Dual Wavelength Laser Writing and Measurement Methodology for High Resolution Bimetallic Grayscale Photomasks

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Abstract

Grayscale bimetallic photomasks consist of bi-layer thermal resists (Bismuth-on-Indium or Tin-on-Indium) which become controllably transparent when exposed to a focused laser beam as a function of the absorbed power changing from ~3OD (unexposed) to <0.22OD (fully exposed). To achieve high accuracy grayscale pattern, the OD must be measured and controlled while writing. This thesis investigates using two wavelength beams for mask writing (514.5nm) and OD measurement (457.9nm) separated from a multi-line Argon ion laser source: a Dual Wavelength Writing and Measurement System. The writing laser profile was modified to a top-hat using a beam shaper. Several mask patterns tested the creation of high resolution grayscale masks. Finally, for creation of 3D structures in photoresist, the mask transparency to resist thickness requirements was formulated and linear slope patterns were successfully created.

Keywords: Grayscale photomask; Bimetallic thin-film; Grayscale mask Laser Writing System; 256 gray-level photomask; Grayscale lithography, Photoresist grayscale response; Microfabricated 3D structures
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# Acronyms and Glossary

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<th>Description</th>
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<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter used to convert analog voltage signals into digital data</td>
</tr>
<tr>
<td>at.%</td>
<td>Atomic Percent unit for representing the atomic percentage of one material in a compound or mixture</td>
</tr>
<tr>
<td>CoG</td>
<td>Chrome-on-Glass common type of photomask consisting of a layer of a patterned layer of chrome on a glass substrate</td>
</tr>
<tr>
<td>CD</td>
<td>Critical Dimension minimum resolvable feature size for a given mask</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter used to convert digital data into a voltage output</td>
</tr>
<tr>
<td>DSW</td>
<td>Direct Step-on-Wafer type of projection exposure system used to expose a photomask onto a portion of a photoresist-coated wafer that is then subsequently stepped to pattern a different area</td>
</tr>
<tr>
<td>GLWS</td>
<td>Dual Wavelength Writing and Measuring System consists of optical components added to the GLWS allowing the system to write the mask and measure OD with two separate wavelengths</td>
</tr>
<tr>
<td>EOM</td>
<td>Electro-optic Modulator component in the Grayscale mask Laser Writing System that modulates the intensity of the Argon Laser</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array field programmable integrated circuit that can be configured to perform a multitude of tasks</td>
</tr>
<tr>
<td>GLWS</td>
<td>Grayscale mask Laser Writing System laser direct-write system used for the production of bimetallic thin-film grayscale masks at SFU</td>
</tr>
<tr>
<td>HEBS-Glass</td>
<td>High Energy Beam Sensitive Glass type of analog grayscale mask where the transparency of the glass decreases with electron beam (e-beam) exposure</td>
</tr>
<tr>
<td>LUT</td>
<td>Look-up Table table of values used as a reference for converting one value into another</td>
</tr>
<tr>
<td>ND</td>
<td>Neutral Density (ND) Filter a filter that generally attenuates all wavelengths of light equally</td>
</tr>
<tr>
<td>OD</td>
<td>Optical Density (OD) a method of measuring the transparency of a given material, the OD of a material is related to its transparency (T) by $OD = -\log_{10}(T)$</td>
</tr>
<tr>
<td>ODMFS</td>
<td>Optical Density Measurement and Feedback Subsystem consists of optical and electronic components added to the GLWS by J. Dykes allowing the system to measure OD and use the measurements to manipulate the writing process for bimetallic thin-film grayscale masks</td>
</tr>
</tbody>
</table>
| PI      | Proportional-Integral- a classic feedback control method where the controller
<table>
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<tr>
<td>Derivative (PID) Feedback Control</td>
<td>consists of three terms: a term directly proportional to the error, a term proportional to the integral of the error, and a term proportional to the derivative of the error.</td>
</tr>
<tr>
<td>Pulse Density Modulation (PDM)</td>
<td>modulation method where the frequency or pitch of a repetitive pattern is adjusted; generally, the pattern’s duration remains unchanged.</td>
</tr>
<tr>
<td>Pulse Width Modulation (PWM)</td>
<td>modulation method where the duration of a repetitive pattern is adjusted; generally, the pattern’s frequency or pitch remains unchanged.</td>
</tr>
<tr>
<td>Scanning Electron Microscope (SEM)</td>
<td>type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons.</td>
</tr>
<tr>
<td>Universal Serial Bus (USB)</td>
<td>serial bus standard for connecting external devices with a host computer.</td>
</tr>
<tr>
<td>Windows Laser Table Control Program (WinLTC)</td>
<td>Windows-based software interface controlling all components in the Laser Micromachining System.</td>
</tr>
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1. Introduction

1.1. Microlithography

Microlithography is the driving force of micro-chip fabrication, the largest manufacturing industry in the world. The word lithography from the latin *Lithos*, ‘stone’ + *Graphein*, ‘to write’ started as a method of printing with stone or metal on a smooth surface. In the Integrated Circuit (IC) fabrication industry, a technique derived from lithography is used referred as Microlithography to transfer the pattern of a circuit into the substrate or film and fabricate the circuit [1].

Using microlithography, very accurate and miniaturized (currently down to 25nm) patterns can be created on a photo-sensitive material or photoresist [2]. As shown in Figure 1.1, using classic microlithography, a 2D or planar pattern is developed in the photoresist which can be then transferred to the substrate material by etching away the material not protected by the remaining resist. Achieving nearly vertical sidewalls in photoresist is a very important factor as any shape other than straight limits the accuracy of the final etched structure in the substrate [2]. This is the process that creates traditional integrated circuits.

![Figure 1.1. Classic lithography to create 2D microstructures](image)

(a) Photoresist flood exposure changing the chemical structure of the photoresist; (b) Developed photoresist; (c) Etching the pattern into the layer.
An extension of traditional microlithography into the third dimension Figure 1.2 uses a grayscale photomask which is capable of creating different exposures levels. This develops into various thicknesses of the resist which can be used to create 3D microstructures and transfer it into the layers below it. As seen in Figure 1.3, the development thickness of the photoresist is a function of the exposure, thus enabling 3D microstructures to be created using grayscale masks by modulating the exposure light intensity. This resist 3D structure is then transferred to the substrate by allowing the etching processes to remove both the resist and the material below at similar rates.

**Figure 1.2. Grayscale microlithography**
(a) Photoresist exposure with a linear variation of transparency in grayscale mask; (b) It translates into a linear variation of photoresist thickness after development; (c) Transferring the 3D structure to the substrate below such as glass after etching

**Figure 1.3. Fraction of positive photo-resist remaining as a function of exposure dose from $D_0$ (threshold dose) to $D_c$ (dose to clear) [3]**
One of the progress measurement factors in microlithography is being able to print ever smaller structures, defined by the minimum feature size or Critical Dimension (CD). As smaller the minimum printable images become (Figure 1.4), the number of transistors in a given area on the semiconductor chip increase by a factor of two every 18 months (based on Moore’s law), which also increase the speed of circuit switching abilities [2]. A critical requirement for creating smaller images is advances in the lithography systems used to create ever smaller devices. The very first semiconductor exposure system used a mask aligner in a contact mode in which the photoresist coated wafer was in contact with the mask containing the lithographic image. This method was later replaced by Optical Proximity Printing as it introduced contamination and caused damages to the photoresist and the photomask. The optical proximity printing used 10-25 µm distance between mask and the wafer to prevent the problems created by the contact printing method.

![Figure 1.4. Trends of lithography techniques and exposure wavelengths (After [4])](image)

Figure 1.4 shows the contact and proximity lithography techniques. In both of them, the designed mask is required to have the same size structures as those created on the wafer which is referred to 1:1 or 1x lithography [4]. The mask must also cover the entire wafer, which became a problem as the wafers grew larger in diameter. Patterning
the wafer in one exposure without using additional optics is considered an advantage for these methods. However, the disadvantages of these methods are achieving low resolution structures due to scattered light, the diffraction produced shadow in proximity printing, and short lifetime of the mask in contact printing [4].

Due to the limitations of these methods and the need to fabricate smaller devices, projection lithography was developed. Using the reduction projection technique, the desired mask pattern was projected onto the wafer by an optical system including lenses and mirrors with 2x to 10x shrinkage ratio. The Reduction Projection technique (Figure 1.6) has the ability to employ the masks with larger features to print on the wafer, as opposed to the contact/proximity methods with 1:1 ratio [4].

Traditionally, using the contact/proximity techniques, the mask or photomask contained the whole design of a single layer of a semiconductor wafer, and it could be transferred to the wafer in a single exposure [4]. With the projection system development, other methods of wafer exposure were introduced which required a reticle or a small part of a pattern to be exposed on the wafer. The methods like the Direct-Step on Wafer (DSW) or Step and Scan used a combination of single reticle mask and wafer movement under the projection system to expose the whole photosensitive material on the wafer.
With an optical system, as a first approximation, the minimum size of a producible structure possible is $\lambda/2$. Hence, many techniques have been used in optical lithography over time, and different wavelengths have been used for each technique. From the time microlithography first was used to date, the exposure wavelengths have been shortened. From mid-1980s which the G-line (436nm) was in use until the early 2000, the exposure wavelength had reached to 193nm. Figure 1.7 shows the relationship between the exposure wavelength used in lithography and the minimum achievable Critical Dimension in IC fabrication industry.

So far, the microlithography with the two most common techniques (contact/proximity and projection printing) have been discussed including brief details on the exposure systems and methods to transfer photomask patterns into the photoresist. The next section looks into the photomasks used in the microlithography as a master pattern to transfer images on the photoresist below it. Two general types of photomasks (binary and grayscale) will be discussed as well as how typical photomasks are created.
The relationship between the exposure wavelength used in lithography and the minimum achievable critical dimension in IC fabrication industry ([4, 5, 6])

1.2. Lithographic Photomasks

A photomask is a plate containing the pattern to be transferred to the substrate. Similar to the photographic negative, the mask contains areas ranging from highly absorbent to nearly transparent. In the case of using positive photoresist, the mask substrate is a transparent material and the patterned media on the substrate is a less transparent or highly opaque. Typical simple masks used for lithography usually consist of a very thin (80-100 nm) layer of chrome on a transparent glass or fused silica substrate [4]. To create a mask, the desired pattern is transferred on the chrome layer using a nearly identical technique to microlithography.

In most commercial systems, to define the patterns onto the photomask, a laser spot or an electron beam are used to create the pattern with various mask writing techniques such as raster scanning. In this method the mask writer uses a pixelated image of the pattern and scans the total mask surface area switching the laser beam or e-beam "on" and "off" [4].
Photomasks consist of two general types (see Figure 1.8); Binary masks used in most IC fabrication industry, and grayscale masks needed for creating 3D microstructures. Sections 1.2.1 and 1.2.2 will further discuss the binary and grayscale photomask details and their applications in industry.

**1.2.1. Binary Photomasks**

Binary masks are two level black (absorbing) and white (transparent) masks which fully blocks or transmits the light. The first binary masks used in early 1960s were emulsion masks made of silver halide and gelatine. The emulsion masks were replaced by Chrome on Glass (CoG) masks as chrome has higher optical absorption and chemical mechanical strength than emulsion. To create a CoG mask, first a thin layer of chrome (80-100 nm) is sputtered on a glass or a fused silica substrate (Figure 1.9(a)). Next, a layer of a photosensitive material (positive or negative resist) is coated on the chrome layer (Figure 1.9(b)), which is patterned using laser or e-beam writing (Figure 1.9(c)). After development, the pattern appears on the photoresist (Figure 1.9(d)). To etch the unprotected chrome, wet or dry etching techniques are used, and the remaining photoresist is removed from the mask (Figure 1.9(e)). Figure 1.9(f) shows a binary photomask which is used to expose the photoresist. As it can be seen, a 2D structure is created on the photoresist after development which is transferred to the film underneath using an appropriate wet or dry etch process.
Figure 1.9. Manufacturing steps of a CoG mask

(a) Chrome is deposited on the mask creating a blank mask;
(b) Negative/Positive resist coated on the Cr;
(c) Direct writing E-beam/Laser beam on the photoresist;
(d) Development of the photoresist leaving the unwanted areas unprotected;
(e) Etching chrome from unwanted area to create the final mask;
(f) Using the created mask in a lithography process, the pattern can be transferred to a photoresist and the desired film creating a 2D microstructure.

To exceed the $\lambda/2$ limit of the optical systems with the binary masks, phase information was added to the already existing amplitude information, which resulted in creation of phase-shift masks [7]. The phase shift can be created by varying the physical thickness of the mask substrate such as quartz (known as alternating phase-shift mask) or by creating a partial transmittance region on the mask (known as attenuated phase-shift mask) [7]. As seen in Figure 1.10, by setting the phase shift to $180^\circ$, high resolution imaging with good depth-of-focus can be obtained. Using a phase shift mask, as oppose to the regular photomasks, can increase the optical system’s resolution in creating minimum feature sizes of $\lambda/4$. 
1.2.2. **Grayscale Photomasks**

The IC fabrication industry is able to create high resolution circuit patterns using binary photomasks. However, many other applications require more complex 3D-microstructures. Integrated micro-lenses on advanced camera sensor arrays, micro-optic arrays, Micro-Opto-Electro-Mechanical Systems (MOEMS), Mechanical MEMS sensors, and Micro-fluid devices are only some of the application examples of the 3D microstructures.

Grayscale optical lithography is the preferred technique of creating 3D micro-structures [9]. While other processes are possible, such as optical interference patterns and laser direct write exposure, they are best applied for limited production of specific structures.

A 3D microstructure can be created with binary photomasks using repeated levels of exposure, development, and etching [10] (see Figure 1.11(a)). However, creating several photomasks, per level alignment (causing errors in lithography), and several lithographic steps result in an increase to the cost of 3D microstructure fabrication. In the example shown in Figure 1.11(a), the areas which have been exposed once are etched to one the depth, and similarly, the areas which have been exposed twice or all three times are etched two or three times the depth, respectively.

![Figure 1.10. Phase Shift Mask technology (After [8])](image-url)

**Figure 1.10. Phase Shift Mask technology (After [8])**
An alternative to this method is coating the wafer with photoresist once and exposing it with only a portion of total exposure using all masks. Although the alternative method avoids all unnecessary development and etching levels, it still needs several binary masks.

Having a mask with several transparency levels (grayscale photomask), a 3D microstructure can be created in a single microlithography step (see Figure 1.11(b)), which is more cost-effective. Grayscale masks consist of two general types: digital and analog in which the quality and number of gray levels are different. In the next two subsections, various types of grayscale masks, production method, material, and quality will be discussed. The next section will look through the bimetallic thin films and their potential to be used as grayscale masks.

Figure 1.11. Fresnel lens created on a substrate film
(a) Repeated exposure, development and etching with 3 levels of binary masks to create a low resolution 8 phase-level (3 bits) microstructure (After [10]);
(b) 256 level grayscale mask to create a high resolution 256 phase-level (8 bits) microstructure in one microlithography step.
Digital Grayscale Photomasks

Similar to newspaper printing, digital grayscale photomasks use halftone process to create different gray-levels on the mask when projected. Figure 1.12 shows different gray-levels created using discrete sets of various size absorbing dots with different spacing. During exposure process, the optical system puts these dots out of focus so that they overlap creating specific gray-level intensity. To create half-tone grayscale masks, the same process of producing a CoG mask is used, which creates a binary mask optimized to have several exposure levels in a specific optical system [11]. Generally, three methods are used to create different exposure levels in half-tone photomasks: Pulse-Width Modulation (PWM), Pulse-Density Modulation (PDM), or a combination of both [12]. PWM utilizes constant pitch size and varying dot sizes, while PDM is a combination of fixed size dots and varying pitch sizes. All of three methods use the same idea of changing the ratio of transparent to non-transparent area to produce different exposure levels. Figure 1.12 illustrates all three methods of creating half-tone grayscale masks. In Figure 1.13, using PWM and PDM techniques, a 16 level grayscale mask representing a wedge structure is shown.

![Figure 1.12](image)

*Figure 1.12. Four grayscale pixels with different exposure levels created using all three half-tone printing methods*

(a) Gray-levels presented in 8-bit grayscale mode;
(b) Grayscale created with PDM method with constant dot size and variable pitch size;
(c) Grayscale created with PWM method with variable dot size and constant pitch size;
(d) Grayscale created with both PDM and PWM methods.
Figure 1.13. 16-level grayscale wedge structure
(a) 8-bit grayscale image of the wedge structure;
(b) Wedge structure created using PDM method of half-tone printing;
(c) Wedge structure created using PWM method of half-tone printing.

As manufacturing the chrome half-tone masks are the same as producing Chrome-on-Glass (CoG) photomasks, it is simple to create them using the same production systems already in use in the industry. Transmission range of a half-tone photomasks is the same as CoG masks varying from less than 0.03% transparency (3.5OD) to ~90% transparency (0.05OD) in I-line (365nm) [4].

The major limitation of the half-tone grayscale masks is the maximum achievable number of gray-levels. Having the dot sizes and shapes changed to produce different levels of gray, only 16 distinguished gray levels can be created, which allows creation of low resolution 3D microstructures in the photoresist [13]. The half-tone masks require defocusing and projection techniques to turn the features on them into grayscale patterns. As the masks are designed for the projection systems, resolution of the patterns on the mask must be higher than the limit of exposure system to prevent transferring patterns to the substrate [11]. Creation of artefacts in the resist, such as moiré patterns, is another inherent limitation of half-tone masks, which causes repeated patterns within the images due to interactions of the half-tone dots. Although the moiré pattern can be avoided by randomizing the dot structures on the mask, it limits the created image resolution and causes variations on the final structures.
To create higher resolution microstructures on the substrate using grayscale masks, other types of high resolution masks have been investigated and used in industry. The next subsection will discuss the most commercially used analog grayscale mask known as High Energy Beam Sensitive (HEBS) Glass.

**Analog Grayscale Photomasks**

The analog grayscale photomasks have a continuous tone of gray-levels (transparency) enabling them to create high-resolution 3D microstructures in the photoresist (Figure 1.2). High Energy Beam Sensitive (HEBS) glass is the most common commercial example of these types of photomasks. This consists of zinc-borosilicate glass containing silver ions in the form of silver-alkali-halide \((\text{AgX})_m\text{(MX)}_n\) complex crystals [14].

To pattern the HEBS glass, a direct-write high power e-beam is required to change the glass’s optical transmission. The glass starts as a transparent substrate and its optical density increases as a function of electron dosage and the acceleration voltage so that higher OD requires higher dosage. As shown in Figure 1.14(a), although the OD of the HEBS glass increases as the electron dosage increases, its OD limit is set by the accelerating voltage. Hence, the HEBS Glass optical range is dependant to the accelerating voltage.

Increasing the e-beam power may be a good solution to the higher achievable optical range, but it creates another limitation known as proximity effect to the grayscale levels. Scattering of the electron beam within the glass during exposure creates unwanted local optical density alteration which in turn contributes to the neighbouring points [4, 15]. Decreasing the e-beam power decreases the scattering effect of the electrons, but it also limits the achievable OD range in the glass.

The HEBS glass is inert to the G-line (436nm) and to shorter wavelengths if it is doped with photo-inhibitors [16]. However, it can be affected with high power wavelengths lower than 300nm [14]. As the recent lithography systems use deep UV wavelengths, the mask is not compatible with them [17]. HEBS glass can be used in contact/proximity lithography systems [11], as it produces continuous gray levels as
oppose to the half-tone printing; hence it does not require defocusing method to compensate for the features on the mask.

Creating a grayscale photomask using HEBS glass and e-beam writer is very expensive due to the expense and time required in the writing system. Another disadvantage of the HEBS grayscale mask is the time required to write it. The HEBS glass starts as an initially transparent glass and it takes a long time of e-beam exposure to convert it to a dark field mask, which is the most common in microlithography. In addition, the other limitation of the HEBS glass is the low OD range of it in I-line (from 0.3OD to 2.3OD) compared to a regular CoG mask (0.05OD to 3OD) [14].

The next section briefly discusses an alternative analog grayscale mask to the HEBS glass, which solves the above mentioned limitations, while having low cost, high throughput, and high OD range in I-line.

![Figure 1.14. (a) HEBS Glass Optical Density as a function of Electron Dosage (After [16]) (b) Bimetallic resist Optical Density as a function of laser power](image)

**1.3. Bimetallic Thermal Resists as Grayscale Photomasks**

The important criteria for grayscale masks are transparency/OD range, number of achievable gray levels, and resolution [18]. Having high optical density range is one of the most important factors in grayscale masks ideally the same as regular chrome mask from >3 OD (<0.1% transmittance) to ~0 OD (~100% transmittance). None of the
commercially available grayscale masks includes all these characteristics. This thesis concentrates on bimetallic grayscale photomasks as an alternative process of creating masks to the HEBS glass. Dry multilayer inorganic alloy thermal resists have been studied at SFU since 2000 that yielded to developing higher quality grayscale masks [19, 20, 21]. Bimetallic thermal resists consist of two separate layers of Bismuth on Indium (Bi/In), or Tin on Indium (Sn/In) deposited on top of a transparent substrate such as glass or quartz. Unlike the HEBS glass which is initially transparent, the bimetallic thermal resists have the advantage of being initially opaque with the desired range of initial OD as a function of resist thickness. Once written by laser, the thermal resists react to the temperature created by the absorbed laser power as oppose to the optical resists that react to the amount of laser light intensity (see Figure 1.14(b)). When exposed by a focused laser beam, it creates a eutectic alloy of low melting temperature, which transforms to a transparent alloy oxide in the presence of oxygen. Accurately controlling the laser power, the bimetallic thermal resists can be used as grayscale masks producing accurate continuous tone gray-levels.

With the focus of this research being accurately measuring and writing the gray-levels on the bimetallic thin films, Chapter 2 will further discuss the bimetallic thermal resist and their characteristics.

1.4. Outline and Research Objectives

This thesis describes the design and implementation of a laser-based direct-write system for the production of grayscale photomasks using bimetallic thin-films. Included in this research is the development of dual wavelength writing and measuring system that writes the bimetallic mask with 514.5nm laser wavelength while measuring its optical density with lower power 457.9nm laser wavelength. The system can be used in open-loop approach, where the achieved OD is measured after the writing process, and closed-loop approach, where the system uses real-time OD measurement of the written mask. In addition, the patterned photomasks are used in creation of 3D-microstructure in a photoresist which yielded in to formulation of the mask transparency vs. remaining thickness. This makes the grayscale lithography process more predictable in advance.
Chapter 2 will provide the background about the bimetallic thin films and their OD range with different ratio and thicknesses of metals as well as their response to the laser power. Sputtering characteristics will be explained as the important factors affecting the quality of the masks, surface roughness, and their final OD range.

Chapter 3 and Chapter 4 discuss the Grayscale Mask Laser Writing System (GLWS) used at SFU to pattern the bimetallic photomasks. These chapters will also discuss the changes and improvements to hardware and software sides of the system that have been occurred because of the work in this thesis.

In Chapter 5, beam shaping techniques used to transform the Gaussian intensity distribution of the laser used in this thesis to flat-top distribution will be explained. Flat-top laser beam having a uniform intensity distribution helps the mask patterning system to create uniform patterns on the mask preventing unwanted gray-level fluctuations.

As the accurate measurement of the optical density of the written pattern on the mask determines how accurate the gray-levels are produced on the mask, Chapter 5 discusses a new method in writing the mask and measuring the optical density using two separate wavelength lasers from a single stabilized laser source. Using this method, the mask can be measured at the same time of writing with a separate constant power laser line, which has closer wavelength to the wavelengths used in microlithography.

Chapter 7 will present the 256-level grayscale patterns written on bimetallic grayscale mask using the new dual wavelength writing and measuring system. This is followed by the grayscale lithography experiments in Chapter 8 to produce 3D microstructures in the photoresist using 256-level grayscale patterns. Additionally, the ability to control the writing process to manipulate the gray-levels to the resist behaviour will be presented.

Finally, Chapter 9 concludes the thesis with the summary of the results demonstrated in previous chapters and future works that can be performed with respect to the production of bimetallic thin-film grayscale masks.
2. Design and Fabrication of Bimetallic Thermal Resists

2.1. Introduction

This chapter will discuss the design and fabrication of bimetallic resists for grayscale photomasks. The first section will discuss the background of bimetallic thermal resists followed by the deposition methods. Next, the optical modeling of the thermal resists will be explained as well as the characterization of the deposited films. Finally, the factors affecting the characteristics of the sputtered films are discussed and the problems related with using the thermal resists as grayscale masks are explained.

2.2. Bimetallic Thermal Resists

Bimetallic thermal resists contain two thin layers of metals (Bismuth-on-Indium or Tin-on-Indium) shown in Figure 2.1, 15-300nm thick on transparent substrates such as glass or quartz. Laser exposure converts the films by thermal reaction into transparent alloy oxide. As the optical density of the thermal resists are controllable by accurately controlling the laser power, the bimetallic thermal resists become suitable to be used as grayscale photomasks. The Optical Density (OD) of the bimetallic thermal resists change from ~3.0OD (unexposed) to <0.22OD (fully exposed), creating either binary or grayscale masks applications. Figure 2.2 shows typical grayscale and binary photomasks used in microlithography. The left (binary) photomask is capable of creating 2 layer structures in the photoresist which are transferred by etching to the substrate below suitable for the standard IC fabrication industry. The right (grayscale) photomask modulates the exposure light developing various thicknesses of the resist which can be used to create 3D-microstructures, such as micro-lens arrays, transferred into the substrate below it.
Bimetallic thermal resist consists of sputtered two thin layers of Bismuth-on-Indium or Tin-on-Indium

Previously, bimetallic thin-film resists and grayscale masks have been made from combinations of Aluminum (Al), Bismuth (Bi), Indium (In), Tin (Sn), and Zinc (Zn) [22, 23, 24], but the optimal combinations with lower eutectic points was found to be combinations of Bismuth, Indium, and Tin. One of the advantages of lower eutectic point combination is having lower melting point which in turn requires less energy to be written. The other advantage can be found in the difference of melting point between the written spot and the outside area which prevents the liquid from spreading to the outside. The next section will discuss the bimetallic film deposition process on glass substrate using Corona Vacuum Coater DC/RF Magnetron Sputter.

Typical steps for lithography using a binary or grayscale mask.
(a) Supplied mask; (b) Photoresist layer deposited on top of the SiO₂ layer; (c) Mask exposes the photoresist transferring the pattern; (d) Resist developed to create the 3D structure; (e) A controlled-etching process transfers the 3D structure into SiO₂ layer.
2.3. Film Deposition Process

By choosing the desired metal layer thicknesses based on the eutectic ratios and the optical modeling discussed in the next section, the films can be created on the selected substrate using a sputtering machine. From the previous research on bimetallic thermal resists as grayscale masks, it has been determined that depositing separate layers of thin films results in better quality grayscale mask than co-sputtering the target materials together on a substrate [23]. In this thesis, the same method of sputtering is used to create the thin films. The thickness of layers is always kept between 30nm to 100nm thick to obtain a continuous layer of metal film, and it is usually deposited in one deposition step.

*Figure 2.3. Corona vacuum coater DC/RF magnetron sputtering system*

To create the metal layers on the desired substrate, a DC sputtering was done using the Corona Vacuum Coater DC/RF Magnetron Sputter, shown in Figure 2.3. The sputtering machine is equipped with a 24” deposition chamber containing five separate targets (Figure 2.4) allowing up to five separate film depositions without an air break, preventing contamination or oxidation at the interfaces. The substrate holders are shown in Figure 2.4 where the desired substrates are placed in the center of them using double sided or scotch tape. The substrates used in this work are standard laboratory glass slides of 2.5cm by 7.6cm. Using this size of the glass slides, each of the holder plates can hold up to 3 substrates for deposition process.
Before starting the deposition process, the substrates must be cleaned from any organic or metallic contaminations and then accurately weighed for further measurements. To clean the substrates, standard RCA clean procedures are performed. Table 2.1 shows the required chemical solutions and the procedure of RCA1 and RCA2 cleaning methods [32]. Prebaking the substrates after cleaning in 100 °C oven for 20 minutes removes any traces of moisture from their surface.

### Table 2.1. Substrate Cleaning Process Prior to Sputtering Deposition [25]

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<thead>
<tr>
<th>Step</th>
<th>Chemical Content</th>
<th>Temp</th>
<th>Duration</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA1</td>
<td>NH3OH:H2O2:H2O = 1:1:5</td>
<td>80±5 °C</td>
<td>10 min</td>
<td>Removes organic contaminants</td>
</tr>
<tr>
<td>Rinse</td>
<td>DI H2O</td>
<td>NA</td>
<td>&gt;3 min</td>
<td>Halts RCA1 reaction</td>
</tr>
<tr>
<td>RCA2</td>
<td>HCl:H2O2:H2O = 1:1:6</td>
<td>80±5 °C</td>
<td>10 min</td>
<td>Removes metallic contaminants</td>
</tr>
<tr>
<td>Rinse</td>
<td>DI H2O</td>
<td>NA</td>
<td>&gt;3 min</td>
<td>Halts RCA2 reaction</td>
</tr>
<tr>
<td>Bake</td>
<td>-</td>
<td>100 °C</td>
<td>20 min</td>
<td>Removes moisture</td>
</tr>
</tbody>
</table>

After performing the RCA clean, the desired metals deposition starts by placing the substrates into the deposition sputtering chamber with the appropriate targets. Then, the chamber is sealed and pumped down to a baseline pressure between 8µTorr to 10µTorr using a high vacuum system including a two-stage mechanical roughing pump combined with an oil-diffusion pump. The next step is introducing Argon gas into
the chamber, and maintaining its pressure based on Table 2.2 for each target being deposited until completion of the process. The substrates inside the deposition chamber then must be repositioned with a computer program to face the desired target. The duration of sputtering is determined based on the deposition rate of each material (Table 2.2), and the film with desired thickness is sputtered by setting the specific duration, measured in watt-minute.

**Table 2.2. Sputter characteristics for Bismuth, Indium, and Tin [23]**

<table>
<thead>
<tr>
<th>Target</th>
<th>Sputter Pressure (mTorr)</th>
<th>DC Sputter Current (A)</th>
<th>DC Sputter Voltage (V)</th>
<th>DC Sputter Power (W)</th>
<th>DC Rate (nm/W.min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi</td>
<td>4.1</td>
<td>0.15</td>
<td>354</td>
<td>53</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>In</td>
<td>4.1</td>
<td>0.15</td>
<td>467</td>
<td>69</td>
<td>0.4 ± 0.06</td>
</tr>
<tr>
<td>Sn</td>
<td>3.1</td>
<td>0.21</td>
<td>385</td>
<td>80</td>
<td>0.64 ± 0.1</td>
</tr>
</tbody>
</table>

2.4. Optical Modeling and OD Characteristics of Sputtered Thermal Resists

Creating thermal resists with the desired OD require determining their optical characteristics before sputtering. In 2001, Dr. Sarunic developed an optical model to determine the Reflection, Absorption and Transmittance (RAT) of unexposed bi-layer thin-films for his thesis based on Airy summation [24]. Since the complete explanation of this model can be found in [24], the optical model will be discussed briefly in this section. Using the optical model is a useful method for helping to choose the thickness and materials for a given mask as it predicts the optical absorption of the bimetallic resist film. The materials used to create the thin films are highly absorbing, and hence this model is different than the other types of optical modeling. The refractive index of an absorbing material is defined as a complex number given in Equation 2.1.

\[
\tilde{n} = n + ik
\]  

2.1

Where \( \tilde{n} \) = complex index of refraction, 
\( n \) = real part of index of refraction, 
\( k \) = absorption index.
In a simple single film case, the Beer-Lambert law predicts that there is a logarithmic dependence between the transmission of the light through a solid substance and the product of the absorption coefficient of the substance and the distance the light travels through the material, given in Equation 2.2. Referring to Equation 2.3, the value of a material's extinction coefficient can be used to indicate how much light will be absorbed by a given thickness of material at a constant wavelength.

\[ T = \frac{I_o}{I_i} = e^{-\alpha d} = e^{-\frac{4\pi k d}{\lambda}} \quad 2.2 \]

\[ A = -\ln(T) = \frac{4\pi k}{\lambda} d \quad 2.3 \]

Where
- \( T \) = transmission of light,
- \( A \) = Absorption of light,
- \( \alpha \) = absorption coefficient of the substance,
- \( k \) = extinction Coefficient,
- \( d \) = distance the radiation travels through the material,
- \( \lambda \) = wavelength of the light,
- \( I_o, I_i \) = input and output light intensities.

Having the thin-layers of metal on the substrate, the electric field of the light going through the film interacts with the free electrons causing a decrease in strength of the E field. This phenomenon causes the electric field’s and the magnetic field’s phase to separate resulting in a divergence between the two phases. To calculate the electric field’s magnitude, the Airy summation was used by Dr. Sarunic in his thesis. As shown in Figure 2.5, the laser beam reflects and refracts at each of the interfaces inside the bi-layer film on the glass substrate. The Airy summation adds up all the electric field vectors reflected and refracted waves within each layer and at each interface of a multilayer film. Adding up all the reflected electric fields on the air film interface and the first reflection, the total reflection ‘R’ is calculated. If all the refracted and reflected beam path electric fields on the glass side are summed, the total transmission ‘T’ is calculated. Having the total amount of ‘R’ and ‘T’, the total amount of absorption can be calculated using the following equation:

\[ A = 1 - R - T \quad 2.4 \]
Using the Airy summation model, the absorption of the bi-layer Bi/In film with 90nm thickness (45nm/layer) at 457.9nm wavelength is predicted to be 4.01OD. However, the error range of the film deposition process presented in Table 2.2 will result in achieving an OD range rather than one specific OD value. For example, aiming for 45nm Bismuth deposition, the actual achieved thickness can be <52.5nm and >37.5nm. Similarly, aiming for 45nm Indium deposition, the actual achieved thickness can be <52nm and >38nm. Hence, the obtained OD range for 90nm thick Bi/In film (45nm/layer) is <4.4OD and >3.4OD.

Although the Airy summation model can be used for multi-layer films, it had been designed only for two layer bimetallic thin-films. For this thesis, the original model was upgraded to predict tri-layer films optical characteristics as well as bi-layer films. This upgrade was prepared by W. Boonyasiriwat for his undergraduate thesis which will be used in this work for characterization of trimetallic thin films [26]. For example, for three layer Bi/Sn/In film with 90nm thickness (30nm/layer), the upgraded Airy summation model predicts having a film with absorption of 4.36OD at 457.9nm wavelength. The next sections describe the process of creating thin films using the deposition process explained in the previous section and comparing their real characteristics with the obtained ones through the upgraded Airy summation model.

2.5. Bimetallic and Trimetallic Mask Deposition and Thickness

As explained in Section 2.2, many metallic combinations have been studied at SFU to reach the lowest eutectic point. Bi, In, and Sn were the most used metals to
create the bimetallic thermal resists for many years, and in this thesis, the same usual combinations were also sputtered to be used as grayscale masks. The sputtered bimetallic films were Bi/In and Sn/In with various thicknesses to achieve several optical ranges to be used in various conditions with GLWS. Table 2.3 presents the expected and achieved thicknesses of Bi/In and Sn/In films sputtered specifically for this work with the sputtering characteristics discussed in the Section 2.3.

The thicknesses of the sputtered masks were measured using Tencor Alpha Step 500 Profiler, shown in Figure 2.6. As presence of spikes on the surface of the films was observed, the average thickness was performed after removing the spikes from the data set. Since the edge is known to create spikes, the Standard Deviation (σ) of the data set except the ones closer to the edge was calculated. Then, any data point above 3σ was removed for the average thickness. Although the total film thicknesses were expected to vary by an error range, the measured thicknesses by average for Bi/In films were ~1.95±0.57 times and for Sn/In films were ~1.37±0.26 thicker than the expected values (see Table 2.3). One of the reasons these thicknesses were different can be that typically the densities of thin-films tend to be lower than the expected bulk densities.

**Table 2.3. Expected and real thicknesses of sputtered Bi/In and Sn/In films**

<table>
<thead>
<tr>
<th>Layers</th>
<th>W.min (Bi)</th>
<th>W.min (Sn)</th>
<th>W.min (In)</th>
<th>Expected Thickness</th>
<th>Actual Measured Thickness</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bi</td>
<td>Sn</td>
<td>In</td>
</tr>
<tr>
<td>44</td>
<td>Bi/In</td>
<td>40.1</td>
<td>64.6</td>
<td>48 ± 8nm</td>
<td>0</td>
<td>26 ± 4nm</td>
</tr>
<tr>
<td>47</td>
<td>Bi/In</td>
<td>54.2</td>
<td>65.04</td>
<td>65 ± 11nm</td>
<td>0</td>
<td>35 ± 5nm</td>
</tr>
<tr>
<td>50</td>
<td>Bi/In</td>
<td>93.2</td>
<td>143.4</td>
<td>112 ± 18nm</td>
<td>0</td>
<td>57 ± 9nm</td>
</tr>
<tr>
<td>62</td>
<td>Sn/In</td>
<td>0</td>
<td>40.1</td>
<td>70</td>
<td>0</td>
<td>26 ± 4nm</td>
</tr>
<tr>
<td>65</td>
<td>Sn/In</td>
<td>0</td>
<td>57.3</td>
<td>100</td>
<td>0</td>
<td>37 ± 6nm</td>
</tr>
<tr>
<td>68</td>
<td>Sn/In</td>
<td>0</td>
<td>75</td>
<td>130</td>
<td>0</td>
<td>48 ± 7nm</td>
</tr>
</tbody>
</table>
Using the profilometer, the surface profiles of films were measured at the substrate surface/film border, where the glass slide was taped to the substrate holders of the sputtering machine, thus creating a step. Figure 2.7 shows the output of the surface profiler for one of the Bi/In films (Mask 50), and Figure 2.8 shows the surface profile of the Sn/In films (Mask 65). Comparing the Bi/In and Sn/In films surface profiles, it can be seen that the surface of the Sn/In film is more uniform than the Bi/In film surface.

Figure 2.6. Tencor Alpha Step 500 Profiler

Figure 2.7. Surface profile of Bi/In film (Mask 50) using the Profiler at the substrate surface/film boundary (average peak is ~550nm)
Figure 2.8. Surface profile of Sn/In film (Mask 65) using the Profiler at the substrate surface/film boundary (average peak is ~28nm)

Using the optical model (explained in Section 2.4), Table 2.4 presents the expected OD and the measured averaged unexposed OD of the Bi/In and Sn/In films. As it can be seen, the real OD of the films is significantly lower than the OD predicted using the optical model. One of the reasons is the lower densities of thin-film in comparison with the bulk densities [22]. Some other factors that affect the sputtering characteristics can also be involved in this effect, which are explained in the next section.

Table 2.4. Expected and real optical density of bimetallic films sputtered for this thesis

<table>
<thead>
<tr>
<th>Mask #</th>
<th>Layers</th>
<th>Total Expected Thickness</th>
<th>Max Calculated OD</th>
<th>Min Calculated OD</th>
<th>Average Calculated OD</th>
<th>Averaged Actual OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>Bi/In</td>
<td>74±12nm</td>
<td>3.49</td>
<td>2.54</td>
<td>3.01</td>
<td>2.19</td>
</tr>
<tr>
<td>47</td>
<td>Bi/In</td>
<td>100±16nm</td>
<td>4.7</td>
<td>3.43</td>
<td>4.06</td>
<td>2.61</td>
</tr>
<tr>
<td>50</td>
<td>Bi/In</td>
<td>169±27nm</td>
<td>7.86</td>
<td>5.73</td>
<td>6.8</td>
<td>3.02</td>
</tr>
<tr>
<td>62</td>
<td>Sn/In</td>
<td>54±8nm</td>
<td>3.62</td>
<td>2.69</td>
<td>3.15</td>
<td>1.75</td>
</tr>
<tr>
<td>65</td>
<td>Sn/In</td>
<td>77±12nm</td>
<td>5.11</td>
<td>3.79</td>
<td>4.45</td>
<td>2.22</td>
</tr>
<tr>
<td>68</td>
<td>Sn/In</td>
<td>100±15nm</td>
<td>6.63</td>
<td>4.9</td>
<td>5.77</td>
<td>2.41</td>
</tr>
</tbody>
</table>
The need to create newer masks with better quality and lower eutectic point resulted in exploring trimetallic films using specific percentage of Bismuth, Tin, and Indium known as Field’s metal or Field’s alloy. The bimetallic and trimetallic eutectic compositions of the Bismuth, Tin, and Indium are shown in Table 2.5. The best eutectic temperature of a bimetallic combination for the above mentioned metals is 72°C for Bismuth and Indium with 66.1% of eutectic mass ratio for Indium [22]. Using the mass ratio of 32.5% for Bismuth, 51% for Indium, and 16.5% for Tin, the Field’s metal can produce the eutectic temperature of 62°C. This reduction in melting point of the film can help the GLWS to pattern the grayscale masks using lower power lasers with the same results as before.

Table 2.5.  
**Eutectic Temperature/Compositions for Bismuth, Indium, and Tin [22]**

<table>
<thead>
<tr>
<th>Target #1</th>
<th>Target #2</th>
<th>Target #3</th>
<th>Eutectic Temperature °C</th>
<th>Eutectic Mass Ratio of #1 (%)</th>
<th>Eutectic Mass Ratio of #2 (%)</th>
<th>Eutectic Mass Ratio of #3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi</td>
<td>In</td>
<td>N/A</td>
<td>72</td>
<td>43.9</td>
<td>66.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Bi</td>
<td>Sn</td>
<td>N/A</td>
<td>139</td>
<td>57</td>
<td>43</td>
<td>N/A</td>
</tr>
<tr>
<td>In</td>
<td>Sn</td>
<td>N/A</td>
<td>120</td>
<td>50.9</td>
<td>49.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Bi</td>
<td>Sn</td>
<td>In</td>
<td>62</td>
<td>32.5</td>
<td>16.5</td>
<td>51</td>
</tr>
</tbody>
</table>

Using the idea of creating tri-metallic masks, a few sample masks were sputtered using Corona Vacuum Coater DC/RF Magnetron Sputter system. In Section 2.3, an upgraded version of optical model with the ability of predicting the trimetallic films optical density was explained. Using the upgraded model, Table 2.6 presents the predicted OD of the trimetallic masks and their actual OD. Similar to the bimetallic films OD prediction, the optical model calculations in the trimetallic films also predicts the optical density being significantly higher than the real OD.
Table 2.6.  Expected and real optical density and thickness of trimetallic films sputtered for this thesis

<table>
<thead>
<tr>
<th>Mask #</th>
<th>Layers</th>
<th>Max Calculated OD</th>
<th>Min Calculated OD</th>
<th>Average Calculated OD</th>
<th>Averaged Real OD</th>
<th>Total Expected Thickness</th>
<th>Actual Measured Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>Bi/In/Sn</td>
<td>5.46</td>
<td>4.01</td>
<td>5.04</td>
<td>2.84</td>
<td>100±16nm</td>
<td>147±15nm</td>
</tr>
<tr>
<td>35</td>
<td>Sn/Bi/In</td>
<td>5.46</td>
<td>4.01</td>
<td>5.04</td>
<td>2.31</td>
<td>100±16nm</td>
<td>140±10nm</td>
</tr>
<tr>
<td>38</td>
<td>Bi/In/Sn/In</td>
<td>5.46</td>
<td>4.01</td>
<td>5.04</td>
<td>2.37</td>
<td>100±16nm</td>
<td>155±6nm</td>
</tr>
<tr>
<td>41</td>
<td>Sn/In/Bi/In</td>
<td>5.46</td>
<td>4.01</td>
<td>5.04</td>
<td>2.37</td>
<td>100±16nm</td>
<td>145±6nm</td>
</tr>
</tbody>
</table>

2.6.  Sputtering Factors Affecting the Characteristics of Thermal Resists

In Section 2.3, the films deposition process using Corona Vacuum Coater DC/RF Magnetron Sputter was described. As the deposition process can affect the quality and characteristics of the sputtered films, this section focuses on the problems related to the process.

Some of the sputtering parameters like current, applied voltage and background pressure are the values which have been determined by sputtering machine users before and remained constant over the years. As the current determines mainly the rate of the deposition process, it can greatly affect the achieved thickness accuracy of the target material on the substrate. The maximum energy with which the sputtered particles can escape from the target is determined by the applied voltage, and the pressure in the sputter chamber determines the mean free path for the sputtered material. Over the years, the constant values for each of the Bismuth, Tin, and Indium targets has been created for Corona Vacuum Coater DC/RF Magnetron Sputter, and were also used to create the films used for this thesis, presented in Table 2.2.

Having almost no control over the sputtering factors can be compensated by measuring the thicknesses of each sputtered material and determining the deposition rate of each target which was done in Y. Tu’s thesis [23] and was presented in Table 2.2. Although this method can be reliable for the time these measurements were
performed, as the sputtering machine has been intensively used over the years, the contamination of sputtering chamber by other metals, lifetime of the target metals, level of the vacuum the deposition chamber can achieve, slight offset of the substrate holders from the target metals, and some other factors affect the quality of the created films.

The most important problem with the deposition chamber which can cause the biggest problem with the deposited films is the substrate holder (see Figure 2.4). The substrate holder consists of 5 plates located in a ring about the sputter chamber, each holding up to 5 different substrates. As they are all positively charged while sputtering process, the escaped metal atoms can be attracted to any of the plates, which in turn can change the thickness of the deposited material on the substrates being held on the other plates. This was tested using blank microscope glass substrates on the holder during the deposition. It could be seen that after each deposition process, some amount of material is also sputtered on the blank glass. This effect results a change in thickness of the desired mask, causing the total expected thickness to increase and the initial optical density differ from the expected OD.

2.7. Problems with Bimetallic Thermal Resists as Grayscale Photomasks

Using bimetallic thermal resists as grayscale masks have many advantages over the other types of analog grayscale masks, as explained before, but it also creates some difficulties in accurately creating the gray-levels which must be overcome. The bimetallic thermal resists react to the amount of absorbed laser power and any exposure below the threshold is not accumulated with time as the heat flows away. Hence, the exposure is required to exceed a specific temperature before any reaction will occur, which means the bimetallic thermal resists does not follow the principals of superposition or reciprocity [27]. Regular resists follow the concept of superposition (reciprocity) in which the exposure accumulates over time. For example two exposures at the same intensity for time T are the same as one exposure of time 2T. Having the thermal resists sensitive to the intensity of the laser power, thus it is more sensitive to power variations after achieving the threshold exposure, which can change the alloy oxidation reaction and hence, the gray-level achieved on the mask. Accurately controlling and measuring the
laser power is one of the biggest challenges in using the thermal resists as grayscale photomasks, since any power fluctuation directly results in gray-level variation on the grayscale mask.

Laser beams when focused tend to have a Gaussian (bell curve) shape intensity distribution. Using a Gaussian beam to pattern the thermal resists results in creation of gray-level variations along the written raster-scanned lines causing darker region between the lines which resemble the "prison bars" (Figure 2.9). As the thermal resists require a minimum threshold amount of laser beam intensity for oxidation, as the power increases the transparent area of the focused beam changes. Hence, the prison bar effect varies depending on the spacing and/or the amount of laser power. Although reducing the written lines spacing and/or increasing the laser power reduces the effect of the "prison bars", shown in Figure 2.9, the overlap of the Gaussian beams affects the gray-level achieved with the previous written line and slightly increases its transparency.

![Figure 2.9. Backlit microscope Images of raster-scanned lines on Sn/In film](image)

Several methods have been studied since 2005, trying to alter the laser intensity distribution to a more uniform pattern to eliminate the Gaussian laser profile effects on the thermal resist [28, 29]. Enlarging the beam with a beam expander and using only the middle portion of the beam with an aperture [28], and using a beam shaping mask in
the beam path to alter the power distribution [29] are some of the methods tried to eliminate the problem. Although there was a partial success in transforming the laser beam, a more permanent solution is using of a commercially available beam shaper to shape the Gaussian intensity distribution to a flat-top laser beam. Section 5 will discuss more in using a commercial beam shaper and the results achieved in transforming the beam profile.

2.8. Grayscale Variations Due to Bimetallic Film Uniformity

One additional problem with the bimetallic resist is that the film is not fully uniform after deposition. Looking at Figure 2.9, the presence of dark spots at the written areas impacts the variability in the film which causes an issue for grayscale masks. One of the hypotheses about the reason of having the dark spots is the mask’s surface non-uniformity as seen in Figure 2.7 and Figure 2.8. At the final stages of writing this thesis, a paper was found written by Guo et al. [30] suggested that sputtering thick layers of target material results in formations of large metal grains on the substrate surface creating an inhomogeneous morphology, which makes it difficult to obtain high-resolution and grain-less grayscale patterns. Using Chemical Vapor Deposition (CVD) process to deposit the target materials, the method of preventing formation of large grains, suggested by Guo et al. [30], is deposition of several thin layers of target material onto the substrate. Each deposition is followed by a short oxygen exposure to create a thin layer of oxide around each grain which prevents the other atoms to stick to them and forming large grains (Figure 2.10). Using this method, the surface quality of the deposited films can be more uniform resulting in creation of better gray-scale masks. Previous work by Y. Tu at SFU showed that adding oxygen during the sputter deposition produced a more uniform film. However, this increased the minimum achieved OD of the film. That work was focused on decreasing the transition slope of the mask, which results in more accurate gray-level control [31]. Guo’s paper suggests that smaller amounts of oxygen may improve film uniformity without affecting its OD characteristics.
Figure 2.10. Schematic illustration of the metallic films preparation with the same nominal thickness (After [30])

(a) Depositing the metallic film in one layer, creating large grains of metals on the substrate;
(b) Depositing the metallic film in multiple levels with surface oxidation in between the deposition levels to create smaller grain metals on the substrate.

2.9. Chapter Summary

In this chapter, details of creating bimetallic and trimetallic thin-film thermal resists were described. Multi-layer metallic thin films with the total thickness of 15nm to 300nm can be sputtered on a transparent substrate without an air break and their optical characteristics are calculated using the optical model. In addition to the film creation process, some of the factors affecting the sputtered films quality were explained. Using laser exposure, these films oxidize and create a transparent alloy oxide allowing the creation of grayscale masks. Previous researches have shown that although by accurately controlling the laser power, high resolution grayscale masks can be created, some factors such as beam shape and line spacing influence the resulting mask patterns. The next chapters look in more detail at experiments done to reduce the effect of the beam shape and line spacing, as well as a new method of measuring the films optical density while being written by the laser.
3. Grayscale Mask Laser Writing System

3.1. Introduction

The quality of bimetallic thin films discussed in the previous chapter and their response to the laser power are some of the most important factors in creating high quality grayscale masks. While the film sets the ultimate limit, the optical system used to pattern the mask sets the achieved resolution of the pattern and the accuracy of gray-levels. The Grayscale mask Laser Writing System (GLWS) has been developed at SFU in 2001 as the grayscale patterning system tool, and it has been improved to be capable of producing higher quality grayscale masks. This chapter describes the GLWS and the improvements to the system to increase its accuracy in producing gray-levels written on the bimetallic thin-films.

3.2. The Grayscale Mask Laser Writing System (GLWS)

The Grayscale mask Laser Writing System (GLWS) (Figure 3.2) consists of a high precision X-Y-Z table (±0.1µm) which positions the mask plate under a focused high power laser beam controlled with an Electro-Optic Modulator (EOM). The whole system is under computer control using a computer program called Windows Laser Table Control (WinLTC).

The X-Y linear induction motor air-bearing positioning table (Figure 3.1) moves the sample mask under the focused laser spot and is controlled by a HeNe laser interferometer-based positioning system with the precision of ±0.1µm. The Z-axis elevator can move with the precision of ±0.1µm under the objective lens focusing both the laser spot on the target film and the microscope camera image of the film. A multi-line Continuous Wave (CW) Argon ion laser (Coherent Innova I-305) with the total maximum beam power of ~6W is used for patterning the masks. The Argon laser’s
beam is a perpendicularly polarized at TEM\(_{00}\) mode with a 1/\(e^2\) diameter of \(\sim 1.5\)mm. The EOM with microsecond response time modulates the laser power by changing the beam polarization under voltage control. A computer controls the gray scale values for the position on the mask using the function generator which applies appropriate voltages to the amplifier modulating the beam power.

Figure 3.1. The X-Y linear induction motor air-bearing positioning table and z-axis elevator holding the mask on the mask plate

Several dielectric mirrors direct the modulated laser beam to the central z-axis mounted on the X-Y table containing the mask plate. Depending on the lens used to focus the laser beam, the spot size can vary from \(\sim 10\)\(\mu\)m to \(\sim 1\)\(\mu\)m. Five times to 50X objective lenses or simple Plano/Bi-convex lenses are commonly used, but to increase the resolution of the patterning mask, aspherized achromatic lenses with shorter focal length are preferred. The components of the GLWS for writing grayscale masks are shown in Figure 3.2 before being changed for this thesis.

To further control the focused laser power, a feedback system developed by J. Dykes in 2010 [22] as part of his thesis uses several photo-diode sensors placed in the beam path measuring the power of the laser at some key positions. The Input power sensor is the first sensor in the system placed before the EOM, and measures the laser power entering the system before being modulated. The second sensor in the system called the Reference sensor is placed after the EOM, and it is used to measure the laser power after being modulated. The beam power measured at this point is the laser power used to write the mask. The third detector, the Sample sensor, is placed below the mask plate to measure the laser power attenuation after being absorbed by the film which measures the gray level as the mask is written.
**Figure 3.2. The Grayscale mask Laser Writing System (GLWS) (original)**

Using the combination of the sensors, the system is able to calculate the optical density of the mask during the writing process, which enables the system to work in a closed-loop mode. The GLWS can also be used with low power laser to scan through an already written pattern to confirm the achievement of the desired optical density, which is called an open-loop mode. The real-time measurement of OD allowed implementing a feedback system based on a proportional-integral-derivative (PID) controller given in Equation 3.1, which resulted in self-correcting laser writing and measurement system, published in [32].

\[
DAC[k] = DAC[k-1] + \frac{Err[k]}{k_1} - \frac{Err[k-1]}{k_2}
\]

**Equation 3.1**

Where
- \( DAC[k] \) = the DAC output at sample time \( k \),
- \( Err[k] \) = the desired OD minus the measured OD at sample time \( k \),
- \( k_1 \) = constant proportional to Trans. % vs. Pow. slope parameter\(^1\),
- \( k_2 \) = constant proportional to anticipation factor parameter\(^2\).

\(^1\) \( k_1 \) = Laser Power vs. DAC Slope × Transparency % vs. Power Slope
\(^2\) \( k_2 \) = Laser Power vs. DAC Slope × Anticipation Factor
The original mask writing system, shown in Figure 3.2, uses the Argon laser with Gaussian intensity distribution which, as discussed in Section 2.7, causes gray-level fluctuations in the written mask. To improve the gray-level accuracy, a beam shaper was added to the original system. However, the addition of the beam shaper to the system did not result in achieving a flat-top profile in the multi-line mode as it is designed to work with a single wavelength laser line. To improve the quality of the shaped beam, as well as achieving a better writing and measuring system, the GLWS was modified again to have multiple individual laser lines using a prism. Comparing Figure 3.3 with Figure 3.2, major changes have occurred to the system resulting in many hardware and software modifications to the both GLWS and WinLTC. Among all the improvements, separation of the writing and measuring processes using two laser beams is the most important change to the system. This improvement was done after addition of a prism to the beam path, which separates the multi-line Argon laser beam to individual lines. Another important change in the software side of the system is the new method of calibrating the sensors which is explained in the next chapter. Table 3.1 and Table 3.2 provide a summary of the hardware and software changes, which will be discussed further in subsequent sections.

Figure 3.3. The new Grayscale Mask Laser Writing System
Table 3.1. Hardware modification to the GLWS for this thesis

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Reason</th>
<th>Influence to GLWS</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial Communication Speed Upgrade</td>
<td>Increasing GLWS efficiency in communicating with other equipments.</td>
<td>Increases the total speed of mask writing.</td>
<td>Refer to Section 3.3.1</td>
</tr>
<tr>
<td>Improvement to the DAC Interface Card</td>
<td>Low voltage stability due to the use of regular ICs rather than precision ICs.</td>
<td>Increases the accuracy of OD measurement.</td>
<td>Refer to Section 3.3.2</td>
</tr>
<tr>
<td>Removal of ND Filter from the Beam Path</td>
<td>ND filters caused slight distortion to the beam while in the beam path. ND filters were no longer required to protect the sample sensor from high power writing laser.</td>
<td>Increases total available writing laser power.</td>
<td>Refer to Section 3.3.3</td>
</tr>
<tr>
<td>Increased Light Collection to Sample Sensor</td>
<td>Having smaller focused spot because of larger diameter input laser, increase the beam expansion after the focusing position.</td>
<td>Increases the accuracy of OD measurement as it lets the sensor to measure all portion of the probing beam after the mask.</td>
<td>Refer to Section 3.3.4</td>
</tr>
<tr>
<td>Electro-Optic Modulator Voltage Level Change</td>
<td>To increase the available resolution of voltage levels produced by the function generator</td>
<td>Increase the accuracy of mask writing by increasing the resolution of input voltage.</td>
<td>Refer to Section 3.3.6</td>
</tr>
<tr>
<td>Laser Beam Expansion with Beam Expanders</td>
<td>Required by the characteristics of the beam shaper.</td>
<td>Decreases the size of focused laser beam resulting in higher resolution pattern on the film.</td>
<td>Refer to Section 5.2</td>
</tr>
<tr>
<td>Changing the Beam Intensity Distribution Using a Beam Shaper</td>
<td>To create uniform intensity distribution of the laser power to avoid gray-level fluctuation on the patterned mask.</td>
<td>Creates more uniform patterns on the photomask.</td>
<td>Refer to Section 5.5</td>
</tr>
<tr>
<td>Added Prism at the Beam Path</td>
<td>To separate the multi-line Argon laser lines.</td>
<td>Required a major change to the GLWS setup.</td>
<td>Refer to Section 6.3</td>
</tr>
<tr>
<td>Separation of the Measurement Process Using Second Laser Beam</td>
<td>To protect the Sample sensor from high power laser and achieve more stable measurement near microlithography wavelengths.</td>
<td>Required a separate beam path and extra optics to combine the separate beams.</td>
<td>Refer to Section 6.4</td>
</tr>
<tr>
<td>Filtering out the Laser Beam Used for Writing of the Grayscale Mask with a Laser Line Filter</td>
<td>To prevent the high power laser line to effect the measuring process.</td>
<td>Increases the accuracy of OD measurement.</td>
<td>Refer to Section 6.9</td>
</tr>
</tbody>
</table>
Table 3.2. Software modification to the GLWS for this thesis

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Reason</th>
<th>Influence to Photomask Writing</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Calibration Fit for System Sensors</td>
<td>To increase the accuracy of laser power measurement</td>
<td>Increase the accuracy of mask OD calculation.</td>
<td>Refer to Section 4.2</td>
</tr>
<tr>
<td>Optimized OD Conversion Routine</td>
<td>Optimizing the FPGA software code to faster convert the sensor’s voltage to equivalent laser power using a polynomial sentence.</td>
<td>Increases the total speed of mask writing.</td>
<td>Refer to Section 4.3.1</td>
</tr>
</tbody>
</table>

Most of the changes to improve the GLWS system, most of them were required to create more accurate gray-levels on the film as they increase system stability and reduce the laser power fluctuations. However, some modifications were not related to the writing grayscale masks, but happened to add a new functionality to the GLWS. In Section 3.3, hardware improvements that have occurred to the GLWS system will be explained. The software improvements will also be discussed in Chapter 4 which are the modifications to the WinLTC program and to the FPGA C-code.

3.3. Hardware Improvements to the Grayscale Mask Writing System

In addition to the optical setup changes, some modifications also were required to the electronic hardware system resulting in more stable signals with lower noise levels, which increased the accuracy of grayscale mask writing and optical density measurement. Figure 3.4 shows the hardware interconnection of the GLWS and how they are controlled with the computer through serial ports connected via a USB to Serial converter.
Figure 3.4. Hardware Connections of the Grayscale Mask Laser Writing System (After [22])
3.3.1. **Serial Communications Speed Upgrade**

As seen in Figure 3.4, as the components used in the GLWS are connected to the computer via a RS-232 port. It is important to be able to communicate with them with the highest speed possible to eliminate any bottleneck in the mask patterning process and reduce unnecessary delays. One of the most important areas acting as a bottleneck in the GLWS is the FPGA board. The board is responsible for collecting data from the sensors with the maximum speed of ~500Hz. Using this speed, the usual data collected in one single line writing with 1000 µm length and the speed of 100µm/s is ~5000 data points. Transferring the collected data points from the FPGA to the computer can take more than 20 minutes for only one single line if the RS-232 connection is working in low speed. For this reason, the WinLTC was never allowed to collect data from the FPGA board while writing large bitmap files to save time with the price of having no measurement of the written lines.

Increasing the speed of serial connection to the FPGA requires recompiling the FPGA hardware as well as some changes to the WinLTC program to initialize the port with the correct bit rate. Although the FPGA board used in GLWS can be programmed to support up to 192,000 bits/s, the computer sets the speed limit to a maximum of 115,200 bits/s. Once the maximum speed is set for both devices, despite the computer being able to communicate with FPGA board directly through other serial communication software, the WinLTC refused to connect to the FPGA board. Hence, the speed had to be lowered to 38,400 bits/s where the WinLTC software was able to correctly communicate with the FPGA board. The new communication speed is 4X faster than the initial communication speed of 9,600 bits/s.

The function generator's RS-232 connection speed was also increased to its maximum rate at 19,200 bits/s. Although the function generator usually does not require high volume of data being transferred to it, some arbitrary waveforms are required to be loaded to the function generator by the WinLTC when writing a bitmap picture on the mask. Having a bitmap file with more than 100 lines to write, loading data faster to the function generator can increase the total speed of writing.
3.3.2. Improvement to the DAC Interface Card

The DAC interface card is an electronic board providing the regulated power supply for the sensors and an output voltage used to control function generator’s amplitude when needed. To control the function generator’s output voltage scale, the FPGA board’s internal DAC is used. As the output is a digital signal resembling an analog output, it passes through a 10kHz RC filter created on the DAC interface card in Part 4 of the circuit schematic shown in Figure 3.6. Using LT1413 OpAmp, the output signal becomes isolated from the input DAC signal creating an appropriate voltage level.

To provide the regulated power to the photodiode sensors, as shown in Parts 2 and 3 of the circuit schematic in Figure 3.6, an unstabilized input voltage source has been regulated using voltage regulator ICs. Knowing the fact that sensor’s output voltage range for the FPGA board must be <10V and >-10V, Part 1 of the circuit schematic has been designed to create appropriate bias voltage to the sensors negative rail which is found to be approximately -16.84V. The DAC interface card has been created by J. Dykes in 2010 as part of his research [22], but due to using of non-precision ICs the output voltage of the board had high noise levels with low voltage stability. Lower voltage stability for the positive and negative rails of the sensors caused the output signal to vary for a constant amount of laser power causing incorrect power conversion. The new improved DAC interface card shown in Figure 3.5 has been created using precision ICs to generate output with higher stability and lower noise levels.

![Figure 3.5. DAC Interface Card](image)
3.3.3. Removal of ND Filter from the Writing and Measuring Beam Paths

As the bimetallic grayscale films transparency is dependent to the alloy oxide created via thermal reaction caused by the laser intensity, it is important to control the power accurately while writing the film. As accurate as the laser power can be controlled, the stability of the laser power is still an issue in mask writing process. The Argon ion laser power stability is <1% (refer to Section 6.8), which limits the amount of gray-level accuracy can be reached in mask writing process. The laser power stability increases when used in higher power outputs. Hence, using high power laser with ND
filters to reduce the power back to the desired level can decrease the amount of power fluctuation (see Figure 3.2). Although this method can improve the gray-level accuracy on the mask, the high power laser causes permanent damage to the ND filter. For example, if a low ND filter (0.4OD) is placed in the beam path, it absorbs ~60% of the incoming laser power which expands the glass and creates a permanent dome resulting in the laser beam alteration.

The Argon laser stability issue can be minimized by increasing the writing velocity. Previously, the masks were written with 20µm/s velocity, which can be increased 25-50X (500µm/s to 1000µm/s) depending on the ODMFS sampling rate. Increasing the writing velocity eliminates the need for ND filters in the beam path to reduce the fluctuation of the beam power. However, the power stability still remains an issue for the OD measurement system.

The old GLWS system used the Argon laser to write the mask and measure its OD using a single multi-line laser. This created issues in the measurement process as the Sample sensor could be damaged with the modulated high power laser for writing. Placing ND filters on the sensor plate reduced the laser power for sensor protection, but it was also reducing the sensor sensitivity in the low power modulated laser beams. Separating the writing and measuring processes using two separate laser lines in this thesis enabled the GLWS to be used with no ND filter in its beam paths.

3.3.4. Increased Light Collection to the Sample Sensor

Shaping the Gaussian laser beam to a flat-top profile is a useful method to eliminate gray-level variations. To shape the laser beam, a refractive field-mapping beam shaper was used. Chapter 5 will discuss more about beam shaping techniques used in this thesis. Using a beam shaper required the laser beam to be expanded to ~4mm to 8mm in diameter from ~1.5mm initial diameter. Equation 3.2 shows the focused spot size calculation based on the input beam diameter [33]. As it can be seen, using a 50mm Plano-convex lens to focus the 514.5nm green laser beam, the focused spot size reduces from 21.8µm with a 1.5mm diameter input beam to 8.1µm with a 4mm diameter input laser.
Figure 3.7. Short Focal length lens added to the beam path after the focusing lens to collect the spread laser light at the Sample sensor

\[ D = \frac{4\lambda f M^2}{\pi D_0} \]

Where \( D \) = the focused spot diameter (at the 1/e\(^2\) point),
\( \lambda \) = the laser wavelength,
\( f \) = the lens focal length,
\( M^2 \) = the laser quality factor (1 for a theoretical Gaussian beam),
\( D_0 \) = the input beam diameter (at the 1/e\(^2\) point).

The Numerical Aperture (NA) number of laser beam is related to the focused laser spot size. Using Equation 3.3 [34] for the 8.1µm focused spot, the NA value becomes 40, while using 21.8µm, the value becomes 15. This shows that the smaller focused laser spot spreads out more quickly than a larger focused laser spot.
\[ NA \approx \frac{\lambda_0}{\pi \omega_0} \]

Where \( NA \) = the Numerical Aperture of the laser,
\( \lambda_0 \) = the laser wavelength,
\( 2\omega_0 \) = the diameter of the beam at its narrowest spot.

In this thesis, a beam expander is used to expand the original 1.5mm to 4mm beam compatible to use with the beam shaper. As the laser beam spreads out very quickly after its focal point, and as the sensor area is smaller than the spread laser beam, a short focal length lens (+25mm bi-convex) is added to the beam path before the Sample sensor (Figure 3.7). Using this technique, the entire laser beam is measured by the sensor enabling it to calculate an accurate OD of the written film.

Although this technique is a good way to collect the entire light after being spread, as the laser light entering the short focal length lens is not collimated, any change to the input beam characteristics has a significant impact in the focused laser spot size. This issue will be further discussed in Section 7.4.

### 3.3.5. **Electro-Optic Modulator Driving Amplifier**

The Electro-Optic Modulator (EOM) is a Pockel Cell system which modulates the laser beam intensity by applying an electric field across an electro-optic crystal which affects the beam polarization angle. An amplifier controls the required voltage levels (Figure 3.8(a)). This amplifies an input voltage from a function generator which outputs a DC voltage with a limited amplitude (Usually <2V_{pp}). The required voltage level for intensity modulation is different for each specific laser wavelength. For example, the \( \frac{1}{2} \) wave voltage for 500nm wavelength laser beam is ~465V, which result to \( \frac{1}{2} \) wave voltage of ~478V for 514.5nm wavelength Argon laser used in this thesis. To set the off state of the EOM, the voltage must be biased for the crystal angle, so the amplifier is connected to the bias power supply (Figure 3.8(b)). The driver works in three different modes: Unipolar negative, Unipolar Positive, and Bipolar. In any of these modes, the input voltage to the amplifier cannot exceed maximum of 2V_{pp} which generates a maximum output voltage of 750V_{pp} resulting in a forward gain of ~375V/V push-pull [35].
The EOM output power response to the amplifier output voltage levels is shown in Figure 3.9. As seen in the figure, the EOM output power response is a Sin$^2$ function to the input voltage. In this specific case, it can be seen that the fully ‘On’ state of the EOM occurs at $\sim$303V and fully ‘Off’ state occurs at $\sim$132V, resulting in the range of 435V$\text{pp}$ approximate to the theoretical calculated value.

Previously, the driver was set to work in unipolar negative mode. Having the driver working in this mode, it cannot accept any positive voltages. Mistakenly setting the function generator to any positive voltages, the amplifier could be damaged. The other limitation of using the driver in unipolar negative (or positive) mode is the inability of the function generator to produce high resolution output to feed the amplifier for any voltage range $<-1\text{V}$ ($>1\text{V}$). To protect the amplifier from any possible damage and to
increase the resolution of its input voltage, the driver was switched to be used in bipolar mode. The next section discusses the advantages of using the driver in bipolar mode.

### 3.3.6. Function Generator Voltage Output Resolution and Stability

To better control the laser power with the EOM, the voltage output and resolution of the signal generator needs to be accurately controlled. Having the amplification factor of 375V/V suggests that the amplifier input voltage accuracy must be in the order of 1mV to achieve a reliable control over the laser power. Reproducibility and resolution of the DC voltage from the function generator are some of the critical factors in controlling the laser power as any change in the input voltage results in laser power variation causing the gray-level shift on the mask.

The function generator DC voltage output has the resolution of 0.1mV for the voltages between -0.1V and 0.1V, the resolution of 1mV for the voltages between -1V and 1V, and resolution of 10mV for voltages above 1V or below -1V. Previously, using the driver in unipolar negative mode, the resolution of the input voltage was limited to 10mV, which only allowed producing ~300 distinguished voltage points in writing the mask. After switching the driver to the bipolar mode, the function generator is set to work in -0.75V to 0.75V range that can be controlled by the resolution of 1mV being able to produce ~1500 distinguished voltage points. Finally, as the resolution in the desired voltage range is 1mV, the reproducibility of the output voltage is also ~1mV, which is good in controlling the laser power with <1mW accuracy.

Using the DAC output instead of the function generator, the amplifier can be controlled directly with the FPGA board. In theory, as the DAC output is a digitally created TTL level analog signal with arbitrary bit numbers, it can generate very accurate voltages with very high resolution. However, the resolution and reproducibility test of the DAC signal revealed that its output accuracy is >2mV, while the behavior of the signal becomes random by increasing the number of DAC bits. Hence, the FPGA DAC interface could not be used to replace the Function Generator for this thesis.
3.4. Electro-Optic Modulator Alignment Procedure

As discussed in Section 3.3.5, the EOM modulates the laser beam when high voltage is applied to parallel plates surrounding an electro-optic crystal, which rotates the laser beam polarization. By passing the laser through a polarizer, only the correct portion of the beam transmits and the rest reflects out. Alignment of the EOM determines the amount of the laser ‘On’ to ‘Off’ ratio, which can be as high as 1000:1 in low power input laser to 500:1 in higher power input lasers.

Referring back to Figure 3.3, several optical components were placed before the EOM diverting laser light into the EOM. The components can be moved unintentionally by any object slightly hitting them changing the position of the laser entering the EOM. Previously, alignment of the EOM was adjusted only if any major change happened to the GLWS or optical components requiring the GLWS to be completely realigned. The new alignment procedure will help to keep track of EOM alignment all the time and readjust it whenever the efficiency or ‘On’ to ‘Off’ ratio is lower than expected.

Looking at Figure 3.10, to align the EOM for better efficiency and higher ‘On’ to ‘Off’ ratio, it needs to be adjusted for roll, pitch, and yaw as well as its input aperture position relative to the laser light. In case of the first time alignment of the EOM, it must be positioned such that a low power laser beam roughly passes through the center of both input and output apertures of EOM. As the laser beam power needs to be measured during the alignment procedure, a power meter is placed in the beam path at a far distance from the EOM to prevent any scattered laser light affecting the measurements. For this thesis the FieldMaster GS power meter from Coherent Inc. with the LM-2 Silicon head detector was used to measure the laser power. By placing the LM-2 detector in the beam path, and having the EOM input and output apertures roughly aligned with the laser beam, the EOM roll can be adjusted until the maximum power is achieved. To perform this procedure, the input voltage of the EOM needs to be disconnected from the amplifier. Having the EOM adjusted for maximum power, the combination of X-Z position, yaw, and pitch alignment needs to be done together to achieve the output power of ~85% of the input power, which is close to the EOM efficiency.
Achieving the maximum output power of EOM, the voltage inputs can be connected at this point. Next, the function generator’s output voltage needs to be set to +0.75V, and then by turning the potential pot located in the front panel of the bias power supply (Figure 3.8(a)), the amplifier’s output voltage must be set to 0V. Up to this point, the +0.75V was mapped to the maximum laser power passing through the EOS.

The final stage in EOM alignment is the ‘On’ to ‘Off’ ratio adjustment. By changing the function generator’s output voltage to -0.75V, the EOM blocks most of the laser beam and only a small portion of it passes through the EOM. However, the amount of the light can be reduced by further aligning the combination of X-Z position, yaw, and pitch. The alignment procedure is considered done if the laser ‘On’ to ‘Off’ ratio is already >500. However, the ‘On’ to ‘Off’ ratio must be tested with a high power laser to confirm its value stays >500.

3.5. Microscope View Alignment Procedure

As in any optics system, the alignment of the microscope is important to gain access to all its advantages such as finding the position of writing on the mask, visual inspection of the quality of written mask and finding the exact focusing position of the
laser beam. Previously, the microscope was treated as a fixed optical element, so the focusing lens and the mask must have been aligned from its view point. In this section, a simple microscope alignment procedure will be presented.

The first step in aligning the microscope view angle is alignment of the tilting stage on the z-axis to the incoming laser beam. Using a mirror on the z-axis (or the diving board above it) and autocorrelation method (where the reflected beam is aligned to the source beam), the stage can be aligned to be perpendicular to the incident laser light without any focusing lens installed. Next, after having the stage perfectly perpendicular to the laser, the microscope view can be aligned with the same mirror on the table using the screws on its mounting stage (the microscope aperture must be at its smallest size and the light intensity should not be high). By seeing the microscope light exactly at the center of the image, the microscope view is perfectly aligned in parallel to the incoming laser light. Next step is installing the focusing lens such that the laser light passes exactly from the center of it. To verify the alignment, an aperture can be used. Finally, looking at the microscope image on the computer screen, the X-Y position of the microscope can be aligned relative the focusing lens, if the microscope light seems to be at the edge of the aperture.

### 3.6. Chapter Summary

In this chapter, the improvements and modifications to the Grayscale mask Laser Writing System (GLWS) hardware were described particularly in regards to adding new optical equipment, and electronic hardware improvements. These modifications were as a result of low signal stability and high noise levels, such as the DAC Interface Card, or to protect the system while gaining more advantages like modifications to the EOM amplifier, or as methods of adding new functionality to the GLWS, such as addition of the measuring beam to separate writing and measuring processes. Although most of the changes act to improve the GLWS ability to produce higher quality grayscale masks, the most influential change is the separation of the measuring beam, which will be discussed in Chapter 5. The next section will discuss the new software functionality added to the GLWS to increase the accuracy of the control and OD measurement of the masks.
4. Improving Control and Measurement of Bimetallic Grayscale Writing Process

4.1. Introduction

This chapter will discuss the improvements in the Grayscale mask Laser Writing System (GLWS) sensor calibration procedure. The new calibration routine provides a more accurate relationship between the output of the sensor and laser power, which enhances the ability of the system in calculating the bimetallic grayscale mask true Optical Density (OD). To perform the sensor calibration routines, statistical fitting methods will be used.

4.2. New Per-Channel Laser Power Calibration Procedure

The photo-diodes used in the system are responsible for measuring the amount of laser power at several key locations in the beam path. Each sensors output is connected to a 24-bit ADC channel that converts the sensor’s signal (from -10V to +10V) to their corresponding 24-bit digital value. To use the sensor's digital output value easier in data processing, they must be converted to their corresponding laser powers. To correctly convert the outputs to the laser intensity, the voltages need to be compared versus a standard measurement of the power. For this thesis, a set of different external stand-alone power meters have been used. However, to automate the comparison process using WinLTC, only the FieldMaster GS power meter with LM-2 silicon detector head and LM-30 Thermal detector head have been used. The following subsections will discuss the calibration procedures for the Input Sensor, the Reference Sensor, and the Sample sensor (see Figure 4.1).
4.2.1. Input Sensor Power Calibration

Before the addition of the second wavelength as mask measurement beam to the system (discussed in Chapter 5), the Input sensor (see Figure 4.1) was responsible to measure the main power of Argon laser entering the EOM. Comparing the main laser power with the power measured with the Reference sensor (see Figure 4.1), the stability of the Argon beam and the effect of the EOM on the beam was determined. However, as the second wavelength (457.9nm) was introduced to measure the optical density of the written mask, the Input sensor was used to measure the power of the measuring wavelength as a reference power in OD calculation. Having the 457.9nm wavelength as the lowest power line in the multi-line Argon laser, the previously used 1OD and 0.8OD filters before the Input sensors were removed from the setup.

![Figure 4.1. Input, Reference, and Sample sensor positions in the GLWS](image1)

**Figure 4.2. Possible positions of ND filter use in the beam path for calibrating sensors**
To start calibration procedure, the FieldMaster LM-2 detector head is placed after the beam sampler which samples a portion of the beam for the Input sensor, but before the beam expander. As the measuring beam does not pass through the EOM, the laser power needs to be altered by altering the multi-line Argon power from ~0.4W where the 457.9nm wavelength starts emitting to the laser’s maximum power at ~6W. The details about the Argon laser’s wavelength relative power portion at each commanded power can be found in Section 6.3.1. As the maximum measurable power with the LM-2 silicon detector head is 50mW, ND filters are required to be used before the sensor to reduce the laser power where needed. To obtain the Input sensor’s response for its non-linear part, the ND filters are used in pre-sensor position (see Figure 4.2) which results in collecting un-attenuated data points. However, in order to fit the full voltage range of the Input sensor, the ND filters need to be used in post-sensor position. Placing the ND filters before the FieldMaster LM-2 head attenuates the laser power only for the power meter, but the Input sensor measures the full laser power. Once all the data is gathered into excel sheet, a scaling factor is applied to the attenuated data so that it adjusts to the trend of the un-attenuated data. Figure 4.3 and Figure 4.4 illustrate the measurements taken from the Input sensor. As it can be seen in Figure 4.3, the un-attenuated data covers the non-linear part of the output voltage range from -10V to -9V (0 to 1mW) with higher resolution, and the rest of the curve is covered with the attenuated data points, shown in Figure 4.4.

![Figure 4.3. 0 to 1mW (-10 to -9V) range of the Input sensor voltage vs. laser power](image)

**Figure 4.3.** 0 to 1mW (-10 to -9V) range of the Input sensor voltage vs. laser power
The next step is creating the calibration file which will act as a Look-Up-Table (LUT) for the FPGA while converting the sensor’s output to the corresponding laser power. Previously, the calibration was performed visually on the plot. By positioning a limited number of data points on the sensor’s voltage versus laser power curve, the visual fit is created. Visually fitting the sensor’s response introduces a large range of human error to the calibration process. In addition, using limited number of data points for fitting the curve introduces calculation error in the power conversion routine. Although the calculation error could be reduced by increasing number of points, it limits the maximum FPGA processing time. Figure 4.5 shows a visually created calibration fit on the curve shown in Figure 4.4 with 10 data points.
As a part of this thesis, an improvement in creating the calibration fit was introduced to the GLWS software. In the new method, the calibration fit starts by converting the sensor’s output voltage $V_{sensor}$ to its equivalent 24-bit ADC value using Equation 4.1. Then, to easily use the ADC values in the upcoming calculations, the resulting number is divided by $10^5$. 

$$ADC\ value = \left[ \frac{(V_{sensor} + 10) \times 2^{24}}{20} + 0.5 \right]$$ \hspace{1cm} 4.1

Having the laser power values vs. the sensor’s ADC values, a curve fitting tool like Excel or Matlab can be used to generate a fit over the resulting curve. For this work, regression analysis in Excel was used to statistically fit the data for up to 6th order polynomial curves (the maximum order possible on the FPGA) and determining which fit gives the best results using statistical methods. After generating the fit for a specific order, the residuals (the difference between the data and the fit) were plotted against the actual data to visually check for existing of a pattern in the plot. Ideally, the residuals should be randomly distributed. If the residuals plot shows a pattern, it means that there was a parameter that has not been accounted for. Since patterns are harder to see in the visual inspection, statistical analysis was performed using runs test methodology [36]. In brief, the test was done by asking the question of how often the sign of the residuals change. In an ideal random pattern, the sign of the residuals are expected to change frequently. Figure 4.6 shows two residual plots from Table 4.4, which clearly shows a wavy pattern in the 3rd order fit (left) compared to the 6th order (right) which is nearly random. Once a randomness of $>1.5\sigma$ to $2\sigma$ ($\sim85\%$ to $\sim95\%$) is achieved for a specific order, the fit is considered good for the data set, and higher order are ignored as adding more terms does not benefit the fit’s goodness.

![Figure 4.6. Residuals Plots of 3rd order and 6th order fit (see Table 4.4)](image-url)
Before creating the fits, the curve is divided into several intervals that appeared to have the same behaviour. To easier fit the curve of the Input sensor (Figure 4.4), the collected data was divided into 4 intervals; Interval #1 from 0 to 0.3mW (-9.88 to -9.3V of the sensors output signal), interval #2 from 0.3 to 1.1mW (-9.3 to -9V), interval #3 from 1.1 to 16mW (-9 to -3.5V), and interval #4 from 16 to 80mW (-3.5 to 10V). Using mathematical equations (Equations 4.2, 4.3, and 4.4) from [36], the residual analysis of each used interval for up to 6th order is shown in Table 4.1 to Table 4.4.

\[
\mu = \frac{2n_1n_2}{n_1 + n_2} + 1 \hspace{2cm} 4.2
\]

\[
\sigma^2 = \frac{2n_1n_2(2n_1n_2 - n_1 - n_2)}{(n_1 + n_2)^2(n_1 + n_2 - 1)} \hspace{2cm} 4.3
\]

\[
z = \frac{u - \mu + \frac{1}{2}}{\sigma} \hspace{2cm} 4.4
\]

Where

\[
\mu = \text{mean value},
\]

\[
\sigma^2 = \text{variance},
\]

\[
z = \text{unit normal deviate},
\]

\[
n_1, n_2 = \# \text{ of positive/negative residuals},
\]

\[
u = \# \text{ of runs}.
\]

It was shown that the probability of the fit being good for the intervals #1, #2, and #3 is between close to 2σ, while the probability of the interval #4 is ~1.5σ. It can be seen that for interval #2, the lowest order which generated the highest probability fit is the 3rd order, while using the 6th order in interval #4 can only reach ~82% probability. These results are statistically significant and higher than any of the lower orders. Also note that in Table 4.1 to Table 4.4, the residual range for the best fits is smaller than for the lower order fits. Based on the analysis results shown in the tables, the fits are created and shown in Figure 4.7, for interval #1, Figure 4.8, for interval #2, Figure 4.9, for interval #3, and Figure 4.10, for the interval #4. After choosing the fits for each interval, the boundaries are adjusted such that the values match at that point. To do so, the difference of the values for the boundary of each interval is solved to achieve the lowest amount. In case of the fits given below, the range of difference error percentage is in the order of 1e-5% which is negligible. In terms of slope difference however, it varies from 1 to 8%.
### Table 4.1.  Goodness of fit based on examination of residuals for 0 to 0.3mW

<table>
<thead>
<tr>
<th>Interval #1 (30 Data Points) 0 to 0.3mW (-9.88 to -9.3V)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit Order</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td># of Positive Residuals ( (n_1) )</td>
<td>14</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td># of Negative Residuals ( (n_2) )</td>
<td>16</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td># of runs ( (u) )</td>
<td>8</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>( \mu ) (Mean)</td>
<td>15.93</td>
<td>15.73</td>
<td>14.93</td>
</tr>
<tr>
<td>( \sigma ) (Standard Deviation)</td>
<td>2.68</td>
<td>2.64</td>
<td>2.49</td>
</tr>
<tr>
<td>Residual Range</td>
<td>±0.003</td>
<td>±0.001</td>
<td>±0.0006</td>
</tr>
<tr>
<td>( z ) (Unit Normal Deviate)</td>
<td>-2.78</td>
<td>-0.09</td>
<td>1.83</td>
</tr>
<tr>
<td>Probability of Being Random, NormDist( (z) )</td>
<td>0.28%</td>
<td>46.48%</td>
<td>96.65%</td>
</tr>
</tbody>
</table>

### Table 4.2.  Goodness of fit based on examination of residuals for 0.3 to 1.1mW

<table>
<thead>
<tr>
<th>Interval #2 (44 Data Points) 0.3 to 1.1mW (-9.3 to -9V)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit Order</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td># of Positive Residuals ( (n_1) )</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td># of Negative Residuals ( (n_2) )</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td># of runs ( (u) )</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>( \mu ) (Mean)</td>
<td>22.82</td>
<td>20.09</td>
</tr>
<tr>
<td>( \sigma ) (Standard Deviation)</td>
<td>3.25</td>
<td>2.83</td>
</tr>
<tr>
<td>Residual Range</td>
<td>±0.01</td>
<td>±0.008</td>
</tr>
<tr>
<td>( z ) (Unit Normal Deviate)</td>
<td>-2.56</td>
<td>2.97</td>
</tr>
<tr>
<td>Probability of Being Random, NormDist( (z) )</td>
<td>0.52%</td>
<td>99.85%</td>
</tr>
</tbody>
</table>
Table 4.3. **Goodness of fit based on examination of residuals for 1.1 to 25mW**

<table>
<thead>
<tr>
<th>Interval #3 (80 Data Points)</th>
<th>1.1 to 25mW (-9 to -3.5V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit Order</td>
<td>2</td>
</tr>
<tr>
<td># of Positive Residuals ($n_1$)</td>
<td>45</td>
</tr>
<tr>
<td># of Negative Residuals ($n_2$)</td>
<td>35</td>
</tr>
<tr>
<td># of runs ($u$)</td>
<td>24</td>
</tr>
<tr>
<td>$\mu$ (Mean)</td>
<td>40.38</td>
</tr>
<tr>
<td>$\sigma$ (Standard Deviation)</td>
<td>4.37</td>
</tr>
<tr>
<td>Residual Range</td>
<td>±0.1</td>
</tr>
<tr>
<td>$z$ (Unit Normal Deviate)</td>
<td>-3.63</td>
</tr>
<tr>
<td>Probability of Being Random, NormDist($z$)</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

Table 4.4. **Goodness of fit based on examination of residuals for 25 to 80mW**

<table>
<thead>
<tr>
<th>Interval #4 (45 Data Points)</th>
<th>25 to 80mW (-3.5 to 10V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit Order</td>
<td>3</td>
</tr>
<tr>
<td># of Positive Residuals ($n_1$)</td>
<td>24</td>
</tr>
<tr>
<td># of Negative Residuals ($n_2$)</td>
<td>21</td>
</tr>
<tr>
<td># of runs ($u$)</td>
<td>7</td>
</tr>
<tr>
<td>$\mu$ (Mean)</td>
<td>23.40</td>
</tr>
<tr>
<td>$\sigma$ (Standard Deviation)</td>
<td>3.30</td>
</tr>
<tr>
<td>Residual Range</td>
<td>±0.2</td>
</tr>
<tr>
<td>$z$ (Unit Normal Deviate)</td>
<td>-4.82</td>
</tr>
<tr>
<td>Probability of Being Random, NormDist($z$)</td>
<td>0.00%</td>
</tr>
</tbody>
</table>
Figure 4.7. Interval #1: 0 to 0.3mW (-9.88 to -9.3V), 6th degree polynomial fit on the laser power vs. Input sensor voltage

Figure 4.8. Interval #2: 0.3 to 1.1mW (-9.3 to -9V), 3rd degree polynomial fit on the laser power vs. Input sensor voltage
Figure 4.9. Interval #3: 1.1 to 25mW (-9 to -3.5V), 6th degree polynomial fit on the laser power vs. Input sensor voltage

Figure 4.10. Interval #4: 16 to 80mW (-3.5 to 10V), 6th degree polynomial fit on the laser power vs. Input sensor voltage

The resulting 2nd degree to 6th degree polynomial sentences will later be loaded into the FPGA board to accurately convert the sensor’s output to the equivalent laser power. This new improvement eliminates human error factor in the calibration file creation phase as well as the calculation error in the voltage to power conversion phase.

As the ADC values calculated in Equation 4.1 have been divided by $10^5$ before the curve fitting, the coefficients must have at least 7 significant digits in the fit equations.
Having less significant digits will result in large errors in the calculation of the laser power.

The new method of creating calibration fit is statistically superior way of reducing any laser power conversion errors in the software, resulting in more accurate measurement of Optical Density (OD) in the mask patterning process. Unfortunately, calculating a high degree polynomial sentence can result in a long processing time in the FPGA’s voltage to power conversion routine. Hence, optimizing the code in the FPGA to reduce the execution time is required. Section 4.3.1 will discuss the optimization of the voltage to power conversion routine.

4.2.2. Reference Sensor Power Calibration

The Reference sensor (see Figure 4.1), measures the modulated writing laser power after the EOM. Using the FieldMaster LM-2 detector to measure the laser power, the process can start by placing the detector after the focusing lens such that the detector’s silicon plate is not in the focusing plane of the lens (as it might damage the detector). The reason for using the detector below the focusing lens is the addition optical equipments like the beam shaper (discussed in Chapter 5), and beam combiner (discussed in Section 6.5), which reduce the total available power of the laser. As the second laser beam is combined to the main beam path just before the focusing lens, it must be blocked before joining the main path. In the beginning, using low power multi-line Argon laser such that the maximum power reaching the FieldMater is <50mW, the power measurement can be done sweeping the EOM voltage arbitrarily from -0.75V to +0.75V resulting in collection of un-attenuated data points. Next, to cover all 20V of the Reference sensor range, different set of ND filters should be used in the beam path after the Reference sensor and before the FieldMaster, similar to the Input sensor calibration process. The ND filters can be damaged with the laser powers above ~200mW, so the LM-30 detector head can be used instead of LM-2 head for the powers above that.
Figure 4.11. Full range of the Reference sensor voltage vs. laser power for 0 to 1.5W (-10 to 10V)

Figure 4.11 illustrates the Reference sensor's output voltage to the laser power response at the focusing lens position. Using the fitting techniques discussed in the previous section, the fit curves for the Reference sensor are created and shown in Figure 4.12 to Figure 4.15.

Figure 4.12. Interval #1: 0 to 2.6mW (-9.89 to -9.47V), 5th degree polynomial fit on the laser power vs. Reference sensor voltage
Figure 4.13. Interval #2: 2.6 to 29mW (-9.47 to -8.89V), 5th degree polynomial fit on the laser power vs. Reference sensor voltage

Figure 4.14. Interval #3: 29 to 250mW (-8.89 to -6V), 6th degree polynomial fit on the laser power vs. Reference sensor voltage
4.2.3. Sample Sensor Power Calibration

With the old GLWS setup and the same laser beam to write and measure the photomask, the sample sensor calibration was the most complicated measurement of all sensors. As the sensor was struck directly by the laser rather than a sampled portion of the beam, ND filters were required to be used directly on the sensor to prevent any damage to it. Additionally, as the sensor was exposed to the widest power range, ND filters had to be used such that the lowest laser powers could be detected.

Using the second beam with a constant power throughout the writing process significantly reduced the complexity of the sample sensor calibration allowing it to be able measuring wider OD ranges of the photomask while writing. However, as the sensor still received the total amount of the measuring laser light rather than a sampled portion of it, the FieldMaster power meter could not be used as a reference to calibrate the sensor. Instead, the Input sensor was used as the reference power measuring device to calibrate the sample sensor. Similar to the Input sensor calibration, altering the multi-line Argon laser power directly and using several ND filters in post-sensor and/or pre-sensor positions (see Figure 4.2), the Sample sensor’s voltage response vs. the laser power was measured and presented in Figure 4.16. Figure 4.17 to Figure 4.19 show the resulting fit curves and the equations for different voltage intervals of the Sample sensor’s response curve, shown in Figure 4.16.
Figure 4.16. Full range of the Sample sensor voltage vs. laser power for 0 to 0.33mW (-10 to 10V)

Figure 4.17. Interval #1: 0 to 5.1µW (-9.88V to -9.57V), 3rd degree polynomial fit on the laser power vs. Sample sensor voltage
Figure 4.18. Interval #2: 5.1 to 19 µW (-9.57V to -8.88V), 6th degree polynomial fit on the laser power vs. Sample sensor voltage

Figure 4.19. Interval #3: 19 to 330 µW (-8.88V to +10V), 3rd degree polynomial fit on the laser power vs. Sample sensor voltage

The previous method of calibration required a standardized Input sensor for calibrating the Sample sensor. The new method does not need any of the sensors being calibrated in advance. As there will be an equation for Input sensor's response, its output voltage can be converted to power even after the calibration routine is performed, which is more time saving and efficient as oppose to the old method. The other advantage of the new method is its fitting ability which can be performed several times with different intervals until the best fit is achieved for both Input and Sample sensors.
4.3. Command Unit Software Improvements on FPGA Board

Created in 2010 by J. Dykes [22] as part of his thesis, the FPGA board was added to the GLWS to increase the ability of the system by adding feedback control to the GLWS via photodiode sensors. The FPGA board consists of several components, e.g. processors, interfaces, etc which are controlled with the main processor on the FPGA and WinLTC software connected via RS-232 serial connection. The main processor executes commands issued via the serial port from WinLTC software and mainly is responsible to collect measurement data from the ADC interface units. ADC interface units are the secondary processors connected to the ADC cards collecting data from the photodiode sensors. The following subsection will present an improvement on the command unit’s C-code (main.c), which helps to increase the speed of the data processing by optimizing it in the voltage to power conversion routine.

4.3.1. Optimized Power Conversion Routine

Generally, calculating a 6th degree polynomial sentence requires doing six exponentiations, six multiplications and seven summations. The simplest way of computing the polynomial sentence in the C-code was by using an already created power function in c library to calculate the exponentiations, “pow (double x, double y)”, and multiplication and summation operands. However, the long execution time of this method limited the FPGA abilities in processing data. Optimizing the polynomial sentence computing in the FPGA could be performed through several methods. However, as the maximum speed of the FPGA in power conversion was known, any method converting the voltage to power in the same range of time was the final goal in this optimization process. To compute the 6th order polynomial sentence, a loop method was used. The function started with a loop calculating and storing all the exponentiations upfront just before calling the power conversion function. The second loop later used the values from the previously calculated group of maximum 7 values, and it calculated the final power value. Using this method of calculation helped the FPGA processing time to decrease from ~135000µs (7.4Hz) with only one calibrated sensor to ~9000µs (111.11Hz) with all three sensors calibrated. As the achieved speed was the maximum limit of the FPGA processing speed, no more optimization process
could be performed on the conversion routine. Although the FPGA speed limit was achieved using this method, improving the FPGA processing time will require investigation in a more efficient methods of converting voltage to power.

4.4. Chapter Summary

In this chapter, the improvements to the GLWS control and measurement was discussed. The new method of sensor calibration increased the OD measurement accuracy as well as reducing the time required for calibration. Accurate OD measurement results in improving the quality of the patterned grayscale mask, in terms of increasing gray-level accuracy and reducing gray-level fluctuation. Although the gray-level fluctuation was reduced by improving the OD measurement process, it also requires addition of optical elements to the GLWS. The next chapter discusses methods of further reducing the gray-level fluctuations using a beam shaper.
5. Shaping Laser Spot Profile for Direct Writing of Gray-Scale Masks

5.1. Introduction

Patterning a grayscale mask with 256-gray levels is the objective of this thesis. Decreasing the gray-level variation due to laser beam intensity distribution is also an important factor in creating high accuracy grayscale mask. This chapter will discuss the effect of the laser beam intensity distribution on patterning of the grayscale masks. The beginning sections will talk about the Gaussian and Flat-top beam shapes and the effect of writing bimetallic mask with each laser profile. The later chapters will discuss the method of transforming the Gaussian beam to a flat-top profile using a beam shaper. Finally, beam shape modeling and test structures will be presented at the last sections of this chapter.

5.2. Laser Beam Expansion with Beam Expanders

Converting a laser beam from its common Gaussian profile into a more uniform shape is often done using diffractive optics setup called a beam shaper. One problem with using the beam shaper to control the spot profile is that it requires the laser to have a specific wavelength, large beam size, and initial pure Gaussian shape characteristics. The beam shaper is optimized for a green single-line laser beam with 1/e² diameter between 4mm to 8mm and 532nm wavelength. This chapter targets controlling for these spectral and shape characteristics. For the shape of the beam, the Argon laser output aperture is ~1.5mm, so in order to use it with the beam shaper, a 3X to 5X beam expander needs to be installed in the beam path before the beam shaper. The beam expander used in this thesis is a 3X Galilean expander created with -50mm Plano-concave and 150mm Plano-convex lenses aligned in a tube. Figure 5.1 shows the beam expander mounted in the beam path of the GLWS. To get a single wavelength,
the multi-line Argon ion laser can be separated to six individual laser lines, with only the longest and the most powerful wavelength (514.5nm in the green) passing through the beam shaper. The discussion about the Argon laser beam separation is presented in Section 6.3.

Figure 5.1. 3X Galilean Beam Expander created with -50mm Plano-concave and 150mm Plano-convex lenses

Increasing the laser beam diameter also helps to achieve higher resolution on the photomask as it reduces the focused laser spot diameter. However, as explained in Section 3.3.4, the larger in diameter the input laser beam is, the greater the expansion rate of the beam after the focused laser spot, which causes problems in measuring the beam power after being passed through the sample mask.

5.3. Gaussian Laser Beam Profile and Problems

The Gaussian laser is a beam whose intensity distribution can be approximated by Gaussian functions [37] using Equation 5.1, shown in Figure 5.2.

\[ I(r) = \frac{2P}{\pi w^2} \exp \left( -\frac{2r^2}{w^2} \right) \]  \hspace{1cm} 5.1

Where \( I(r) \) = Gaussian shaped beam intensity in radius ‘r’

\( P = \) Total power in the beam

\( w = 1/e^2 \) beam radius
Using the Gaussian beam to pattern the mask creates grayscale variations due to the thermal reaction patterning the mask. Since the bimetallic thermal resists are sensitive to the amount of absorbed laser power, the Gaussian intensity distribution creates a grayscale variation on the resist, meaning that the transparency at the center of the written spot is the highest and it reduces with the radius of the beam toward the edges of the spot. Figure 5.3 illustrates the effect of using Gaussian laser beam to raster-scan a grayscale photomask if the bimetallic resist transparency responded linearly with the absorbed power density across the spot. When parallel exposed lines are written with a fixed spacing, as in Figure 5.3, the overlapping Gaussian power distributions create an oscillation of the effective transparency. The thermal resist nature of the bimetallic films means that the material records only the highest power density in the overlapping beams as shown in the figure. The amount of the variation is a function of the writing spot size and the spacing between the lines.

The transparency variations shown in Figure 5.3 are called as “prison bars” in this thesis as they resemble the prison bars on the written mask. Figure 5.4 show the resulting variation for a raster scanned bimetallic mask done at a constant Gaussian beam power for a wide spacing between the lines. To reduce or eliminate the prison bar effect, the Gaussian beam must be transformed to a more uniform distribution. The next section discusses flat-top laser beams as the best option of eliminating the prison bar effect in grayscale mask patterning process.
Figure 5.3.  Effects of a Gaussian beam power distribution

(a) raster-scanned pattern; (b) OD variation of the overlapping Gaussian raster-scanned lines

Figure 5.4.  Back-lit 5X magnified part of the written pattern on 100nm Bi/In mask with Gaussian beam shape

5.4. Flat-top Laser Beam Profile

In principle, to pattern a uniform grayscale structure on the bimetallic mask, the laser intensity distribution must be transformed to a uniform intensity across the laser
spot called a flat-top beam. Figure 5.5 shows the flat-top vs. Gaussian intensity distributions. Using a laser beam with flat-top intensity distribution to pattern the grayscale photomask helps eliminating the prison bars. As is seen in Figure 5.6, using a flat-top beam profile, the grayscale pattern can be written on the mask with no gray-level variation, and with minimal overlap in patterned lines. Since the bimetallic resists almost are not changed when written twice at the same power (i.e. no superposition), the overlapping top-hats have little effect and create a uniform pattern.

![Flat-top laser beam distribution vs. Gaussian laser beam distribution](image1)

**Figure 5.5.** Flat-top laser beam distribution vs. Gaussian laser beam distribution

![Effects of a flat-top beam distribution](image2)

**Figure 5.6.** Effects of a flat-top beam distribution

(a) raster-scanned pattern (b) flat-top raster-scanned overlapping lines showing nearly uniform OD
The next section describes the techniques of transforming the laser beam intensity distribution, as well as the method used in this thesis to shape the Gaussian Argon laser to different shapes.

5.5. Changing the Laser Beam Intensity Distribution Using a Beam Shaper

Generally, to change the laser beam intensity distribution, beam integrators or field mappers are used. Beam integrators (homogenizer) use lens arrays to break the input beam into many beamlets and superimposes them on the output plane by the primary lens [38]. On the other hand, field mappers (Figure 5.7) transform the input field into the desired field in a controlled manner using diffractive optics [38]. Field mappers only work with beams with known field distribution, like single mode Gaussian beams [39], and they are very sensitive to alignment and beam dimensions. Hence, using these types of beam shapers require very accurate beam alignment and laser diameter control. Unlike the field mappers, beam integrators work with both coherent and multi-mode beams, where the input field distribution may be unknown. The integrators are much less sensitive to alignment and beam size; however interference effects are a problem with these types of beam shapers.

![Gaussian beam shaping to a uniform beam](image)

Figure 5.7. Gaussian beam shaping to a uniform beam (After [39])

In this thesis, a refractive field mapping beam shaper is used to shape the Gaussian Argon ion laser beam to a flat-top beam. The next section will discuss more about the beam shaper.
5.5.1. **Focal Pi-shaper Beam Shaper and Characteristics**

In this thesis, beam modification has been done with a refractive field mapping beam shaper from MolTech Company, called a Focal-piShaper_9_532 (see Figure 5.8) [40]. The beam shaper is a telescopic refractive optical system which transforms a Gaussian intensity distribution to an adjustable beam profile providing manipulation of intensity shape in area of focal point of the objective lens [40]. It requires a single-line laser of TEM$_{00}$ mode source with a diameter of between 4mm to 8mm. The Focal-piShaper is designed to work with the laser wavelengths between 470nm to 590nm, but the optimum range of wavelengths is 520nm to 550nm with the central wavelength of 532nm [40]. As seen in Figure 5.8, the beam shaper’s optical components are movable through the magnification and focusing rings. The magnification factor is from 0.75X to 1.33X depending on the orientation of the beam shaper in the beam path and the set of engravings which can be selected under various settings of magnification ring.

![Focal-piShaper beam shaper in the beam path](image)

Based on the experiments done with the beam shaper, the optimum input laser beam diameter is 6mm, so the magnification ring should be set such that it magnifies or demagnifies the beam size to 6mm. Based on the application notes of the beam shaper [40], the magnification ring can be set based on Table 5.1 depending on the input beam size. As it can be seen in the table, having 6mm laser beam does not require any modification to the beam size, but using smaller/larger laser beam than 6mm requires direct/reverse beam path orientation of the beam shaper with proper setting of the
magnification ring. The Gaussian laser entering the beam shaper transforms through the phase profile manipulation in a controlled manner creating interference fringes (see Figure 5.11) as a non-uniform output to be focused to a flat-top laser beam using a single focusing lens.

### Table 5.1. Magnification Ring setting based on the input beam diameter

<table>
<thead>
<tr>
<th>1/e² Beam Diameter</th>
<th>Magnification Ring Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>20</td>
</tr>
<tr>
<td>5 mm</td>
<td>10</td>
</tr>
<tr>
<td>6 mm</td>
<td>0</td>
</tr>
<tr>
<td>7 mm</td>
<td>-10</td>
</tr>
<tr>
<td>8 mm</td>
<td>-20</td>
</tr>
</tbody>
</table>

The next section will discuss the beam shaper setup in the beam path and the profiles achieved using it to transform Gaussian intensity distribution to more uniform pattern.

#### 5.5.2. Results of Beam Shapes

The beam shaping starts by choosing the single wavelength separated (488nm/514.5nm) from the multi-line Argon laser source. Then, expanding the beam using a 3X beam expander to ~4.5mm in diameter creates the input lasers of the beam shaper. To check the profile of the beam, it was captured using a camera sensor with the setup shown in Figure 5.9. Using the setup, the output beam of the shaper was focused onto the camera imager using several different focal length lenses. Figure 5.10 shows the 514.5nm laser beam picture before the beam shaper (input) and after it (output). The pictures were taken with Basler scA1390-17gm camera with 4.65µm x 4.65µm pixel size and 1392 x 1040 active pixels. As it can be seen, the beam shaper output is a non-uniform beam with fringes structure. Depending on the input beam 1/e² size, the fringes look more distinctly in the picture, as shown in Figure 5.11, where the input laser diameter is approximately 6mm with 488nm laser beam. The picture was taken with SMX-M81M camera from Sumix with 5.2µm x 5.2µm pixel size and 1280 x 1024 active pixels.
Figure 5.9. Setup used to capture the output of the beam shaper using the camera imager

Figure 5.10. 514.5nm Argon laser beam with approximately 5mm 1/e² diameter
(a) Input of the beam shaper (b) Output of the beam shaper
Analysing the input and output beam shapes will further prove the fact that the input Gaussian beam transforms to a non-uniform beam at the beam shaper output (note the interference fringes at the beam shaper output). Figure 5.12 and Figure 5.13 show the 3D and contour plots of the 514.5nm Gaussian input laser beam and its corresponding non-uniform output beam, and Figure 5.14 shows the 3D and contour plots of the non-uniform output beam of a 6mm diameter 488nm wavelength laser beam.

Figure 5.11. Output beam of the beam shaper with the input of approximately 6mm $1/e^2$ beam diameter

(a) 3D plot (b) Contour plot

Figure 5.12. 514.5nm input to the beam shaper with approximately 5mm $1/e^2$ diameter

(a) 3D plot (b) Contour plot
To determine the impact of the beam shaper on the focused laser beam, various tests were done with different focal length lenses from $f=100\text{mm}$ up to $f=1000\text{mm}$. To determine the various achievable beam shapes, pictures were taken at the focusing lens focal plane using the SMX-M81M camera. Having a camera with modest pixel size to analyze the focused beam shapes sets a limit on using smaller focal length lenses with the beam shaper.
Based on the beam shaper specifications, the beam shape is expected to change by approaching to the focusing lens from its focal point, shown in Figure 5.15. At the focal plane of the focusing lens, a highly peaked Gaussian shape beam is expected to be seen. By further moving the camera or the focusing lens closer together, other shapes like donut shape appears.

**Figure 5.15. The beam shape changes by moving the focusing lens from its focal point**

Preliminary results of beam shaping revealed that both 488nm and 514.5nm laser lines have the same pattern behaviour after passing through the beam shaper. Hence, the beam shape experiments were performed using 488nm wavelength. Figure 5.16 shows the beam shapes at the focal point of the tested lenses with 488nm line. The beam shapes were seen to be highly peaked Gaussian with all the lenses, as expected. By moving closer to the focusing lens, the Gaussian beam shape started transforming toward a donut shape distribution. Figure 5.17 illustrates the donut profile of the laser using 100cm, 50cm, 30cm, and 25cm focal length lenses. The donut shape was seen at 95mm, 24mm, 8.5mm, and 6mm after the laser focus position with Gaussian distribution, respective to the used lenses. The same behaviour of the beam shape transformation was seen after further moving close to the focusing lens, where the beam distribution changed to a multi-peaked profile, as seen in Figure 5.18.
Figure 5.16. Digital image, 3D plot, and Contour plot of the optical intensity distribution at the focal point of focusing lenses using beam shaper

(a) f=1000mm lens; (b) f=500mm lens; (c) f=300mm lens; (d) f=250mm lens.
Figure 5.17. Digital image, 3D plot, and Contour plot of the optical intensity distribution of the donut beam shapes

(a) 95mm closer from the focal point of $f=1000$mm lens; (b) 24mm closer from the focal point of $f=500$mm lens; (c) 8.5mm closer from the focal point of $f=300$mm lens; (d) 6mm closer from the focal point of $f=250$mm lens.
Figure 5.18. Digital image, 3D plot, and Contour plot of the optical intensity distribution of the multi-peaked beam shapes

(a) 135mm closer from the focal point of f=1000mm lens; (b) 34mm closer from the focal point of f=500mm lens; (c) 12mm closer from the focal point of f=300mm lens; (d) 8.5mm closer from the focal point of f=250mm lens.
From the test results performed with large focal length lenses, a model was developed to estimate the behaviour of the beam shaper to be used for shorter focal length lenses. One of the important parameters in the model was how the spot size changes by altering the focusing lens. The curve shown in Figure 5.19 illustrates that the spot size of the focused and the donut shapes have a linear relation with the focal point. Hence, the focused beam spot size \( W_{\text{focus}} \) follows Equation 5.2, and the donut shape spot size \( W_{\text{donut}} \) follows Equation 5.3. Using the equations, the beam’s focused spot size using 50mm lens is ~13.5µm, and the spot size of the donut shape is ~26µm.

\[
W_{\text{focus}} = 153.42X + 5.95 \quad 5.2
\]

\[
W_{\text{donut}} = 406.47X + 5.81 \quad 5.3
\]

![Figure 5.19. Focused and donut shapes spot size vs. lens focal length](image)

The other important data required from the model was how the position of different shapes changes with different focal length lenses. As seen in Figure 5.20, the start position of different shapes (in this case the donut and multi-peaked) has a linear relation with the focal length squared. The model indicated that the position of the donut shape \( P_{\text{donut}} \) and multi-peaked \( P_{\text{multi-peaked}} \) shape vs. focal point squared follows Equations 5.4 and 5.5, respectively. Using these Equations, the donut profile is expected to be seen +240µm and the multi-peaked shape is expected to be seen +340µm closer to the 50mm lens from the position of highly peaked Gaussian beam.

\[
P_{\text{donut}} = 95.068X \quad 5.4
\]

\[
P_{\text{multi-peaked}} = 135.05X \quad 5.5
\]
As seen in Figure 5.15, a flat-top shape was expected to be seen before the donut profile. However, further analysis of the shapes from the focal point to the donut profile resulted in finding no uniform distribution of the laser beam. The reason for this issue might have been the sensitivity of the beam shaper to the alignment/beam dimensions, as the field-mapping beam shapers are very sensitive to those parameters. The other possible reason could be the lack of proper test and measurement equipments, e.g. beam profiler that could have been used to profile the beam in real-time with movement of the lens position.

The next two sections will show the patterns written with the original Gaussian beam shape and the highly peaked Gaussian to confirm the effectiveness of the beam shaper in reducing the grayscale fluctuations, even with a non-uniform beam shape.

5.6. Test Patterns Written Using Gaussian Beam

Referring back to Figure 5.4, it illustrated a back-lit magnified part of a 256-level grayscale pattern written with Gaussian laser on a 100nm Bi/In mask in which the prison bars are visible. Although the 256-level grayscale mask was written with ±0.3 gray-level error in vertical direction, the gray-level fluctuations due to the Gaussian profile resulted in 30 times more gray-level variation in horizontal direction. An optical cross section OD measurement of the image (Figure 5.4) is shown in Figure 5.21. The maximum gray-level variation between the lines is seen to be of ±0.05OD which is equivalent to ±10 gray-levels in the patterned image.
Using the beam shaper to create more uniform beam profiles, the amount of gray-level variation is expected to be reduced. The next section presents a pattern written using the shaped beam and its optical cross sectional measurement.

### 5.7. Test Patterns Written Using Shaped Beam

The best test of a shaped beam is how much it improved the uniformity of the written pattern. As the flat-top profile was not identified in the beam shapes seen by camera sensor, the highly peaked pattern was selected to write the mask. Using the highly peaked beam, a 16 gray-levels structure was written over the full OD range of 100nm Bi/In film (Figure 5.22). The pattern was written using 4µm line spacing where each gray-level includes 10 lines and is separated by 100µm distance.
To compare the gray-level fluctuations using highly-peaked beam with the fluctuation happened in the mask written with Gaussian intensity distribution, the system was used in reading mode employing low power laser to perform an optical cross section measurement. The cross-section OD measurements for 3 sample levels of all 16 levels are shown in Figure 5.24. Based on the cross-sectional measurements, it is shown that the transparency variations reduces from a maximum ±0.05OD (±10 gray-levels) for the pattern written with Gaussian laser to a maximum of ±0.01OD (±2 gray-levels) between the lines written with the shaped beam.

![Figure 5.23. Back-lit picture of 16-gray-level structure on a 100nm Bi/In film taken with 20X objective lens](image)

(a) Gray level #10 (b) Gray level #5 (c) Gray level #0
Figure 5.24. Cross section OD measurement of 16-gray-level structure shown in Figure 5.22
(a) Gray level #10 (b) Gray level #5 (c) Gray level #0
As the test structure was written with the highly-peaked Gaussian shape, it can be expected that the gray-level fluctuation can be eliminated using more uniform beam profile. However, the variation in gray-level is greatly reduced even using the highly-peaked Gaussian shape rather than the normal Gaussian beam.

5.8. Chapter Summary

In this chapter, the beam shaping techniques were described particularly using a refractive field-mapping beam shaper from MolTech Company. The beam shaper was used with the single laser line (488nm or 514.5nm wavelengths) to produce a uniform intensity distribution. Using several focal length lenses to focus the non-uniform output of the beam shaper, its characteristics of the beam profiling was calculated. Although the beam shaper was used in its optimum conditions, the real flat-top beam could not be achieved. Hence, the highly peaked Gaussian shape was used to pattern the grayscale mask. It was seen that using the highly peaked Gaussian shape could also reduce the grayscale variation at least by a factor of 5.
6. Dual Wavelength Laser Writing and Measuring System

6.1. Introduction

This chapter will discuss the design of the Dual Wavelength Laser Writing and Measuring System. The first section describes the separation of the laser wavelengths from a single stabilized multi-line Argon ion source followed by the discussion of the relative power of each wavelength. Using the Argon highest power laser green line for writing and the shortest wavelength (violet) for measuring the written mask transmission, the grayscale accuracy can be improved. As both of the wavelengths need to be focused at the same spot of the mask, the next section provides a beam combination method and alignment procedure to merge the writing and measuring laser lines and discusses how to filter out the writing laser before being measured by the sensor.

6.2. Background

In producing high accuracy grayscale masks with the Grayscale mask Laser Writing System (GLWS), measurements of the film’s OD change in response to the laser power are valuable. As discussed in the previous chapter, a single wavelength (514.5nm green) has been used to write the grayscale mask to create accurate beam shaping. Using a second single shorter wavelength (457.9nm violet) for OD measurement is also an improvement, which allows the separation of the writing and the measurement processes. Another important reason for using 457.9nm for OD measurement is that it is closer to the wavelengths used in microlithography mask aligner or some DSWs (340-365nm). If a single wavelength is used for both writing and measuring processes, as it was done previously, it decreases the sensitivity to the OD change on the photomask as ND filters are required to protect the sensor from high power writing laser. The Optical Density Measurement and Feedback Subsystem
(ODMFS) was developed by Dykes [22] for his thesis. This was the main grayscale patterning system before 2012 that used a multi-line Argon ion laser beam to write the grayscale mask and measure its OD.

As a part of the research for this thesis to create higher quality grayscale masks, a second beam was introduced to the GLWS which is only used in optical measurement process. Before going into the details regarding the Dual Wavelength Writing and Measuring System, it is important to know how to separate the multi-line Argon ion laser wavelengths to obtain several single lines.

6.3. Argon ion Multi-line Laser Beam Separation Using a Prism

Patterning the grayscale masks with green Argon ion laser and measuring its written mask OD using the same wavelength results in a few problems. First in measurement process, the patterning laser power is constantly changing, making it harder to accurately measure the OD change. Secondly, it is important to measure the mask transparency at the violet or ultra-violet wavelengths used for micro-lithography. To obtain these advantages, the grayscale mask is written with a single laser line and is measured with another line closer to the wavelengths used in microlithography. One way of doing the OD measurement is to introduce another separate laser source of shorter wavelength to the GLWS specifically for the measurement purposes. However, this adds the cost the new source, which must have a high quality beam, and significantly complicates the alignment issue. Fortunately, as the Argon laser used to pattern the grayscale mask contains multiple wavelengths (514.5nm, 501.7nm, 496.5nm, 488nm, 476.5nm, and 457.9nm), they can be separated into its individual lines.

To separate the Argon laser lines, a diffraction grating method or a prism can be used. Using the diffraction grating to separate lines affects the laser beam shape, making it asymmetric. This creates a problem with beam shaper as it requires the TEM\(_{00}\) Gaussian laser beam. Hence, a special highly dispersive equilateral prism from Thorlabs made of N-SF11 glass was used to separate the laser lines (see Figure 6.1).
The high dispersion prism separates the lines into spread of angles which gives a large amount of dispersion over a short distance of the beam path.

Figure 6.1. Diagram of the Dual Wavelength Writing and Measuring System

The prism can be mounted in two orientations in the beam path (see Figure 6.2). Figure 6.2(a) shows a vertical mount with the sides of the equilateral prism generating the separation, while Figure 6.2(b) shows a horizontal mounted prism. The advantage of the vertical mounted prism in Figure 6.2(a) is that it gives better control over the angle of incident with respect to the surface normal. But as the prism is designed to work with the p-polarized or parallel polarized orientation, using the prism in s-polarized or perpendicular polarized orientation introduces ~55% laser light reflection from the surfaces of the prism. The intensity of reflection at each angle to the surface can be calculated from the Fresnel S or perpendicular polarized reflection of Equation 6.1.

\[
R_s = \left( \frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \right)^2 \tag{6.1}
\]

Where \( R_s \) = Amount of reflection for a S polarized laser  
\( \theta_i \) = Incident light angle  
\( \theta_t \) = transmitted light angle

To avoid >50% laser power loss, the prism was horizontally mounted in Figure 6.2(b), creating the beam paths shown in the system diagram in Figure 6.1, where the prism is marked as (1). Knowing the fact that the incident light to the prism surface normal must be ~60° to achieve the maximum laser line separation, a 32° angle block with the prism was used. With the parallel orientation, the total reflection from
prism surfaces was reduced to ~1%, which can be calculated from the Fresnel P or parallel polarization with the surface reflection of Equation 6.2.

\[
R_p = \left(\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}\right)^2
\]

Where \( R_p \) = Amount of reflection for a P polarized laser
\( \theta_i \) = Incident light angle
\( \theta_t \) = transmitted light angle

The multi-line Argon laser is a perpendicularly polarized laser; hence, using the prism in the orientation shown in Figure 6.2(b) to separate the wavelengths rotates the laser's polarization by 90° changing it to a parallel polarization.

Figure 6.2.  **Prism setup in the beam path with**
(a) Perpendicular orientation, and (b) Parallel orientation

Figure 6.3.  **Six single laser lines separated using the prism. The separation distances as seen at the aperture**
Figure 6.3 shows the six separated wavelengths from the single stabilized Argon ion laser source after ~30cm from the prism at the position of the aperture (marked as (2) in Figure 6.1). In selecting which two wavelengths for writing and measuring processes, the power of each wavelength must be measured. The highest power laser line will be chosen as the writing laser line and the laser with the least power will be chosen as the measuring beam. The next subsection will talk about each wavelength in details and will present the power portions of every single laser line in the multi-line Argon ion laser.

6.3.1. **Argon Laser Wavelengths Relative Power Portion**

Using a multi-line Argon mode to write the mask, it was important to know which wavelength contains most of the laser power, as the FieldMaster, by which the powers are compared, is calibrated for specific wavelengths. Without a prism in GLWS beam path to separating the Argon laser wavelengths, a SPM-002 spectrometer from Photon Control was used for relative power measurement and laser beam analysis. Figure 6.4 shows the relative intensity of each wavelength from 50mW to 800mW of commanded laser power (note that the laser displays power for the multi-line mode). As seen in the figure, except in 50mW where the 488nm wavelength is dominator, 514.5nm wavelength has the highest power among all other wavelengths. Note that this change in the relative intensity of the Argon lines with power is specific to each type of laser, and is generally not listed in their specification sheets.

With the prism separation of the wavelengths, the exact power of each laser line was measured separately using the FieldMaster power meter. Using LM-2 silicon detector head for low laser powers and LM-30 detector head for high laser powers (with the wavelength calibration of those), Figure 6.5 shows the output power of each Argon laser line as a function of multi-line Argon laser power. The power measurement analysis showed that the 514.5nm contains on average ~48% of the Argon laser power, which is, as expected, the most powerful wavelength among all other lines. Although the 496.5nm and 488nm contain ~16% of the total power in average, the 488nm takes a larger portion of the Argon laser at higher multi-line laser powers. For the remaining lines, the 476.5nm gives ~12%, the 501.7nm gives ~4% and the 457.9nm gives 3% of the Argon laser power.
Figure 6.4. Multi-line Argon laser spectrometry results for 50mW, 400mW, and 800mW multi-line laser powers

Figure 6.5. Multi-line Argon laser wavelengths relative power portions from 50mW to 5.5W multi-line laser power settings measured by FieldMaster with LM-2 and LM-30 detector heads
6.4. **Wavelength Separation of the Writing and Measurement Processes**

As shown in Figure 6.3, the Argon wavelengths are spread over ~15.1mm (514.5nm to 457.9nm) after traveling ~30cm distance beyond the prism. An aperture, created from a piece of Aluminum (painted in black) with a 3mm hole for each desired wavelengths, completely blocks four of the laser lines letting only the 514.5nm and 457.9nm wavelengths to pass through. The reasons for these wavelength selections will be presented in the next two subsections. The 514.5nm is then diverted to the writing laser beam path passing through the EOM modulating its power for grayscale mask writing process. A beam sampler then samples ~5% of the power for the reference sensor to measure. The 457.9nm laser uses another beam path to bypass the EOM, as it is valuable to have a constant power for OD measuring process. The 457.9nm line then passes through a beam expander to expand the laser to the same diameter of the writing beam to have approximately the same size focused spot after the focusing lens (the exact size depends on the lens used). Figure 6.6 shows the actual experimental setup of the Dual Wavelength Writing and Measuring System. The beam path drawn on Figure 6.6 specifies the 457.9nm laser path (marked as (2)) which is fully separated from the 514.5nm path (marked as (1)) passing through the EOM.

Both writing and measuring laser beams then need to be combined before the focusing lens to a single path that can be focused at the same spot on the photomask. Section 6.5 will describe how to combine two laser lines together followed by the method of writing and measuring beam alignment to create the same focused spot location on the photomask.
Figure 6.6. Beam path of the writing (514.5nm) and OD measurement (457.9nm) lines in the actual dual wavelength GLWS setup

6.4.1. 514.5nm Wavelength as the Writing Beam

The photomask laser writing process is a thermal reaction which changes the masks transparency level based on the absorbed laser power. To achieve the maximum transparency, the laser must have enough power to create the full oxidation process on the bimetallic film. As discussed in Section 6.3.1, the 514.5nm wavelength contains the maximum power among all other Argon laser lines. As discussed in Chapter 5, 514.5nm wavelength is the closest line to the 532nm laser which is the optimized wavelength of the beam shaper. For these reasons, the green laser line with 514.5nm wavelength was selected as the writing beam and diverted to the beam path through EOM.

6.4.2. 457.9nm Wavelength as Measuring Beam

To create 3D-microstructures using grayscale photomask, the microlithography systems usually use the G-line (435.8nm) to I-line (365.4nm) range as the light source. Measuring the optical density of the grayscale mask in wavelengths close to G-line and I-line is an advantage for the mask patterning system. Looking at the list of available
wavelengths of multi-line Argon laser, the 457.9nm wavelength is the closest which can be used as probing beam to the microlithography lines. In addition, referring to Figure 6.4 and Figure 6.5, the 457.9nm always has the lowest power among the other wavelengths, which makes it suitable to be used with the Sample sensor as it will not affect the already written pattern on the mask. In addition, as the 457.9nm does not need any power modulation through the EOM, its power remains constant throughout the mask writing process which results in more accurate OD measurement. Separating the writing and measuring wavelengths is the opportunity which is provided to the GLWS by using the prism in the beam path. Adding the 457.9nm wavelength to the GLWS, it must be combined with the main writing beam before the focusing lens. The next section discusses the method used to combine both wavelengths to a single laser line.

6.5. Combining Writing and Measuring Beam

Addition of the second wavelength to the GLWS as a measurement probe requires a separate beam path which avoids the EOM and beam shaper as a non-modulated line is required to measure the optical density of the written mask. The violet measuring beam then needs to be recombined with the green writing beam before the focusing lens, where both of the lines can be focused on the mask. To do this, a beam combiner mirror from Edmunds (NT86-390) was placed before the focusing lens at 45° angle, as shown in Figure 6.7. The combiner reflects the wavelengths from 439nm to 457.9nm and transmits 473nm to 647.1nm. Hence, the writing 514.5nm wavelength passes through the beam combiner, while the 457.9nm measuring wavelength is reflected toward the focusing lens to create the combined beams. As the combiner directly in the microscope optical path it does slightly affect the imager observing the writing of the mask.

Using the GLWS in closed-loop mode, the OD measurement needs to be taken in real-time on the same position where the writing laser is patterning the mask. The next section discusses the alignment procedure of two combined laser lines to be focused at the same position on the mask.
6.5.1. **Alignment Procedure of Combined Measuring and Writing Laser Beams**

The GLWS can be employed in open-loop and closed-loop (feed-back) modes. To use the system in open-loop, the line used for measurement is not necessarily required to be perfectly aligned with the writing line as it is used for probing after the mask is patterned. The main advantage of aligning the writing and measuring laser beams is the addition of the ability to measure the optical density of the written spot in real-time which can be employed in feedback system.

The alignment procedure starts with increasing laser power to the point that 457.9nm Argon laser line starts emitting. An ND filter must be used to reduce the power of 514.5nm laser line to approximately the same intensity as the 457.9nm line, so that beam can be easily seen. At this point, as the writing laser line is aligned within the GLWS with other optical elements like microscope and focusing lens, the 457.9nm line will be aligned with respect to the 514.5nm beam. By removing the focusing lens and the mask, the 457.9nm beam can be aligned by adjusting the beam combiner location/angle and three measuring path mirrors before the beam combiner. This is
done such that the 457.9nm line passes through the center of the focusing lens mount and hits the same spot of 514.5nm laser at the bottom of the X-Y table, which gives enough distance from the beam combiner to adjust for smaller angle difference of the beams. By achieving this alignment, the first step of the rough alignment is finished and the focusing lens can be placed back in the beam path.

The second step in aligning the writing and measuring lasers happens using a dummy bimetallic mask underneath the focusing lens. After removing the ND filter from the 514.5nm laser path, a single spot must be written on the mask to locate the writing lasers position on the mask, which can be marked with the crosshair on the microscope image on the computer screen. Next, the multi-line laser power must be increased enough in order to achieve higher laser power for the 457.9nm laser be able to write another spot on the mask. The 457.9nm laser spot can be refined by adjusting the beam combiner, and the procedure can be repeated until both spots are aligned to the same position on the mask.

Having the laser lines perfectly aligned rises other issues when their reflection affects the amount of power seen by the sensors and super cavity effect with the Argon laser. The next subsection will present the problems caused by the lasers reflection back to the beam path.

6.5.2. Effects of Writing and Measuring Laser Misalignment on OD Measurement

This section discusses the issue of keeping the two beam paths stable in the dual wavelength system. Even though the system sits on an optical table, small changes in the optical path or the laser might affect the relative position of the two line spots on the photomask. The spot shift at this point can be as small as 1µm, but it would be large enough to affect the OD measurement process. Figure 6.8 shows the OD response of a 100nm trimetallic Bi/Sn/In film (51% In, 16.5% Sn, and 32.5% Bi) written with laser powers from 2mW to 120mW while measured in real-time with the 457.9nm probing beam. The mask was written with 16 power levels per line for three times each. As it can be seen, two completely separate OD measurements have been achieved with the same power levels. The OD response resembling a linear curve is a result of slightly
misaligned measuring laser beam to the edge of the writing path, while the second curve is the real OD response of the same film after laser realignment. To prevent the misalignment effect, the alignment procedure of the writing and measuring laser beams must be performed every time the laser turns on or before patterning a grayscale mask to avoid any problems to OD measurement by the beam misalignment.

![Graph showing OD response comparison](image)

**Figure 6.8.** OD response of 100nm trimetallic Bi/Sn/In film (51% In, 16.5% Sn, 32.5% Bi) using the 457.9nm measuring laser beam aligned and slightly misaligned with the 514.5nm spot

As much as the writing and measuring laser alignment is important, finding the exact laser focus position is important. The next section will show the effect of the mask writing with an unfocused laser light and will describe a quick way to find the laser focus position on the mask while writing on it.

**6.5.3. Issues with Reflection of Lasers from Target Mask to the Main Laser Source**

By aligning the writing and measuring beams, the reflection from the mask surface introduced another problem to the GLWS. The 457.9nm wavelength starts emitting at ~400mW multi-line Argon power, and it is not very stable at the bottom-end of its emission. The 457.9nm laser reflection from the mask surface back into the Argon laser head will create a super cavity, where the returned beam causes more stimulated emission inside the laser tube resulting in the 457.9nm line power to increase. Since the
amount of power change is a function of the surface reflectivity, it can cause problem in optical density measurement by shifting the apparent transmission through the mask.

In trying to solve the reflection problem, several methods were tested. The reflected beam polarization from a surface is often expected to be different than the incoming beam. Hence, a polarization filter was added to the beam path to filter out the returned beam. However, the polarization filter was not able to filter the reflected beam, which suggests that the amount of polarization change was not sufficient. The other method used to reduce the super cavity effect was to increase the multi-line laser power to amounts where the 457.9nm wavelength was more stable, so the reflected beam would not affect the stability of the laser beam. With several optical elements in the measuring beam path, any planar reflective surface was prevented from facing towards the incoming laser beam. For example, as the lenses used in the beam expander are Plano-concave and Plano-convex lenses, having the flat surface of both lenses away from incoming laser beam helped reducing the reflection in the beam path. Finally, placing ND filters in the beam path before the bimetallic mask helped to reduce the laser power to the measurable range for the Sample sensor, and also reduced the reflected laser power to a range where it could not cause the super cavity effect.

6.6. Voltage Stability of Sensors Used in the GLWS

To create a reliable optical density measurement of the written mask, the sensors need to have a stable output signal, and be able to reproduce a constant output voltage for a constant amount of laser power. To test the voltage stability of the sensors, their output voltage was measured in a dark environment without laser as the laser stability is an issue by itself.

The sensors output voltage when measured in dark environment without laser light striking them is ~-9.95V. The voltage output of the sensors is measured with 100Hz frequency for duration of 10 seconds. In the 10 seconds, the FPGA gathers 1000 data points. The curve for the Input sensor is presented in Figure 6.9, for the Reference sensor is shown in Figure 6.10, and for the Sample sensor is seen in Figure 6.11. The figures show that the range of voltage fluctuation from the average output voltage of the
sensors is < |0.0015%|. This amount of fluctuation is only ~0.3mV\textsubscript{pp} in 20V\textsubscript{pp} range of the sensor outputs, which can be considered as a stable output voltage.

**Figure 6.9.** Output voltage fluctuation of the Input sensor in dark environment relative to the average

**Figure 6.10.** Output voltage fluctuation of the Reference sensor in dark environment relative to the average
6.7. 457.9nm Wavelength Laser Beam Power Stability

Using a separate laser line to measure the optical density of the photomask, the power stability of the laser is a key factor in OD measurement accuracy. As the sample sensor is designed to be very sensitive to even a very slight amount of power change (<1µW), the measuring laser must be stable enough for that range. Having the multi-line Argon laser power to 2W, the 457.9nm beam power portion becomes 41.1mW. As seen in Figure 6.12, the 457.9nm beam is stable within ±0.15% of the laser power. Despite the reasonable stability of the 457.9nm wavelength laser, the amount of fluctuation is much higher than the Sample sensor’s sensitivity, which will result in a higher output voltage fluctuation in the sensor output. One of proposed methods to increase voltage stability is using ND filter in the beam path. This reduces the laser power to the Sample sensor’s measurable range, and decreases the power fluctuation’s scale to the Sample sensor’s sensitivity range.
Figure 6.12. 457.9nm laser line power fluctuation at 2W multi-line Argon laser power over 200 seconds relative to the average

6.8. 514.5nm Wavelength Laser Beam Power Stability

Looking at Figure 6.13, it can be seen that the 514.5nm laser line’s power fluctuation in low power multi-line Argon laser output is ~0.6%. Running several other tests in the 514.5nm wavelength power fluctuation measurement, it was shown that the laser line’s change is always <1%. As it can be seen in Figure 6.13, the writing laser power fluctuation is <1mW, and it remains <1mW for the power ranges ~100mW required to write on the bimetallic photomasks.
Filtering out the Grayscale Mask Writing Laser Beam Using Band-Pass Filter

As discussed before, the Sample sensor which is located below the mask plate is responsible to measure the laser power attenuation caused by the photomask to calculate the optical density of the written spot. Previously, as the optical density was measured with a single laser line which was also used for writing on the mask, ND filters were required to be placed on the sensor to protect the sensor from high power laser beam. Adding a second laser line only for OD measuring purpose requires the writing laser line to be filtered out from the beam path before striking the sensor. For this reason, the FL457.9-10 band-pass filter from Thorlabs was used, which has a 65% transmission at 457.9nm wavelength and >4OD blocking power for the rest of the wavelengths [42]. By placing the filter just above the Sample sensor, the writing laser beam (514.5nm) is blocked and the only wavelength being measured by the sensor is the probing 457.9nm wavelength laser beam.
6.10. New Method of Mounting Sample Sensor beneath the Target Mask

Optical density measurement stability is sensitive to the position of the Sample sensor. Having the sample sensor mounted on a non-rigid mount will cause the position of the photodiode sensor to change relative to the incoming laser beam, which will translate to the power variation by the sensor and non-accurate OD calculation in FPGA program.

To place the sample sensor on a rigid mount, optical posts with Ø1/2" connected with 90° clamps holding an optical rail below the mask were used. Then, the sensor was mounted with a rail career in the desired position relative to the mask. The advantage of having this mounting method is its adaptability for placing other optical equipment between the mask plate and the sample sensor if needed. Figure 6.14 shows the Sample sensor mounted below the mask plate, while having the short focal length laser light collecting lens and the beam combiner mounted in a lens tube above it.

![Image](image.png)

*Figure 6.14. OD measurement system with the Sample sensor mounted below the mask plate using rigid optical posts*
6.11. Chapter Summary

In this chapter, the dual wavelength writing and measuring system setup was described in regards of introducing a new laser wavelength to the beam path as measuring laser. Having the system setup with two lasers aligned on the photomask, the system is ready to be tested as the newly created system with writing the photomask and measuring its OD change in real-time, while confirming the OD level achieved by repeating the OD measurement after the photomask has been patterned. In the next chapter, test patterns written on the photomask will be presented in terms of OD measurement accuracy and OD accuracy achieved using the GLWS in open-loop mode using Dual Wavelength Writing and Measuring System.
7. Experiments with Dual Wavelength Laser Writing and Measuring System

7.1. Introduction

This chapter discusses the grayscale mask writing experiments using the Dual Wavelength Laser Writing and Measuring System. For a start, simple grayscale patterns were written on the mask to achieve the OD response curve of the desired film. However, it was noticed that the mask OD measurement during and post writing is different. Several hypotheses were suggested for this issue and tests were created to examine different theories. Using the open-loop method, full 256-level grayscale patterns were written on the mask with linear OD and linear transparency and the results were compared.

7.2. Background

In Chapter 3, some of the new modification to the GLWS were discussed which can potentially increase the accuracy of the grayscale masks. Additionally, the new method of calibrating the photo-diode sensors was described in Chapter 4 that significantly reduces errors in the OD measurement process. In Chapter 5, the addition of the beam shaper to the system was shown to improve the quality of the grayscale mask. In addition to the improvements to the GLWS, Chapter 6 discussed the dual wavelength system which can potentially reduce OD measurement errors in the grayscale mask writing and result in more accurate OD measurement with wavelengths closer to the ones used in photolithography. In this chapter, all the modifications and improvements are used to test the grayscale mask quality being achieved. Full image bitmap files are written on the bimetallic photomasks to test the ability of the system in creating accurate grayscale masks. Before starting to write a full bitmap file on any type bimetallic thin film, the OD response of each film versus laser power must be found. The
next section will discuss writing 16 and 64 gray-levels in order to characterize the change of OD after laser exposure.

### 7.3. Simple Gray Level Patterns Written Using Power-Based Gray-Scale Mask Writing Procedure

Using the newly created Dual Wavelength Writing and Measuring System, grayscale structures are written to test the accuracy of OD measurement and its ability to create precise grayscale masks. To write 256-gray level pictures on the photomask, first the OD vs. laser power response needs to be determined as the response changes with the film thickness and characteristics. For a given film, the curve can be created by writing test grayscale structures of 16 to 64 levels and measuring the OD response to the laser power. Many grayscale masks have been used in this thesis work, but the two mask’s results are presented which have the highest OD range.

- Mask 47, a 100nm Bi/In film with an OD range of 2.57OD (unexposed) to ~0.45OD (fully exposed)
- Mask 68, a 100nm Sn/In film with an OD range of 2.54OD (unexposed) to ~0.36OD (fully exposed).

Table 7.1 shows the 16-levels of gray in terms of 8-bit values and their target OD in the two different methods of Linear OD and Linear Transparency. Using the linear OD method, the mask’s OD range (OD difference from maximum to minimum) is divided linearly between ‘n’ gray-levels. In the linear transparency method, the transparency range of the mask (the difference from blackest to whitest) is divided linearly between ‘n’ gray-levels. It should be noted that the relation of the OD to the transparency is logarithmic. To better achieve the mask OD response vs. laser power, the simple test structures are written with the linear OD method.

After writing each pattern on to the masks, the OD of the film is measured again with the writing laser off to confirm the achieved mask pattern is in agreement with the one expected. The measured OD of the two films was then plotted versus the laser power in two separate curves, and a fit was created for each one of them. The OD vs. exposure powers of Bi/In film (Mask 47) are shown for while writing in Figure 7.1 and for
post writing in Figure 7.2. The related graphs are plotted for Sn/In film (Mask 68), which are shown in Figure 7.3 (while writing) and Figure 7.4 (post writing). Ideally, both while and post writing curves should be the same for each mask, but as it can be seen in the figures, two different curves are created for each mask. Section 7.4 discusses the possible reasons for this occurrence.

Table 7.1. 16 gray-level pattern 8-bit grayscale value and its target OD

<table>
<thead>
<tr>
<th>Pixel</th>
<th>Grayscale</th>
<th>Target OD Based on Linear OD</th>
<th>Target OD Based on Linear Transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mask 47</td>
<td>Mask 68</td>
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<tr>
<td>1</td>
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<td>5</td>
<td>221</td>
<td>2.29</td>
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<td>6</td>
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<td>2.57</td>
<td>2.54</td>
</tr>
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<td>7</td>
<td>204</td>
<td>2.15</td>
<td>2.1</td>
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<td>8</td>
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<td>2.57</td>
<td>2.54</td>
</tr>
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<td>9</td>
<td>187</td>
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</tr>
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<td>0.65</td>
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<td>2.54</td>
</tr>
<tr>
<td>29</td>
<td>17</td>
<td>0.59</td>
<td>0.5</td>
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<td>30</td>
<td>255</td>
<td>2.57</td>
<td>2.54</td>
</tr>
<tr>
<td>31</td>
<td>0</td>
<td>0.45</td>
<td>0.36</td>
</tr>
<tr>
<td>32</td>
<td>255</td>
<td>2.57</td>
<td>2.54</td>
</tr>
</tbody>
</table>
To write any pattern on the mask, the lines are kept closely spaced to avoid effects such as prison bars on the mask. Before the year 2012 [22], having the same laser line to write the mask and measure its OD, the spacing needed to be 12µm with a beam $1/e^2$ diameter of 20µm. Decreasing the spacing less than 12µm resulted in the OD measurement of the current line being influenced by the lines written previously causing incorrect OD measurement. Using the feedback based picture writer, the line spacing should be large enough so the OD measurement is not affected by the previous lines, as the laser power correction depends on the correct OD values.
Figure 7.3. During writing OD versus laser power, Sn/In (Mask 68) patterned with 500 µm/s velocity using a 30mm achromatic lens

Figure 7.4. Post writing OD versus laser power, Sn/In (Mask 68) patterned with 500 µm/s velocity using a 30mm achromatic lens

To test the new system’s ability in writing overlapped lines, patterns of 3 separate lines (numbered 0 to 2) with different line spacing were created. This resulted in finding the limit of the ODMFS system in measuring OD during writing without the OD value being altered by the previous written line’s change in the mask. To write the lines, the laser power steps were chosen such that it resulted in nearly linear OD 16 gray-levels from 1 to 78mW for Sn/In films and 0.5 to 84.5mW for Bi/In films.

Based on Equation 3.2, the spot size for the writing and measuring laser beams were calculated. With the initial expanded Argon laser beam diameter \((D_0)\) of \(~4\text{mm}\), the focused spot \(1/e^2\) diameter \((D)\) of the writing 514.5nm beam was \(~4.5\text{µm} \ (w=2.25\text{µm})\)
and for 457.9nm laser beam was ~4µm. Note that these values are the theoretical minimum and do not take into account problems such as lens aberrations. Using 2µm line separation, Figure 7.5 shows the OD measurement results for Sn/In film. This is a 0.44D spacing which means the line edges are at the 0.88w point and receive ~68% of the peak spot power density (intensity) if an ideal Gaussian is assumed. As it can be seen, the measured OD for Lines 1 and 2 (sequentially written second and third lines) are the same while the measured OD for line 0 (the first written line on an unexposed film) is different. This OD variation is due to the effect of previously written lines to the subsequent lines. Similarly, Figure 7.6 shows the OD measurement results of the 2µm line spacing pattern for Bi/In film. Repeating the tests increasing the line spacing, the figures show the OD measurement results for both masks with 4-6µm separation. Figure 7.7 and Figure 7.8 show 4µm spacing (1.8w) or 21% power density at the overlap edge. The 6µm (2.7w or 2.9% intensity at the overlap edge) spacing results are also shown in Figure 7.9 and Figure 7.10. Looking at Figure 7.9, writing lines with >6µm spacing on the Sn/In film, no interference effect occurs. However, the Bi/In film required more separation, as seen in Figure 7.11, up to 8µm (0% intensity at the overlap edge) so that no overlap effect happens. Figure 7.12 shows the expected overlap using the 4.5µm Gaussian writing spot with different separations.

**Figure 7.5.** Three written lines with 2µm spacing patterned on Sn/In (Mask 68); 1mW to 78mW writing laser power for 16 linear OD steps; OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.
Figure 7.6. Three written lines with 2µm spacing patterned on Bi/In (Mask 47); 0.5mW to 84.5mW writing laser power for 16 linear OD steps, OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.

Figure 7.7. Three written lines with 4µm spacing patterned on Sn/In (Mask 68); 1mW to 78mW writing laser power for 16 linear OD steps, OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.
Figure 7.8. Three written lines with 4µm spacing patterned on Bi/In (Mask 47); 0.5mW to 84.5mW writing laser power for 16 linear OD steps, OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.

Figure 7.9. Three written lines with 6µm spacing patterned on Sn/In (Mask 68); 1mW to 78mW writing laser power for 16 linear OD steps, OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.
Figure 7.10. Three written lines with 6µm spacing patterned on Bi/In (Mask 47); 0.5mW to 84.5mW writing laser power for 16 linear OD steps, OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.

Figure 7.11. Three written lines with 8µm spacing patterned on Bi/In (Mask 47); 0.5mW to 84.5mW writing laser power for 16 linear OD steps, OD measurements taken while writing; 650mW multi-line Argon power; written with 500µm/s velocity using a 30mm achromatic lens.
Figure 7.12. Expected overlap for Gaussian 4.5µm writing spot at 2, 4, and 6µm separations

Figure 7.13 illustrates the resulting patterns on the mask for some of the exposure levels on the Sn/In film. The figure shows that in addition to the line spacing, the laser power can also influence the prison-bar effect, as the bimetallic masks require the intensity reach a threshold power before any change occurs. As seen in Figure 7.13 (4µm spacing), increasing the laser power causes the point where the beam reaches the threshold value to move further out on the Gaussian beam resulting in less visible prison-bars. However, the lines written with 2µm spacing are merged together even when written with low laser power, because the overlap point is above the threshold requirement. This can be expected as not only is the power at overlap 68%, which is significantly above the half way point, heat flow across the line actually makes the achieved temperature closer to that of the spot centre than the intensity suggests. As the line spacing increases, the intra-line area is receiving less and less power causing the variation in the transparency to increase, which makes the prison-bars more visible.
Referring back to 6µm Sn/In (Figure 7.9) and 8µm Bi/In (Figure 7.11) results, it can be seen that the OD fluctuation on the Bi/In mask is significantly higher than that for the Sn/In film. One of the possible reasons for larger OD fluctuation of Bi/In film can be seen by referring back to the surface profiles of Bi/In (Figure 2.7) and Sn/In (Figure 2.8) films after deposition. Those figures were showing that the Sn/In film show spikes with
the average peaks of ~28nm for a 100nm thick film, while the Bi/In film spikes with the average peak of ~550nm for a 300nm film. Generally, the primary impact of the thickness variation of the films is on its initial unexposed optical density. The OD response of a film is dependent on its initial thickness and the type of materials being sputtered. Despite the gray-level fluctuation as a result of thickness variation, the OD response curve is a determining factor to achieve precise gray-levels. From the OD response curve of Sn/In film (Figure 7.3), it can be seen that the number of data points used to create the fit are limited. The direct impact of the limited data points of the fit can be seen in Figure 7.14 showing the gray-level error curve of the lines written on Sn/In film (in Figure 7.9). As the lines were written based on the linear OD method, the error calculation is also performed based on the same scale. Note that the gray-level offset errors are not taken into account as they can be corrected with power level adjustments. The average absolute error of the gray-level fluctuations is calculated ~11.

**Figure 7.14.** Grayscale error for the mask lines written on Sn/In film using OD response curve with limited data points

To write patterns with more control over the achieved OD level, a grayscale with more levels is needed to be written on the mask. This will results in creation of the OD vs. laser power fit curve with more data points. For this test, a 64 gray-level structure shown in Figure 7.15 with the values presented in Table 7.2 was written on the mask and the fit curves shown in Figure 7.16 was created.
Figure 7.15. Original bitmap of the 64-gray structure to be written on Sn/In mask to create OD response vs. laser power fit with more data points

Table 7.2. 64 gray-level pattern 8-bit grayscale value and its target OD

<table>
<thead>
<tr>
<th>Pixel #</th>
<th>Grayscale</th>
<th>Target OD Based on Linear Transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Line 0</td>
<td>Line 1</td>
</tr>
<tr>
<td>1</td>
<td>240</td>
<td>244</td>
</tr>
<tr>
<td>2</td>
<td>255</td>
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</tr>
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<td>3</td>
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<td>4</td>
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<tr>
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<td>4</td>
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</tbody>
</table>
To find the average absolute error of the written structures with the new fit, the 64-gray-level structure was created on the Sn/In mask with the linear transparency method. In this experiment, 4 lines were written with the gray-levels shown in each row of Figure 7.15. Figure 7.17 shows the actual lines written on the Sn/In mask while Figure 7.18 shows the resulting transparency of each line vs. the laser power and the expected transparency.
Figure 7.18. Sn/In film (Mask 69); lines written using 5mW to 28mW laser power, with 1W multi-line Argon power; patterned with 500µm/s velocity using a 30mm achromatic lens; transparency measured after writing

(a) 16 levels shown in the first row of Figure 7.15; (b) 16 levels shown in the second row of Figure 7.15; (c) 16 levels shown in the third row of Figure 7.15; (d) 16 levels shown in the fourth row of Figure 7.15
One of the important points that should be noted is that in higher OD range (lower transparency), a large fluctuation of OD does not translate into significant amount of transparency fluctuation, but in lower OD range, very small amount of OD change translates into very large fluctuations of the transparency. For example, 0.1OD fluctuation on the mask's optical density from 2.1OD (0.79% transparency) to 2.0OD (1% transparency) only results in 0.21% transparency variation, which has almost no effect when exposing a photoresist. However, the same amount of OD change from 0.5OD (31.62% transparency) to 0.4OD (39.81% transparency) results in 8.19% transparency variation which is a significant change in grayscale lithography. For this reason, the gray-level variation in Figure 7.19 is higher when using higher laser powers for <1OD. As the laser power range required to write 256 gray-levels is small (5 to 28mW), the required power difference from one level to another can be as low as <0.5mW. Hence, very small fluctuation in the original laser power or the mask's initial optical density easily changes the achieved gray-level, especially when the open-loop mode is used. For example, when writing on Sn/In (Mask 69), the laser power required for writing gray-level #10 (8-bit scale) was 6.81mW, while the power needed to achieve gray-level #11 (8-bit scale) was 7mW. Assuming that the initial optical density of the mask is constant, >0.19mW alteration in the initial laser power is enough to move the pattern from one gray-level to another.

As it can be seen in Figure 7.19, two different errors can be observed. The first error is due to the laser power reproducibility which causes a shift in gray-levels actually achieved. Several examples can be seen in the figure, where the difference between the desired and the achieved gray-level is all positive or negative. This type of error can be easily fixed by better controlling the produced laser power through EOM. The most important factor however, is the average absolute error which is calculated ~2 gray-levels for Figure 7.19 showing the amount of gray-level fluctuation. As it is seen, using more gray-levels (64) to calibrate the OD vs. laser power for Sn/In film, the amount of the average absolute error is reduced ~5 times from 11 to 2 gray-levels.
Figure 7.19. Grayscale error for the mask lines written on Sn/In film using OD response curve created after writing 64-gray level structure

As the amount of achieved gray-level offset is considerable in Figure 7.19, a simple test was performed to check the laser power stability and reproducibility by the EOM. Using a constant turn on voltage for the EOM and repeating it for 4 times, a constant amount of laser output power was tried to be achieved. The power was measured with FieldMaster power meter with LM-2 Silicon head for 20 seconds at each trial. The tested laser power range was a standard range which was used in the mask writing process: ~3mW, ~11mW, and ~32.5mW. Using the 0.7W multi-line Argon laser power for the test, the required voltages from the function generator were -0.25V (for ~32.5mW), -0.5V (for ~11mW), and -0.65V (for ~3mW). Figure 7.20 shows the reproducibility of the laser power using EOM. As it can be seen, at the low power end, the stability of the modulated laser beam is not as high as when used in the high power. For each single test, the stability of the laser is <1.5% for 3mW, <0.5% for ~11mW, and <0.4% for ~32.5mW. However for the reproducibility test, the power varied for maximum of ~9% when low power output was desired. This can be also seen in the first six gray-levels shown in Figure 7.19, where they are all shifted as a result of laser power reproducibility issue by the EOM.
Figure 7.20. **Green writing laser power reproducibility test**

(a) 3mW laser power output with -3.2% to 6% reproducibility;
(b) 11mW laser power output with -2.3% to 2.3% reproducibility;
(c) 32.5mW laser power output with -0.65% to 0.75% reproducibility.
7.4. Effects of Laser Depth of Focus on Writing the Mask

Assuming that the laser power is accurately controlled within a sub milliwatt range, the focus of the spot on the mask plays an important role in quality of gray-levels achieved. As discussed before, the smaller focused laser beam spreads faster; hence has a small Depth of Focus (DOF). Placing the target mask in the system with only a few microns error above or below the mask surface makes the spot size larger giving poorer resolution, and decrease the maximum laser spot intensity (which varies with the square of the spot size).

To focus the writing and measuring beams on the photomask, various types of lenses may be used. Singlet Plano or Bi-convex lenses or objective lenses depending to their input aperture size can be used as focusing lenses. As most of the lenses used as focusing lens in the GLWS are not corrected for Chromatic Aberration, focusing two different wavelengths on the mask leads to different position relative to the mask (thus distances from the lens), which yields to incorrect OD measurement on the written spot. By using achromatic lenses, the 514.5nm and 457.9nm beams focus at the same distance from the lens, resulting in correct OD measurement.

Despite the focus distance issue, finding the exact focusing position can be more challenging. As the mask is mounted on the z-axis, the camera image of the mask can be focused properly by adjusting the height. However, as the laser beam focus point is at a different position relative to the mask than the focus point of the optical image, it must be found separately. The procedure of finding the proper laser focus position using the mask threshold effect is explained in Section 7.4.1.

Figure 7.21 shows the mask lines written with laser power from 2mW to 76mW on a 74nm Bi/In film (Mask 44) with power steps in order to achieve linear OD structure. As it can be seen in Figure 7.22, the achieved OD vs. laser power response does not match the OD response curve originally created for the film. The reason can be found the error in the focus point of the laser spot. Having the microscope camera focused at the mask, the laser beam would be then slightly defocused. Hence, the light intensity decreased correspondingly causing the film to respond differently to the laser power. Figure 7.23 shows the lines written on the film with a focused spot and Figure 7.24 with
a ~100μm defocused laser beam. As expected, the line widths written with the focused laser beam are smaller than the line widths written with the defocused spot. It is also shown that the transparencies of the written lines shown in Figure 7.23 are higher than the lines shown in Figure 7.24 as written with higher intensity beam.

**Figure 7.21.** 74nm Bi/In (Mask 44); Lines written at optical image focus position (defocused laser beam); Averaged measured OD and laser power; patterned with 500μm/s velocity using a 30mm achromatic lens

**Figure 7.22.** 74nm Bi/In (Mask 44); Lines written at optical image focus position; Averaged OD response; patterned with 500μm/s velocity using a 30mm achromatic lens
To avoid the issue caused by the defocused laser beam, the exact laser beam focus position must be found before writing the mask. As the film mounted on the z-axis may have been also tilted, the focus position should be found in the neighbourhood of the chosen spot for writing. The next section discusses the procedure of finding the laser beam focus position using microscope view image.
7.4.1. Finding Laser Beam Focus Position on the Mask

Based on the Gaussian beam behaviour, the lenses focus the laser beam to a waist to form the writing spot. The beam follows the classic Rayleigh range formula.

\[ w(z) = w_0 \left[ 1 + \frac{z^2}{z_R^2} \right]^{1/2} \]  \hspace{1cm} 7.1

\[ z_R = \frac{\pi w_0^2}{\lambda} \] \hspace{1cm} 7.2

\[ \Delta z = \pm \frac{0.32\pi w_0^2}{\lambda} \] \hspace{1cm} 7.3

Where

- \( z_R \) = Gaussian Laser Beam Rayleigh Range,
- \( z \) = Distance,
- \( \lambda \) = Laser Wavelength,
- \( w_0 \) = Laser Waist Size,
- \( \Delta z \) = Depth of Focus.

The Rayleigh range is defined as the point where the beam expands to \( \sqrt{2} \) from its original waist size. The size of the focused laser spot expands with Equation 7.1 as a function of \( z_R \). Note that \( z_R \) is a function of the focused spot size \( w_0 \) squared and the wavelength as \( w_0^2/\lambda \) (Equation 7.2). The Depth of Focus (DOF) of a laser spot can be calculated from Equation 7.1 as the point where expansion of the spot size is 5% of the original waist with Equation 7.3. From the previous section, if the laser beam is focused to \(~5\mu m\) with 30mm achromatic focusing lens, using Equation 7.3, the 514.5nm writing laser beam DOF becomes \( \pm 12.2\mu m \).

In the GLWS, as the microscope image is the only tool that allows visual check of the mask in real-time, it can be also used to find the writing laser focus position. First, the microscope is focused on a spot on the mask plate. As discussed before, the focus position must be found at the neighbourhood of the desired writing spot. Using the mask’s threshold effect, the laser focus position can be found. To do so, short lines
should be written on the mask using a fairly high power laser (~20mW) at the microscope focus position. When the spot is most finely focused, it has the maximum local power, so it begins writing the lines, if it exceeds the threshold. By roughly changing the z-axis height in ±10µm steps above and below the microscope focus position, the approximate depth of focus of the laser beam can be found. However, as the used laser power is fairly high, the found depth of focus is larger than expected. After centering the z-axis to the approximate DOF, it is the time to repeat the same steps with lower laser powers (so the laser power is closer to the mask writing threshold power) and finer height adjustments.

The laser focus plane found with this procedure might not match the optical image focus plane, because the additional optical elements (e.g. the green/violet beam combiner have shifted the microscope focus point). However, it is the best position where the mask can be written with the smallest spot size and the lowest power requirement.

7.5. Investigating Mask OD Response During and After Writing

As was noted in Figure 7.16, measuring the mask OD during the writing process resulted in a different response than post writing. This showed that for higher absorption areas, those above 1.5OD, the writing and post writing values nearly matched. However for more transparent sections the post writing measurements showed smaller OD values than those obtained during the writing process. Several hypotheses have been considered to explain this behaviour.

The first of these is that the exposed mask needs some extra time to complete the oxidation action. Hence writing the mask with high velocity and measuring the mask OD at the same time does not allow the process to be completed. The observation that the OD results match best when the oxidation is less complete, where there is a smaller change in the OD from the original bimetallic film, agrees with this. Similarly at greater transparencies, where more oxidation must take place, the lower OD after writing tends
to support this. In both cases post writing measurements would occur after all the oxidation is complete.

The other hypothesis is that the high power writing laser causes the temporary formation of a dome shape structure on the mask due to thermal expansion of the bimetallic resist or the glass substrate. Similar effects have been noticed in ND filters inserted in the beam path of high laser powers. This would affect the 457.9nm measurement during writing because it would act as another lens that changes the expansion rate of any beam after the mask (see Figure 7.25). Since a short focal length lens was added below the mask to collect the laser light, changing the expansion rate could result in some light escaping from the photo-diode sensor area and causing higher OD measurement while writing the mask. At low writing power (the higher OD range) the dome is smaller (less thermal expansion) and thus produces little effect. However, at higher beam energies (those below 1.5OD in Figure 7.16) more heating occurs, creating a more prominent dome, and hence a stronger lens effect. The dome occurs only during the writing process, and disappears when the mask cools. When using only the 457.9nm OD measurement by itself, the power is so low the dome does not form, so the true mask OD level occurs. Alternatively the heating may form something in the material that partially scatters the beam creating a similar effect. Possible sources of that scattering are the liquid state of the material during the oxidation process. While the dome effect has been seen many times in solid material the scattering concept is just a suggestion at this point. In either case the hypothesis is that the higher the energy injected in the film (and thus the temperature) the larger the change in the beam expansion.

To test these proposed hypotheses, experiments were designed to test both oxidation and thermal (dome) concepts at the same time. First for the oxidation writing and OD measurements will be performed at high and low velocities. If the oxidation requires some time to proceed then there should be a significant reduction in the difference between the during and post writing OD values for the low speed, but not for the high speed. Second we note the fact that already written areas do not change if rewritten with a laser power below the originally written value. Hence, by writing the lines over already exposed areas, there should be no change in the OD (and thus no thermal effect), if the new line power is below that of the pre-exposed area. However,
changes in the OD (and thus thermal effects) would occur if the line’s power is above that of the previously patterned windows.

Thus, several lines with different velocities and laser powers were patterned over a set of pre-exposed windows (Figure 7.26). If the oxidation process time is causing the OD difference, the mask measurement during and post writing should be much closer if written with low velocity than those written at higher velocities. Results should be different where the lines are written in unexposed areas, than in those of the exposed windows. In windows created with powers below that of the new writing line there should still be a velocity effect. However, if there is a difference in OD measurement during and post writing independent of the writing speed, this suggests the dome effect is the possible reason. To further test the dome effect, structures are written over already exposed windows with the same range of laser powers. Since there is no heating on the window written at a higher power than the new line power, and as the dome effect is a result of the thermal expansion, no measurement difference should be seen as no dome effect is expected on the second pass. However those windows created at lower laser powers than the new writing line, there will be heating and thus the possibility of the dome type effect. The dome effect would not likely be affected by the writing speed as any thermal process becomes nearly constant in extremely short times [23].

Figure 7.25. Beam expansion change due to formation of a dome shape while writing with high power
For these experiments, three windows of 100µm x 50µm were written on the Sn/In mask with 9.15mW for gray-level #200 (0.8OD), 11.8mW for gray-level #150 (0.5OD), and 16.1mW for gray-level #100 (0.8OD) using 500µm/s (Figure 7.26(a)). Similarly, the using 20µm/s velocity, the windows were written on the mask with 5.96mW for gray-level #200 (0.8OD), 7.22mW for gray-level #150 (0.5OD), and 9.01mW for gray-level #100 (0.8OD) (Figure 7.26(b)). The chosen speed of 20µm/s is 25 times slower than the original writing velocity allowing much more time for oxidation to stabilize. The gray-levels were chosen such that the optical density of the film is ranged from less exposed (0.8OD) to highly exposed (0.4OD) covering the range seen in Figure 7.16. Next, three lines were written covering approximately the same power ranges and the same velocities such that they passed through all three windows and the optical density was measured during and after the writing process. For the experiment using 500µm/s velocity, the lines were written with 8.84mW for gray-level #210 (Line L0), 10.8mW for gray-level #160 (L1), and 15.5mW for gray-level #110 (L2). As writing with lower velocities require less power to create the same desired gray-levels, 5.76mW for gray-level #210, 6.61mW for gray-level #160, and 8.68mW for gray-level #110 were used.

Figure 7.26(a) shows the test patterns on windows/lines written with 500µm/s velocity in a back-lit micrograph. Figure 7.26(b) is the same test patterns written on windows/lines created with 20µm/s velocity. It is seen that as expected, the test lines only appear visually on the windows where the line laser power exceeds that of the window. Figure 7.27 shows the OD measurements for these line both in unexposed areas and when crossing the windows at the low speed (20µm/s) while Figure 7.28 is the high speed 500µm/s results. Table 7.3 shows the average OD difference of the written lines measured during and post writing with 20µm/s, while Table 7.4 shows the same results for 500µm/s. Looking at the results at both tables in the unexposed regions, it can be seen that in average, there is 0.14OD average OD difference for the lines written with 20µm/s and 0.15OD average OD difference for the lines written with 500µm/s. This failure of significantly different writing speeds to produce changes in the during and post OD measurements rejects the slow oxidation hypothesis.

Now consider the thermal effect or dome shape structure. In this case, the lines writing over the windows are important. The results shown in Figure 7.27 and
Figure 7.28 and their corresponding tables show that when the lines are written over areas of a higher transparency level (lower OD) than the line writing power produces, almost no difference can be seen between the OD measurements during and after writing. As the transparency of the window decreases, the lines begin to change the OD in the window and the measured OD difference increases. However, the amount of change is still less than the OD difference was seen in the unexposed areas (refer to Table 7.3 and Table 7.4). This shows the measurement difference has a direct relation to the absorption of the laser light in the window. Then it would be expected that the absorbed laser power in those windows may cause creation of dome shape structure. For example, in Table 7.3, writing the third line (L2) with higher laser power (8.68mW) over the first window with lower transparency (created at 5.95mW) results in an OD difference of 0.08OD, about half that as writing on the unexposed regions (0.15OD). The lower value would be expected as the window is already transparent and hence there is less heating. However, writing any lines over the third window (done at 9.01mW) does not cause an OD difference during or post writing measurement. These tests seem to be strong evidence of a heat related OD effect, which are in agreement with the suggested dome hypothesis.

![Figure 7.26](image)

*Figure 7.26. Structures written on Sn/In film (Mask 69) to test hypotheses for two different OD response curves*

Lines and windows written at velocities (a) 500µm/s (b) 20µm/s
Figure 7.27. OD response of Figure 7.26(b); patterned lines with 20µm/s velocity; three windows at gray-levels #200, #150, and #100

Lines written with (a) L0 at 8.84mW (level #210) (b) L1 at 10.8mW (level #160) (c) L2 at 15.5mW (level #110)
Figure 7.28. OD response of Figure 7.26(a); patterned lines with 20µm/s velocity; three windows at gray-levels #200, #150, and #100

Lines written with (a) L0 at 5.76mW (level #210) (b) L1 at 6.61mW (level #160) (c) L2 at 8.68mW (level #110)
Table 7.3.  Average OD difference of the during and post writing with 20µm/s

<table>
<thead>
<tr>
<th>Line #</th>
<th>Unexposed Region</th>
<th>Window 1 #200</th>
<th>Window 2 #150</th>
<th>Window 3 #100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L0</td>
<td>L1</td>
<td>L2</td>
<td>L0</td>
</tr>
<tr>
<td>During Writing Average OD</td>
<td>1.51 1.14 0.90</td>
<td>0.89 0.82 0.74</td>
<td>0.54 0.54 0.53</td>
<td>0.52 0.54 0.52</td>
</tr>
<tr>
<td>Post Writing Average OD</td>
<td>1.41 0.98 0.75</td>
<td>0.87 0.76 0.66</td>
<td>0.52 0.52 0.50</td>
<td>0.51 0.53 0.51</td>
</tr>
<tr>
<td>OD Difference</td>
<td>0.10 0.16 0.15</td>
<td>0.02 0.07 0.08</td>
<td>0.02 0.03 0.03</td>
<td>0.01 0.01 0.01</td>
</tr>
</tbody>
</table>

Table 7.4.  Average OD difference of the during and post writing with 500µm/s

<table>
<thead>
<tr>
<th>Line #</th>
<th>Unexposed Region</th>
<th>Window 1 #200</th>
<th>Window 2 #150</th>
<th>Window 3 #100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L0</td>
<td>L1</td>
<td>L2</td>
<td>L0</td>
</tr>
<tr>
<td>During Writing Average OD</td>
<td>1.59 1.00 0.87</td>
<td>0.85 0.75 0.66</td>
<td>0.48 0.49 0.48</td>
<td>0.40 0.41 0.41</td>
</tr>
<tr>
<td>Post Writing Average OD</td>
<td>1.51 0.80 0.70</td>
<td>0.81 0.64 0.57</td>
<td>0.46 0.46 0.46</td>
<td>0.39 0.40 0.39</td>
</tr>
<tr>
<td>OD Difference</td>
<td>0.08 0.20 0.16</td>
<td>0.04 0.10 0.09</td>
<td>0.02 0.03 0.02</td>
<td>0.01 0.01 0.02</td>
</tr>
</tbody>
</table>

All in all, the true reasons for this behaviour need to be further investigated. Having different OD response curves during and after writing will require modification in the GLWS being used in the feedback mode. For this reason, the experiments in the following sections are performed with the open-loop mode (power based picture writer).

7.6. Full 256 Gray Level Test Photomask Patterns

The most important test of the bimetallic process is the quality of the grayscale masks they create. Patterning a full grayscale image on the photomasks to demonstrate
the ability of the GLWS has been performed previously using the original voltage-based picture writer which used an OD vs. laser response curve established on a separate film. Figure 7.29(a) shows the original bitmap which is 128 pixels wide by 192 pixels tall. The lines were written 5µm apart with the writing velocity of 500µm/s and a multi-line Argon laser power of 155mW which was focused on the mask with a 50mm plano-convex lens [41]. Looking at the patterned structure shown in Figure 7.29(b), although the image shows a grayscale pattern, it clearly lacked the tonal quality of the original image.

![Figure 7.29](image)

**Figure 7.29. Photomask written on a 15 nm Sn/In (95% at.% In) in 2004**

(a) Original bitmap (b) Patterned structure on the film [41]

Another full grayscale image was written in 2010 by J. Dykes as part of his thesis with both open-loop and feedback writing methods. Figure 7.30(a) shows the original bitmap that is 300 pixels wide by 400 pixels tall. The lines were written 12µm apart with the writing velocity of 20µm/s and a multi-line Argon laser power of 250mW which was focused on the mask with a 5X objective lens with ~20µm spot size. The pattern pixel size was 12µm x 12µm written on a 100nm Bi/In film with the transparency range of 2.6% (1.58OD) to 28.2% (0.55OD) [22]. Unlike the voltage-based picture writer, the open-loop and the feedback methods use the OD response curve established on the same mask as the patterns are written. Comparing these written patterns, the
feedback-based picture (Figure 7.30(b)) shows a better tonal response than the open-loop image (Figure 7.30(c)).

Figure 7.30. Back-lit image of the picture written on 100nm Bi/In
   (a) Original bitmap (b) Feedback-based picture (c) Power-based picture [22]

As discussed in Section 7.3, comparing the two bimetallic films, the Sn/In film has a slower change in its OD with the laser power and more uniform surface profile (refer to Figure 2.8) that means more producible results. Choosing the Sn/In film to demonstrate the improvements made to the GLWS, a large full image bitmap was written onto it. As seen in Figure 7.31 the chosen image has a full tonal range, from pure white to pure black, and includes fine details. Figure 7.31(a) shows the original supplied bitmap image and Figure 7.31(b) shows the bitmap where the gray-levels are equalized in Photoshop. To write the picture onto the mask, the power-based picture writer was used as the feedback system’s problem with the during writing fit curve is not fully understood right now. Using the power based picture writer also puts the ability of the mask writing system in controlling the laser beam power to test without any feedback correction. The picture size is 400 pixels wide by 267 pixels tall, and it was written with the velocity of 500µm/s which is 25X faster than previously used 20µm/s to write the picture shown in Figure 7.30.
Figure 7.31. **Test patterns for grayscale mask**

(a) Original bitmap; (b) Equalized in gray-levels with Photoshop.

Before writing the bitmap with large pixel sizes, small test structures are written on the mask to visually see the difference between the mask OD response during and post writing. Using the image shown in Figure 7.31(a), two identical patterns are written with linear transparency, while the only difference is the used OD response curve. The pictures were written with pixel size of 2µm x 2µm where the lines are separated with 2µm spacing which yielded to the patterning of 267 vertical lines for ~150 minutes for each picture. The backlit pictures of the written patterns (shown in Figure 7.32) were
captured with SMX-M81M camera under the microscope with a constant amount of light exposure. Comparing the images, the pattern using the post writing OD response (Figure 7.32(b)) includes more mid-tone gray-levels and details than the patterned image using during writing OD response (Figure 7.32(a)). Hence, for the final test, the post writing OD response will be used.

![Figure 7.32. Backlit image of the patterned mask with power-based picture writer on the Sn/In film with the transparency from 0.3% (2.5OD) to 39.8% (0.4 OD)
OD response measured (a) During writing; (b) Post writing.](image)

As most of the commercial grayscale masks are written with linear OD, the first large scale patterning experiment was performed using that method. Hence, the bitmap file shown in Figure 7.31(b) was written on Mask 68 (Sn/In) with the transparency range of 0.3% (2.5OD) to 39.8% (0.4OD) and 10µm x 10µm pixel sizes. The lines were written 5µm apart with the writing velocity of 500µm/s and a multi-line Argon laser power of 650mW which was focused on the mask with a 30mm achromatic lens. After more test pictures, the final attempt was the large scale bitmap shown in Figure 7.31(a) with linear transparency on Mask 69 (Sn/In) with the transparency range of 0.44% (2.35OD) to 39.8% (0.4OD). The picture was written with 10µm x 10µm pixel size, and the line spacing used was 2µm. Writing two patterns with 5µm and 2µm line spacing allowed comparison of the prison-bar effect due to different separation as well as the visual difference of linear OD and linear transparency on the final patterns. The final dimensions of the written patterns on the mask shown in Figure 7.33 (Linear OD) and Figure 7.34 (linear transparency) were 4000µm wide by 2670µm tall with the total patterning time of >5 hours.
Figure 7.33. Backlit image of the patterned mask with linear OD on the Sn/In film (Mask 68)

Figure 7.34. Backlit image of the patterned mask with linear transparency on the Sn/In film (Mask 69)
Comparing the visual appearance of the written patterns shown in Figure 7.33 (linear OD) and Figure 7.34 (linear transparency), it is seen that the picture written with linear transparency matches the original bitmap (Figure 7.31(a)) better (it shows more details, especially in the darker areas at the image top).

To compare the resolution of the written patterns with 2µm and 5µm line spacing, higher magnification microscopic images are taken with a 20X objective lens which is 4X of the lens used to capture Figure 7.33/Figure 7.34. The magnified pictures of the 5µm and 2µm line spacing patterns are shown in Figure 7.35. As expected, the pattern written with 5µm line spacing (Figure 7.35(a)) visibly shows the prison-bar effect which lowers its final achieved resolution. However, almost no prison bar effect can be seen in the pattern written with 2µm line spacing (Figure 7.35(b)).

![Figure 7.35. Backlit zoomed image of the mask patterned with power-based picture writer](image)

(a) Image patterned with 5µm spacing; (b) Image patterned with 2µm spacing.

Finally, comparing the previously written pattern (the feedback-based written picture shown in Figure 7.30(b)) with the newly written linear transparency image (Figure 7.34), it clearly demonstrates the improvement offered to the system described in this thesis. The achieved results emphasize that although an accurately controlled laser power is required to pattern a high quality grayscale mask, by precisely controlling the film’s OD measurement, accurate grayscale photomasks can be successfully produced on bimetallic thin-films even without any feedback control.
7.7. Chapter Summary

In this chapter, experiments were performed using the Dual Wavelength Writing and Measuring System to pattern grayscale mask lines on 74nm and 100nm Bi/In and 100nm Sn/In bimetallic thin-films. It was shown that how a defocused laser affects the final achieved resolution on the grayscale mask, and a method of finding the laser focus position was suggested. Next, creating a fit to the curve to predict the OD response of the film to the laser power was discussed. However, achieving two OD responses, while writing the mask with the writing laser on and after writing the mask with the writing laser off, suggested an issue with the mask writing process. Several experiments were performed to understand the reason this particular issue was happening. Experiments suggest the possible formation of a dome shape structure on the bimetallic mask which changes the characterization of the measuring laser (457.9nm).

Having created the OD response of the mask versus the laser power, the minimum achievable line spacing without affecting the OD measurement by the previous line was tested. Using 100nm Bi/In mask to pattern grayscale structures, a minimum of 6μm spacing was required to prevent OD measurement conflict, and using 100nm Sn/In film, the spacing was measured to be 4μm. However, as expected, writing lines with ~2μm spacing resulted in structures with no prison bar effect on the grayscale masks.

Using 2μm and 4μm spacing, two large full bitmap images were patterned on 100nm Sn/In film with the power-based picture writer with the OD response measured after writing the mask to present the ability of the new system in creating high accuracy grayscale masks without any feedback control and to show the presence of the prison bars while writing structures with large line spacing.

The next chapter will take the grayscale masks created using all of the improvements and will use them in photolithography experiments to create 3D microstructures in photoresist.
8. Grayscale Mask for Creation of 3-Dimensional Micro-structures on Photoresist

8.1. Introduction

In the previous chapter, a 256-level grayscale mask was created using all of the new improvements reported in this thesis. Although the pattern written on the grayscale photomask was a visually correct one, the gray-levels need to compensate for the behaviour of the photoresist. Classic descriptions of grayscale fabrication generally do not discuss the behaviour of the photoresist to a grayscale exposure in any detail. Hence, this chapter will explore how to change the OD requirements of the grayscale mask to match the requirements of the photoresist to achieve the desired resist thickness. This method will allow the grayscale mask to adapt the standard lithography process which is compatible with IC fabrication processes. The experimental results will be also provided in this section with linear transparency and the altered transparency grayscale masks to achieve linear photoresist behaviour.

8.2. 3D Structures Created Using Linear Transparency Grayscale Masks

To test the quality of the grayscale mask for creating 3D-microstructures in photoresist, several lithography experiments were done on different substrates. The first was using the linear transparency mask (Figure 7.34) to pattern the resist on a silicon wafer with thermally grown SiO₂ of ~0.5µm (green in color). The wafer was coated with 1.3µm Shipley Microposit S1813 photoresist with the standard spin speed of 4000rpm and then soft baked as per the SFU clean room processes described on the standard photo run sheets in [42]. For the first experiment, the photoresist was UV exposed under the mask aligner with 1 second increments from 8 to 12 seconds using the grayscale mask. The grayscale image was only a 3 x 5mm section on a 2.5 x 7.6cm
glass slide. Hence, to pattern the photoresist coated wafer with multiple exposures using a single mask, a large piece of black plastic shield was used as a UV light barrier to cover the entire wafer except the desired mask section. A portion of photoresist area then was exposed each time and the mask moved to new sections before each following exposure. This created a single wafer with 5 separately exposed sections. Next, the whole wafer’s photoresist was developed using MF-319 developer for 60 seconds with slight agitation at room temperature (18 °C).

The developed pattern shown in Figure 8.1 is for the exposure time of 8 sec. Figure 8.2 shows the pattern for exposure time of 9 sec, and the pattern shown in Figure 8.3 illustrates the 10 sec exposure time lithography. Looking at the patterns, the structure with 8 sec exposure did not clear in some areas suggesting that the photoresist was under-exposed. The microscope inspection showed this as some resist left in the open area (darkish green in Figure 8.1). Similarly, looking at the lithography work at 10 sec exposure time, most of the photoresist was cleared on the pattern suggesting that the resist was over exposed for any time >=10 sec. With the 9 sec exposure, the photoresist was cleared properly at the highly transparent areas of the mask and different colors could be seen as a result of several thicknesses of the photoresist.

![Figure 8.1](image.png)

*Figure 8.1. 8 sec exposed photoresist on oxide with linear transparency grayscale on Sn/In film showing under exposure*
Figure 8.2. 9 sec exposed photoresist on oxide with linear transparency grayscale on Sn/In film showing proper exposure

Figure 8.3. 10 sec exposed photoresist on oxide with linear transparency grayscale on Sn/In film showing over exposure

As the silicon dioxide is not conductive, it was difficult to take Scanning Electron Microscope (SEM) images from these samples. Generally, the nonconductive samples can be coated with a thin layer of a metal, such as gold, to prevent charge build up. However, as the minimum thickness step created in the photoresist is ~5nm, coating the sample with a layer of ~50-100nm metal does not allow the very small profiles to be seen. Hence, a new experiment with the same grayscale pattern was performed on a bare silicon wafer, which is conductive. As the photoresist used to coat the wafer was
thin, the charge was drained through the conductive substrate without need for coating the resist with thin layer of metal. For this experiment, the same multi-exposure procedure was performed. The only changes were the exposure time (reduced to 7.2 sec) and the development time (reduced to 50 sec) both as a result of the silicon wafer higher surface reflectivity. A diamond scribe was used to score the wafers and the wafer was broken along the scribe lines. Although the samples were washed and blow dry with a nitrogen gun, some of the silicon particles remained on the sample surfaces which will be seen in the images. The images were taken afterward with a FEI Dualbeam 235 at 4D Labs in SFU Physics department. Figure 8.4 shows the SEM of the whole cat pictures on the photoresist. Looking at the figure, the picture is foreshortened in vertical dimension due to the fact the sample was tilted at 60° angle to enhance the 3D characteristics. To better show the resist profile on the substrate, a close up picture was taken from the cat’s eye area, shown in Figure 8.5. As the image was too complex for profilometry, surface profiles of simpler structures were measured in Section 8.5.

Figure 8.4. SEM of 7.2 sec exposed photoresist on a silicon substrate

Figure 8.5. 5X close up SEM of the cat structure
8.3. Matching Grayscale to Photoresist: Theory

In the first lithography experiment, the grayscale structure used to expose the photoresist was written with linear transparency on the bimetallic grayscale photomask. Ideally, a linear transparency grayscale structure requires a photoresist with low contrast (Gamma) value. However, most of the photoresists have a high contrast as that creates sharper side walls needed in the IC fabrication industry with binary masks. Literature descriptions of the grayscale fabrication generally do not discuss the behaviour of the photoresist or do not include the option of manipulating the photoresist thickness by changing the gray-levels. In the most discussed methods, the resist process is modified to match a limited gray-level mask. For example, a technical report by MicroChemicals [44] suggests several methods for achieving lower contrast from a photoresist by altering the lithographic factors. A short or/and cool soft bake which keeps the concentration of the remaining solvent high; hence increases the dark erosion in the developer. Alternatively, a hot or/and long soft bake decomposes a significant part of the photoactive compound which reduces the development rate and also increases the dark erosion in the developer. Additionally, increasing developer solution concentration is suggested in the report which reduces the selectivity of the photoresist or decreases the contrast value. All the above mentioned methods however alter the standard fabrication process of CMOS mass production which is less desirable for IC fabrication industry.

However, several researchers tried to integrate the behaviour of the mask and the lithography process. Heller et al. [45] uses a 20 level half-tone grayscale photomask on a standard I-line photoresist with 2.5µm thickness to determine its contrast curve and create multiple height structures on it. However, he did not suggest any calibration method for the grayscale mask as he uses a half-tone mask with 20 gray-levels. Using HEBS glass as a continuous tone grayscale mask, Spadaccini [46] has reported using thin and thick photoresist (~1µm to 10µm) for grayscale lithography to create 3D microstructures. However, he only mentions using calibrated HEBS glass for a specific photoresists used in the report and skips the details of calibration.

As the bimetallic grayscale photomasks are capable of creating full-tone patterns which are easier and cheaper to manipulate, it allows the gray-levels to be changed to fit the behaviour of the photoresist; hence the photolithography process can remain as its
standard CMOS compatible procedure. This section focuses on finding a general method of relating bimetallic mask’s gray-levels to resist thickness which allows an easy calibration process for any type of positive photoresist used with grayscale photomasks. An important factor in calibrating the gray-levels with the photoresist thickness is the contrast value as it has a great impact on the development rate versus exposure dose/time.

Consider using an ideal photoresist contrast curve shown in Figure 8.6, where the typical assumption is made that the resist exposure has a threshold $D_0$ below which no development occurs and fully clears at $D_c$. A general equation can be created to obtain the required UV exposure dose ($D_R$) for targeted photoresist thickness ($T_R$). The photoresist response in Equation 8.1 (log format) and Equation 8.2 are based on the resist dose to clear ($D_c$), threshold dose ($D_0$) and the normal remaining photoresist thickness ($T_R/T_0$), where $T_0$ is the original resist thickness. The photoresist contrast value can also be calculated using Equation 8.3.

\[
\frac{T_R}{T_0} = \gamma \log(D_c) - \gamma \log(D_R) \tag{8.1}
\]

\[
D_R = D_c \left( \frac{D_0}{D_c} \right)^{\frac{T_R}{T_0}} \tag{8.2}
\]

\[
\gamma = \frac{1}{\log\left(\frac{D_c}{D_0}\right)} \tag{8.3}
\]

**Figure 8.6.** Fraction of positive photoresist remaining as a function of exposure dose from $D_0$ (threshold dose) to $D_c$ (dose to clear) [3]
Assuming that the transparency of the photomask for the UV light is 100%, the amount of calculated dose $D_R$ represents the required exposure for each targeted photoresist thickness. However, as the maximum grayscale photomask transparency is lower than 100%, the amount of required dose must be increased to compensate for the UV light absorption by the mask. By defining the maximum mask transparency as “$TR_{max}$”, the new amount of required dose ($D'_R$) can be calculated using Equation 8.4.

$$D'_R = \frac{D_R}{TR_{max}} \hspace{1cm} 8.4$$

Having the new required dose/time calculated based on the contrast curve fit for all required thicknesses, the mask’s transparency/OD range can be easily calculated such that it results in a linear response of the photoresist thickness to the calibrated grayscale photomask. Using the maximum transparency “$TR_{max}$”, the required transparency ($TR_R$) for each desired photoresist thickness can be calculated using Equation 8.5.

$$TR_R = \frac{TR_{max}}{D'_R} \hspace{1cm} 8.5$$

![Figure 8.7. Shipley Microposit S1813 photoresist contrast curve (After [48])](image)

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As Shipley S1813 photoresist is used for several experiments in this thesis, an example is given for this specific resist using its contrast curve from the datasheet [48], with the curve shown in Figure 8.7. It can be seen that the fit equation from the datasheet \((y = 4.3416 - 2.2681 \times x)\) is equivalent to the Equation 8.1, where ‘y’ is the ‘\(\frac{T_R}{T_0}\)’ and ‘x’ is ‘Log \((D_R)\)’. Hence, \(\gamma = 2.268\) and \(\gamma^*\log(D_c) = 4.3416\) which then gives \(D_0\) as 29.79mJ/cm\(^2\) and \(D_c\) as 82.07mJ/cm\(^2\). Using Equation 8.2, the amount of \(D_R\) can be calculated based on the required resist thickness, given in Equation 8.6.

\[
D_R = 82.07 * (0.363)^{\frac{T_R}{T_0}}
\]  \hspace{1cm} \textbf{8.6}

If the maximum achievable transparency of the grayscale mask is 39.81% (0.4OD), the new amount of exposure dose \(D'_R\) can be calculated using Equation 8.7.

\[
D'_R = 206.15(0.363)^{\frac{T_R}{T_0}}
\]  \hspace{1cm} \textbf{8.7}

Based on Equation 8.7, \(D'_c\) becomes 206.15mJ/cm\(^2\) and \(D'_0\) becomes 74.83mJ/cm\(^2\). After dividing the dose range into the required number of grayscale levels, the exposure doses can be related to the desired transparencies on the mask. Table 8.1 shows an example of a 4 gray-levels mask calibration for S1813 photoresist. The grayscale photomask transparency characteristics used for this example are assumed 39.81% (0.4OD) for \(TR_{\text{max}}\) and 0.31% (2.5OD) for \(TR_{\text{min}}\).

<table>
<thead>
<tr>
<th>Remaining Thickness Required</th>
<th>(D_R)</th>
<th>(D'_R)</th>
<th>(TR)</th>
<th>Equivalent OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>82.07</td>
<td>206.15</td>
<td>39.81%</td>
<td>0.40</td>
</tr>
<tr>
<td>33.34%</td>
<td>58.54</td>
<td>147.05</td>
<td>28.40%</td>
<td>0.55</td>
</tr>
<tr>
<td>66.67%</td>
<td>41.76</td>
<td>104.90</td>
<td>20.26%</td>
<td>0.69</td>
</tr>
<tr>
<td>100%</td>
<td>29.79</td>
<td>74.83</td>
<td>14.45%</td>
<td>0.84</td>
</tr>
</tbody>
</table>
The example above shows that a large portion of available photomask OD range (from 2.5 to 0.84) remains unused as a result of the offset of the photoresist contrast curve (from 0 to \( D_0 \)). However, as the real photoresist development rate is not 0 for the given range, it causes a non-linear erosion of the photoresist. Considering the non-linear part of the contrast curve in the developed model, the photoresist thickness vs. transparency model can be upgraded to represent the whole range of the curve. The next section will employ the explained model to match the gray-levels with experimentally created S1813 contrast curve.

8.4. Matching Grayscale to Photoresist: Experiment

As the contrast value of each photoresist is a function of developer, development time, agitation, baking time, \( \lambda \), substrate, etc., a curve was obtained experimentally for S1813 photoresist coated on a bare silicon wafer in our lab process. As explained in the previous section, the grayscale pattern can be created such that it compensates for the photoresist contrast value where the developed photoresist would respond linearly to it. However, the grayscale pattern would not be a visually looking correct image as the eye does not respond in the same manner.

Figure 8.8. Quintel Mask Aligner system used at SFU clean room facility
To begin, the silicon wafer was coated with photoresist with the same process explained in Section 8.2. Next, the photoresist was exposed under the Quintel mask aligner (Figure 8.8) with the exposure times from 0.5 sec to 4.3 sec with 0.2 sec incremental steps. To expose the photoresist multiple times with different exposure times, two large pieces of opaque material of aluminum foil was used as a shield along with a large piece of glass on top as a holder. To perform exposure, most of the wafer was covered with the aluminum foil except for a strip opening of 0.5cm width as shown in the diagram below (Figure 8.9). Moving the opening left/right, the total area of the wafer was exposed with different exposure times without affecting the other wafer areas, followed by a long exposure to the bottom half of the wafer for achieving full development of the photoresist as a reference height.

After developing the photoresist for 50 sec, the remaining resist thicknesses were measured using the Tencor Alpha Step 500 Profiler. The experimental contrast curve was created based on the remaining photoresist thickness versus the exposure time, illustrated in Figure 8.10. As the UV source is constant for the used mask aligner (~25mW/cm² measured with the FieldMaster), thus the exposure time was plotted in the curve rather than the energy.

*Figure 8.9. Method for multiple exposure of the photoresist on a single wafer*
Figure 8.10. S1813 photoresist experimental contrast curve (semi-log plot)

As is done in the datasheet and the standard contrast curve, doing the fit on the log linear part of the curve from 1.7 sec exposure, Equation 8.8 is achieved, which shows a gamma of 2.05 for the photoresist. In addition, based on Equation 8.1, the amount of offset (1.42) is defined as gamma multiplied by the log of the time to clear (Log (t_c)), which results in t_c of 4.93 sec. Similarly, using Equation 8.3, the amount of t_0 can be calculated as 1.6 sec.

\[
\frac{T_R}{T_0} = 1.42 - 2.05 \times \log(t_{exp})
\]

Visually checking the goodness of the fit, it is noted that it falls off at the bottom end of the curve. This can be related to the fact that the behaviour of the resist varies depending on the process factors. Also the theoretical photoresist formula actually does not account for the reality that all resists do not follow the simple curve in the regions near D_0, as Figure 8.10 shows in the region where T_R/T_0 >= 0.9. As the fitting was performed based on the simple theoretical formula, it does not fit well to the experimental results. Using the runs test to check for goodness of the fit of the log linear equation, it was noticed that the randomness of the residuals is only 0.5% suggesting a poor fit.
Plotting the photoresist behaviour linearly in terms of exposure time (Figure 8.11), it can be seen that the fit corresponds better to the data. A linear fit was done for most of the curve below $T_R/T_0$ of 0.9. As the photoresist response to the exposures below the threshold value is also important in grayscale lithography, the second fit was also done for that range ($T_R/T_0 >= 0.9$). The runs test also showed that the randomness of the residuals is increased to ~8% which is 16 times more than the log linear fit. The empirical formulas are given for the exposure times below 1.7 sec ($T_R/T_0 >= 0.9$) in Equation 8.9 and for the exposure times above 1.7 sec ($T_R/T_0 < 0.9$) in Equation 8.10.

\[
\frac{T_R}{T_0} = 1.04 - 0.071 \times t_{exp} \quad \text{For} \quad \frac{T_R}{T_0} \geq 0.9 \quad 8.9
\]

\[
\frac{T_R}{T_0} = 1.42 - 0.315 \times t_{exp} \quad \text{For} \quad \frac{T_R}{T_0} < 0.9 \quad 8.10
\]

These will be later used to calibrate the photomask transparency to the photoresist behaviour. Note that the given formulas define a simple linear relation between the exposure time and the remaining photoresist. The next section will present the lithography experiments performed using these equations.

**Figure 8.11. S1813 photoresist experimental contrast curve (normal plot)**
8.5. 3D Microstructures on the Photoresist

After calculating the grayscale transparency required to create linear photoresist thickness with the fit, new structures were written on the grayscale mask based on the calibrated values. The first structure is shown in Figure 8.12 where 16 different gray-levels are written in the photoresist with two different calibrations; linear transparency (which assumes D₀ = 0) and calibrated transparency (from Figure 8.11) to achieve linear resist steps. Table 8.2 is lists the gray-levels versus the required OD based on each calibration.

![Figure 8.12. Backlit of 16 levels grayscale pattern written on Sn/In film with linear transparency (top) and calibrated transparency (bottom)](image)

A lithography experiment was performed using the new grayscale structures shown in Figure 8.12 and it was again diced for imaging. Figure 8.14 shows the Scanning Electron Microscope (SEM) picture of the 16 different gray-levels on the photoresist. The figure shows the structures created with the linear transparency patterns on the grayscale mask (top) and the calibrated patterns for linear resist thickness (bottom). As it can be seen in Figure 8.14 (a), at the top structure (linear transparency), the photoresist has not been developed in the first 2 pads, while in the bottom structure (calibrated transparency), the photoresist is developed from the first pad. The profilometry results also shows that the structure created with a calibrated pattern on the grayscale mask for linear photoresist thickness creates almost a linear slope. Figure 8.13 shows the surface profile measurements of the remaining photoresist versus its equivalent gray-level on the grayscale mask for both structures.
Table 8.2. 16 gray-level pattern grayscale value and its target OD

<table>
<thead>
<tr>
<th>Grayscale 4-bit</th>
<th>Grayscale 8-bit</th>
<th>Target OD Based on Linear Transparency</th>
<th>Target OD Based on Linear Photoresist Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>1</td>
<td>17</td>
<td>0.38</td>
<td>0.37</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>0.41</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>68</td>
<td>0.48</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>85</td>
<td>0.52</td>
<td>0.47</td>
</tr>
<tr>
<td>6</td>
<td>102</td>
<td>0.57</td>
<td>0.49</td>
</tr>
<tr>
<td>7</td>
<td>119</td>
<td>0.62</td>
<td>0.52</td>
</tr>
<tr>
<td>8</td>
<td>136</td>
<td>0.68</td>
<td>0.55</td>
</tr>
<tr>
<td>9</td>
<td>153</td>
<td>0.74</td>
<td>0.59</td>
</tr>
<tr>
<td>10</td>
<td>170</td>
<td>0.82</td>
<td>0.62</td>
</tr>
<tr>
<td>11</td>
<td>187</td>
<td>0.92</td>
<td>0.66</td>
</tr>
<tr>
<td>12</td>
<td>204</td>
<td>1.04</td>
<td>0.71</td>
</tr>
<tr>
<td>13</td>
<td>221</td>
<td>1.21</td>
<td>0.76</td>
</tr>
<tr>
<td>14</td>
<td>238</td>
<td>1.49</td>
<td>0.81</td>
</tr>
<tr>
<td>15</td>
<td>255</td>
<td>2.50</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Figure 8.13. Remaining photoresist thickness on silicon substrate for 16 gray-levels structure
Figure 8.14. **SEM image of 16-level grayscale pattern on the silicon substrate and exposed for 7 sec**

Another experiment was performed with a 5-bit slope on the photoresist. Two patterns with linear transparency and calibrated transparency were written on the grayscale mask which was used to expose the photoresist, shown in Figure 8.15. The SEM picture of the developed resist was captured and shown in Figure 8.16. The bottom structure shown in the figure is created by a linear transparency 5-bit pattern on the grayscale mask and the top structure is created using a pattern calibrated for achieving linear photoresist thickness.

Figure 8.15. **Backlit of 5-bit grayscale pattern written on Sn/In film with calibrated transparency (top) and linear transparency (bottom)**
Figure 8.16. SEM image of 5-bit grayscale pattern on the silicon substrate and exposed for 7 sec

Measuring the surface profile of the 5-bit slope in the photoresist (Figure 8.17) showed that using the calibrated transparency mask (Figure 8.17(a)) resulted in creation of almost linear slope compared to the structure created with linear transparency mask (Figure 8.17(b)). Although the slope shown in Figure 8.17(a) fits better with a 2nd order polynomial sentence, the difference between the two created structures shows that a linear pattern can be easily achieved by a second correction to the mask. A possible reason of this can be the difference in the UV source spectrum (G-line and I-line) used in the mask aligner and the violet line (457nm) used for OD measurement. The shorter UV lines may be more absorbed at the higher transparencies by the bimetallic oxides than the 457nm line.

(a) Slope created with the calibrated transparency grayscale mask showing nearly linear resist thickness behaviour
Figure 8.17. Surface profile of the photoresist exposed for 7 sec with 5-bit grayscale slope pattern on silicon substrate

8.6. Chapter Summary

In this chapter, experiments were performed using the created grayscale structures in the previous chapter. It was shown that although using linear transparency to write patterns on the grayscale mask results in a visually correct grayscale images, the gray-levels must be calibrated for the photoresist used in grayscale lithography. Having gray-levels calibrated for achieving linear thickness on the S1813 photoresist, photolithography experiments were successfully performed to illustrate the capabilities of the grayscale masks in creating 3D-microstructures on the photoresist. Creating microstructures in the photoresist is the first step in 3D-structure creation in the desired substrate. To do so, future experiments are necessary to accomplish a process to transfer the microstructure from photoresist to the substrate below, which is not at the scope of this thesis.
9. Conclusion and Future Work

9.1. Thesis Conclusions

This thesis targeted improving the accuracy of the bimetallic grayscale photomasks. The work discussed several aspects of the problems which limited the final achieved resolution of the grayscale in these masks. However, to achieve precise grayscale mask, the optical density of the mask must be accurately measured and controlled. In Chapter 4, it was shown that the OD measurement process can be improved by adjusting the output signal of the photo-diode sensors. For this, statistical methods were used to identify the best fit for the response of the sensors. Using the best equation for each laser power range in the sensors, the response of the system was improved which resulted in more accurate control over the achieved gray-level on the mask.

One of the main issues impacting the gray-level accuracy was the Gaussian laser beam creating the prison-bar (edges of lines) effect on the mask, discussed in Chapters 2 and 5. To decrease the prison-bar effect, a refractive field-mapping beam shaper was used to manipulate the Gaussian beam and change it to a flat-top profile (Chapter 5). As one of the beam shaper requirements, the multi-line Argon laser was separated into individual lines using a prism. Despite the beam shaper installation in the system and trying to characterize it with the single 488nm and 514.5nm laser beams, the desired flat-top profile could not be achieved with sufficient accuracy. However, separating the multi-line argon wavelengths to six individual beams created an opportunity for dual probing method.

By using the Argon laser's highest power green laser line as writing wavelength (514.5nm) and using the shortest violet line as probing wavelength (457.9nm), the Dual Wavelength Writing and Measuring System was created (Chapter 5). Employing the
second unchanging power laser line during mask writing process, the system was able to measure higher OD range masks with more accuracy.

In Chapter 7, to test the ability of the new system in producing high accuracy grayscale masks, several simple and complex patterns were written. During the simple structure patterning, it was noticed that the mask OD measurements done at the two times, during and post writing, were different. Two possible causes were investigated. First, the measured OD was found to not change with the writing velocity, thus the problem was not related to the oxidation process rate. However, it clearly was related to the laser beam power absorbed by the film, thus to the heating of the film. This suggested that the high laser power causes the film to affect the expansion rate of the beam after the mask, modifying the measured OD value.

Using the post writing OD response as the correct measurement of the mask optical density, full 256 gray-level complex patterns were written on Sn/In mask using linear OD and linear transparency, where the OD range or transparency range were divided linearly over the 256 levels of gray. Looking at the test patterns written with linear transparency and comparing it with the original pictures, it could be seen that this method corresponded very well to the provided bitmap.

Chapter 8 then looked at how the grayscale masks translated into patterns in the photoresist. It considered that using linear OD patterned mask with standard photo-lithography, the created structures greatly emphasized on the top-end and bottom-end of the gray-levels. However, using linear transparency mask with the standard lithography, the resist response was better but not linear, as the photoresist exposure threshold and gamma were not taken into account. Looking in the literature for grayscale lithography, it usually employs a linear OD/transparency grayscale mask with ~16 gray-levels. With such limited gray-levels, the lithography processes were adjusted to the grayscale mask to create linear resist steps. However, this is not desired in fabrication industry. Using a full-tone grayscale mask, the ability to control the writing process to manipulate the gray-levels to the resist behaviour is achieved.

Typically in the literature, based on the classic contrast curve formulations, to fabricate a precisely 3D shaped device, a cyclical methodology of adjusting the mask
and/or the process is performed to achieve the desired result. However, it is difficult to
do so if the masks are expensive and harder to manipulate. This thesis sought to use
gray-scale lithography flexibility in gray-level control, so that the process becomes more
predictable. In addition, the bimetallic grayscale masks are easier to be altered to adjust
to the resist's behaviour. For this, equations were developed relating the response
curves of the resist to the grayscale (transparency) required to achieve a given resist
thickness. Then masks could be written with the gray-levels needed for the desired
structure.

Using Shipley S1813 photoresist for several experiments, some initial
formulations were developed to relate the gray-levels on the mask to the resist's contrast
curve in order to achieve a linear response. To test the calibrated grayscale mask,
several structures were patterned on the Sn/In mask. The first tests were two identical
16 gray-level structures which were written with linear and calibrated transparency for
comparison. In the second experiment, 5-bit slope structures were written on the Sn/In
mask with linear and calibrated transparency. In both experiments, after development,
SEM photographs, and height measurement of the photoresist, it was shown that the
structures with calibrated transparency resulted in the creation of an almost linear
structure on the resist.

9.2. Future Work

This thesis has significantly improved the accuracy at which bimetallic grayscale
masks can be produced using the second wavelength to measure the thin-films optical
density separately and improvement to the OD measurement software. In addition, by
relating the gray-levels to the desired mask thicknesses, the photoresist behaviour could
simply be controlled by altering grayscale mask's pattern. However, the only photoresist
characterized in this thesis was S1813 thin photoresist. The following sections list some
of the future works that requires further investigation.
9.2.1. Further Investigation on Photoresist to Grayscale Response

In this thesis, S1813 photoresist was characterized on a silicon substrate to the standard lithography process with the mask aligner used at SFU. Using the achieved contrast curve, the bimetallic grayscale mask was calibrated such that it resulted in a linear response of the resist. Although the experiments with this specific photoresist were successful, this process requires further investigation on characterizing different types of photoresists on several substrates.

As the S1813 photoresist is a thin resist with only 1.3µm thickness, controlling the patterned height for 256 levels is hard, as the thickness control becomes ~5nm which the resist cannot achieve. To better test the full-tone grayscale mask in creating 3D structures, using thicker photoresist is required. Looking in the literature, the photoresists with the thickness of ~10µm (e.g. AZ4620) are used to perform high resolution grayscale lithography. Additionally, to create and test micro-lens arrays, using transparent substrates such as glass are necessary. As the amounts of substrate reflection and/or the resist’s UV light absorption are different, the full characterization of the process with each used resist/substrate combination is needed.

After successfully creation of the 3D micro-structure in the photoresist, it is then required to transfer the pattern to the substrate below. The 3D micro-structure etching requires erosion of the resist and the substrate at the same time. However, the rate of erosion is a function of the photoresist thickness to the substrate thickness which needs investigation as it was out of the scope of this thesis.

9.2.2. Improving the Quality of Bimetallic Thin films

As the optical density of the films is dependant to the sputtered film’s thickness, uniformity of the bimetallic thin-films can increase the quality of the written grayscale masks. With the non-uniform bimetallic films, the initial OD of the film will change with respect the thickness. Hence the laser power needed to create a specific optical density will be different in various spots. As discussed in Section 2.7, the suggested method considers sputtering several thin layers of target material on the substrate followed by a short exposure to oxygen rather than a single thicker layer film. This prevents any large
grain creation on the substrate which creates smoother surface films with less optical density fluctuation.

9.2.3. **Improving the Grayscale Mask Laser Writing System**

As the bimetallic grayscale masks are sensitive to the amount of laser intensity, any type of power fluctuation results in gray-level variation on the mask. Using a Gaussian beam to write the masks causes non-accurate grayscale patterns. Although using a beam shaper to create a more uniform laser spot was investigated and resulted in some improvements to the written structures, the real flat-top profile was not achieved due to the shaper optics which did not behave as expected.

Beside the shape of the beam, the power fluctuation of the laser source can also cause gray-level variation. Knowing the fact that the power difference to pattern each gray level is <0.5mW at some gray-levels, small amount of laser power fluctuation can easily change the achieved gray-level on the mask. Hence, stabilizing the laser power can significantly improve the achieved grayscale mask accuracy.

Writing the mask with higher velocities can reduce the sensitivity of the mask to the laser power fluctuation. However, one of the main limitations in increasing writing velocity is the FPGA board's limited sampling rate. The maximum sampling rate of the FPGA (100Hz or 10ms) allows the system to pattern the mask with no more than 500µm/s. Reconfiguring the FPGA board to process the sensor's output signals differently can increase the sampling speed (hence velocity) up to potentially 3 times faster.

9.2.4. **Further Exploring the During Writing and Post writing OD Measurement Effect**

As discussed before, using 457.9nm laser line as a probing beam improved the quality of the grayscales on the mask by increasing the accuracy and the range of OD measurement. However, it was seen that the OD measurements done during and post writing were different. Although it was showed that the resist material alters the beam characteristics in some way while it is still being written, more investigation is required to
find the actual cause of this occurrence. The followings are suggested hypothesis that can be further explored in the future.

- Absorption characteristics of the hot oxide are different than the cool oxide.
- The hot oxide scatters the violet probing beam, which can be tested by measuring the level of the scattered light during and after writing.
- The hot oxide forms a dome shape structure, which can be tested using a different lens system to collect light.
- The dome shape structure is created on the glass substrate, which can be tested by changing the glass substrate with quartz.

Investigation of the causes will help characterize this. However the current tests show that the relationship of this effect to the OD error seems to be quite consistent. This suggests two short term solutions. First, to simply create a correction curve that related the post OD measurement to the as written OD value. Since this effect is clearly related to the power of the beam a new calibration curve can be created. Secondly it is possible that changing the lens arrangement below the mask may be able to correct this by collecting all of the light in the new beam distribution below the mask. Future work will investigate these two options.
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