(ii)= TpI(ii)/TsI(ii);
end

semilogy(lambda, ExtRatio, 'r')
legend('Period=200nm; Thickness=300nm; ff=70%')
xlabel('
\lambda (\mu m)')
ylabel('Extinction Ratio')

%%

hold on

% Define setup for the gratings
% All length units is micron
% Lambda is wavelength
% perm1 and perm3 are permittivity of super- and sub-strate
% perm2 is permittivity of grating material
% X is the period of grating

para.X=0.2;
para.perm1=1.5^2; % Superstrate
para.perm3=1^2; % Substrate
para.Theta=0;
para.Phi=0;
para.Psi=pi/2; % for TE
para.Lambda=5;

fillfactor=0.5;
% tran gives the transition points of grating
para.tran=[0 fillfactor 1];

althick=0.3;
% Slabdepth gives depth of each layer
para.Slabdepth=althick;

% -rth to rth orders are kept
% total number of orders kept is s=2*r+1
para.r=100;

% Setting up polarization
PsiTM=0; % TM
PsiTE=pi/2; % TE

lambda=[0.750 0.660 0.633 0.532 0.488 0.442];
k=[4.60676 3.75051 3.41279 2.59313 2.52814 2.35593];
n=[0.23088 0.21442 0.24869 1.065 1.14156 1.17027];
% oxide dispersion--Al2O3
oxide=[1.76147 1.76507 1.76636 1.77225 1.77569 1.78025];

for ii=1:length(lambda)
    para.Lambda=lambda(ii);
    % perm2 gives the permittivity of each corresponding slab
    para.perm2=[(n(ii)-1j*k(ii))^2 oxide(ii)^2];
    out=rcwte(para);
    Ts=out.DET;
    TsI(ii)=Ts(para.r+1);
    out=rcwtm(para);
    Tp=out.DET;
    TpI(ii)=Tp(para.r+1);
    ExtRatio(ii)=TpI(ii)/TsI(ii);
end

grid on;
semilogy(lambda,ExtRatio,'b')
legend('\Lambda=200nm; Thickness=300nm; ff=70%', '\Lambda=200nm; Thickness=300nm; ff=50%')
xlabel('\lambda (\text{mum})')
ylabel('Extinction Ratio')