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# FABRICATION OF MICRO-OPTICS USING BINARY AND GRAYLEVEL MASKS

by

Daniel Simon

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In Partial Fulfillment of the Requirements
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In the Graduate College

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1998

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## APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Michael R. Descour
Professor of Optical Sciences

6/30/98
Date

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Although it is impractical to adequately list all the members of the Optical Sciences Center who have helped me day in and day out, you know who you are, and I thank you for your help.

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## DEDICATION

To my family, especially my parents, for the love, support, and encouragement they have given me, whatever my pursuit.

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## ABSTRACT

This thesis provides step by step instructions on how to design, layout, and fabricate diffractive optical elements (DOE). While there has been a great deal published on the design of DOEs, there are few publications detailing how to transform a design into a physical element. The thesis describes how to order a photomask and pattern an element. It provides recipes that I have used to etch DOEs with both an ion mill and a reactive ion etcher (RIE) at the Optical Sciences Center. The thesis includes characterization of the elements fabricated using these recipes. In addition the thesis looks at the design and fabrication of ring toric lenslets. A ring toric lenslet is a DOE that focuses light to a ring instead of a point. The ring toric lenslet has potential applications in the optical data storage industry. This thesis includes macros for the design and mask layout of binary and grayscale ring toric lenslets. Grayscale elements require special design, calibration, and mask layout steps not necessary for binary elements. Details of the design, calibration, mask layout, and fabrication of the grayscale element are included.

# CHAPTER 1

# INTRODUCTION

## 1.1 General Introduction

Diffractive optics employ the principle of diffraction, namely the bending of light rays around the edge of an obstruction, to manipulate light. Diffractive optics are by nature wavelength specific and thus best suited for use at a single wavelength, or over an extremely narrow bandwidth. Consequently diffractive optics were not of significant interest before the advent of the laser 35 years ago. Since diffractive optics can have a negative Abbe number they can be added to broadband systems to correct for chromatic aberration.[1, 2] Diffractive optics also typically require the ability to fabricate very small features. For example, in the case of a diffractive lens, the smallest feature size equals half the F/# in microns at 500nm for a binary element. Thanks to advances in the semiconductor industry over the past ten years, printing features this size is no longer an obstacle, even for very fast systems (F/1 or smaller). The use of diffractive optics is growing due to the significant benefits they can bring to an overall systems design.

Some benefits of using diffractive optics in a system design include the use of fewer elements, better system performance, novel lens surfaces and potential for mass production. For example, a diffractive optical element (DOE) designed to perform the equivalent function as system element A, may be 'printed' on system element B creating a single hybrid (diffractive/refractive) element AonB. Welford has shown that a meniscus lens with a diffractive surface on one side allows for correction of both

spherical aberration and coma.[3] A system using a hybrid element can lead to a compact (shorter length) and lighter system. Using diffractive optics (in conjunction with refractive lenses) in achromats or apochromats results in lens elements with reduced curvature (or a larger aperture for the same curvature) thus improving their performance.[4] Perhaps most interesting is the potential to design arbitrary phase profiles which integrate additional functionality into the lens system. One example of this type of application is the ring toric lenslet which will be discussed at length in Chapter 6.

## 1.2 Theoretical Models

There are four standard models for describing how diffractive optics work, the phase model, the hologram model, the grating model and the Sweatt model.[5, 6, 7] In the phase model the diffractive optic is described by its phase profile $\phi(x, y)$, a design wavelength, $\lambda_0$, and the surface on which the element lies. The phase can contain a spherical term and an aspheric term but either can be made equal to zero allowing the designer considerable freedom in the phase profile he can replicate. The hologram model treats the diffractive optic as a hologram with the object located $z_0$ from the hologram, a source located at a distance $S_0$, and a recording wavelength $\lambda_0$. In a similar manner the image is located $z_i$ from the hologram plane, the readout source located at a distance $S_r$, and the readout beam has a wavelength $\lambda_r$. The grating model is based on the grating equation (see Figure 1-1).

$$m\lambda = \sigma(\sin\alpha + \sin\beta) \qquad (1)$$

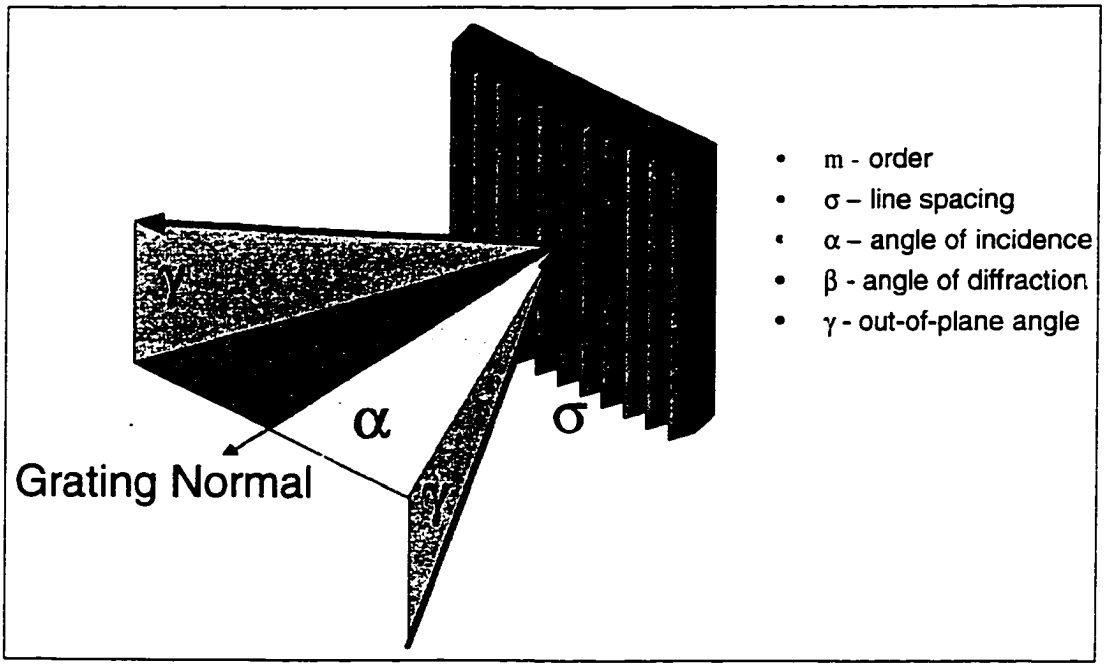



**Figure 1-1.** An illustration of the grating equation. Often $\gamma$ is assumed to be zero.

and treats the diffractive optic as a grating whose period can vary with position. The Sweatt model treats the diffractive optic as a thin lens with quasi-infinite index ($n \approx 10{,}001$ for single wavelength and $n \propto \lambda$ for broadband). Since this model is based on the thin lens approximation, a good deal of aberration theory has been applied to determine what aberrations can or cannot be corrected when using diffractive optics in either broadband or monochromatic systems.[5] For example a diffractive singlet used at a single wavelength and with the appropriate stop shift will produce only distortion and spherical aberration, while eliminating coma, astigmatism and Petzval curvature, the third order aberrations which usually limit the off-axis performance of a lens.[8]

## 1.3 Fabrication Overview

Diffractive optics can be produced using optical lithography (sometimes called photolithography), diamond turning, direct electron beam writing,[9] laser ablation,[10] embossing or epoxy casting.[1] Fabrication of diffractive optics, specifically binary optics, can be accomplished using photolithography, the same technology with which microprocessors and integrated circuits are fabricated. To fabricate an optic in this manner there are three basic steps: (1) mask generation, (2) sample patterning, and (3) etching of pattern into the element substrate.

Once the mask has been written, the sample can be patterned using contact, proximity or projection lithography. I have only patterned samples using contact printing. To perform contact printing, the sample is coated with photoresist, the mask is placed in contact with the photoresist, and then the sample is exposed through the mask. Developing the photoresist will remove areas that were exposed to the light for a positive type photoresist. Finally, the pattern of remaining photoresist is transferred into the substrate by means of ion milling or reactive ion etching (RIE).

The processes outlined above will result in a two level diffractive optic, and can be repeated to obtain multilevel diffractive optics. Although some care must be taken in aligning additional patterns, multiple levels result in a dramatic improvement in the diffraction efficiency of the optic because the resulting profile more closely approximates the true phase profile i.e. $\phi(x, y)$ modulo $2\pi$. For example, the theoretical diffraction

efficiency, $\eta$, of a binary (N = 2) diffractive optic is $\eta = 0.41$ meaning that it diffracts about 41% of the light into the first order. In contrast, a multilevel diffractive optic using eight levels (N = 8) has a diffraction efficiency of $\eta = 0.95$. While the high theoretical diffraction efficiency means multi-level optics can be used in real systems, the many fabrication steps involved allow ample opportunity for efficiency losses due to fabrication errors, such as incorrect etch depth, and misalignments.

## 1.4 Thesis Outline

All of my work was done using tools and equipment available at the Optical Sciences Center. While this equipment is used frequently, it is not often used for the fabrication of diffractive optics. Based on my experience, I will discuss how one uses optical lithography tools to fabricate diffractive optics. I provide step by step instructions on how to fabricate elements and recipes that I have used. The thesis is organized as follows. In Chapters 2 and 3 I will cover some of the details encountered when designing diffractive optics, using elements I have designed to illustrate the process. In Chapters 4 I will explain and provide 'recipes' detailing each of the steps necessary to transfer a diffractive element from a design to a final fabricated element. In Chapter 5 I include a section which discusses how to determine the etch depth desired and show some elements I fabricated using the recipes provided. In Chapter 6 I examine the design and fabrication of a binary ring-toric lenslet, including experimental results. In Chapter 7 I look at fabricating a ring-toric lenslet using a grayscale photomask. The grayscale photomask is

a relatively new technology that allows one to fabricate a multi-level diffractive optic in a single fabrication step.[11, 12]

# CHAPTER 2

# SIMPLE APPLICATIONS

## 2.1 Lenslet Arrays

One early and simple diffractive optical elements is the Fresnel zone plate,[13] or lenslet. It consists of concentric rings, or zones, of alternating phase whose radius is determined by $m$, the number of the zone (i.e. $m$ for the $m^{th}$ zone), $f$, the focal length of the desired lens, and $\lambda$, the design wavelength, in the following manner:

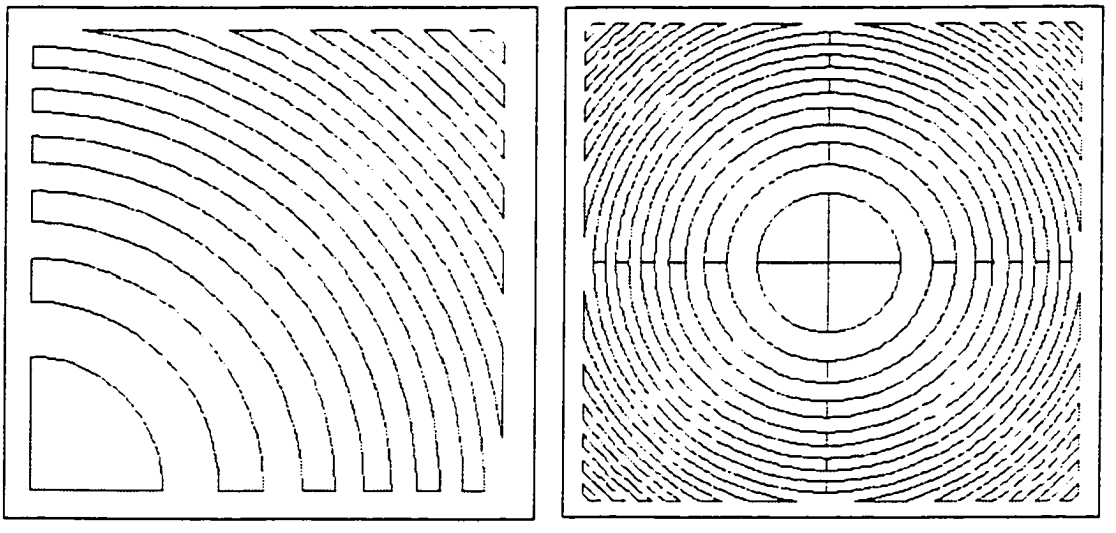
$$r_m = \sqrt{2m\lambda f + (m\lambda)^2} \tag{2}$$

This design is ideal for a binary optic scheme since it calls for zones of alternating phase value corresponding to transparent or opaque on the photomask. Each of these zones can later be divided into two smaller zones, one light the other dark, for a total of four possible phase values. In this manner a staircase phase profile $\phi_s(x, y)$ can be constructed that closely approximates the desired continuous phase profile $\phi(x, y)$. Moreover, once the focal length and wavelength are specified, the zone radii are easily computed. I used dw-2000,[14] an integrated circuit layout package, to lay out the zones for the following lenslet configurations:

| Lenslet arrays | Size | Focal length (mm) | λ (nm) | Dia (mm) | F/# | Level |
|---|---|---|---|---|---|---|
| 4mm | 32x32 | 4 | 632.8 | 0.3 | 13.333 | 2 |
| 3-5mm block | 16x16 | 3 | 632.8 | 0.3 | 10 | 2 |
| | | 3.66 | 632.8 | 0.3 | 12.2 | 2 |
| | | 4.33 | 632.8 | 0.3 | 14.433 | 2 |
| | | 5 | 632.8 | 0.3 | 16.667 | 2 |
| 50vis | 6x6 | 50 | 550 | 3 | 16.667 | 2 |
| 50ir | 6x6 | 50 | 10000 | 3 | 16.667 | 8 (3 layers) |

**Table 2-1.** List of Lenslet Arrays designed with dw-2000.

A copy of the dw-2000 macro used to layout the lenslets is included in Appendix A. The quarter lenslet that is an example of the output this macro produces appears in Figure 2-1 (a). The full lenslet is shown in Figure 2-1 (b).



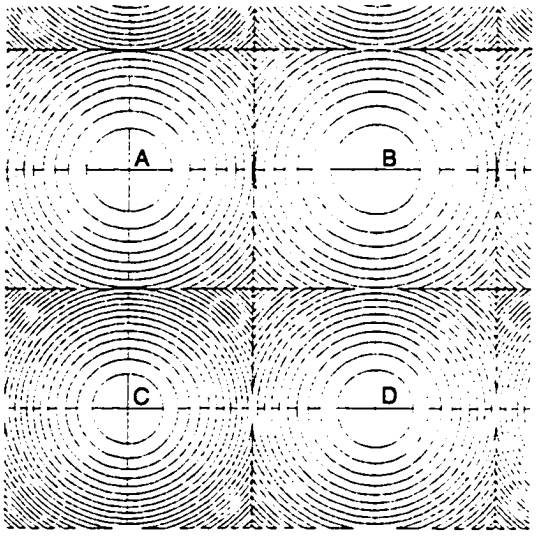
(a) (b)

**Figure 2-1.** Mask layout of a binary lenslet, with 3mm focal length using dw-2000. Part (a) shows the upper right quarter of the lenslet. Part (b) shows the full lenslet.

## 2.2 Confocal Microscope

The two lenslet arrays named *4mm* and *3-5mm block* were created to be part of a confocal microscope intended to image the cornea and measure the effects of refractive surgery. The lenslet *3-5mm block* array is composed of 4 lenslets, see Figure 2-2, with slightly

different focal lengths which make it possible to gather data from different depths inside the cornea.




(a) (b)

**Figure 2-2.** *3-5mm block* binary lenslet array. Part (a) Mask layout of the 4 lenslets in *3-5mm block* array. Part (b) Image taken of *3-5mm block* array focusing collimated light.

Figure 2-3 shows a schematic layout of the confocal microscope system and the placement of the lenslet array.

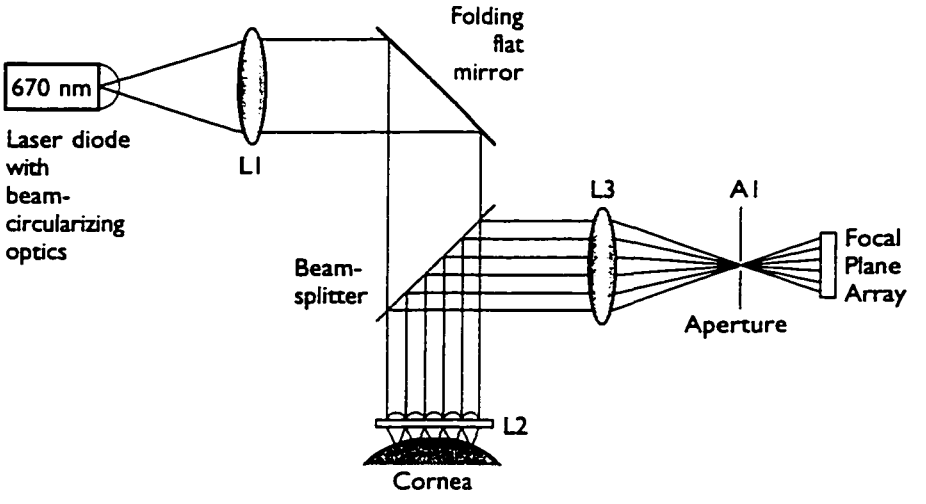



**Figure 2-3.** Schematic of confocal microscope layout using a lenslet array. The lenslet array is labeled L2 in the diagram.

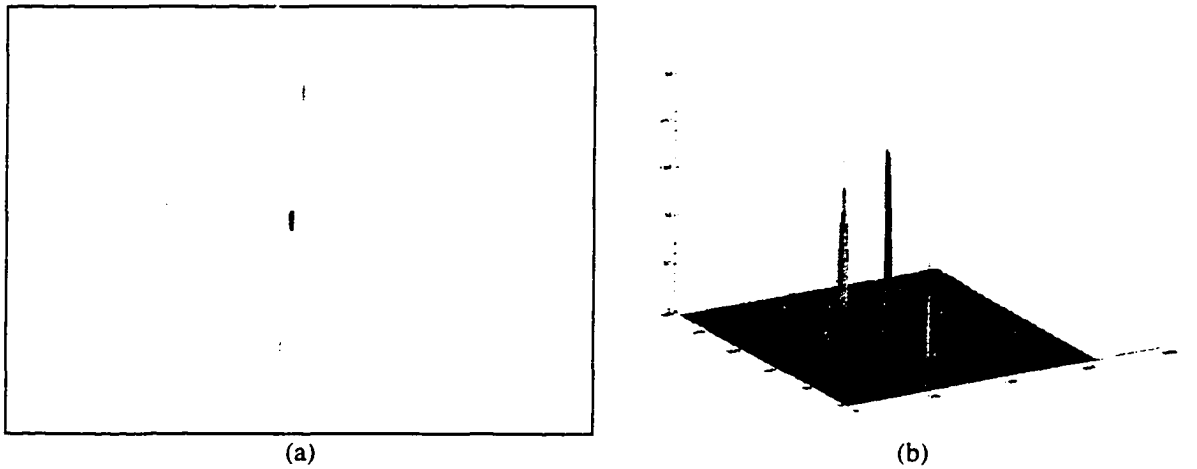
### 2.3 Fourier Transform Spectrometer

The lenslet array named *50vis* was made to test a multiple image Fourier transform spectral imaging concept.[15] If it works, then we are prepared to fabricate a high-efficiency infrared version listed above as *50ir*.

### 2.4 Infrared Disperser

Another simple diffractive optical element that I designed in collaboration with J. Garcia and then fabricated was a disperser for an infrared computed tomography imaging spectrometer (CTIS).[16] The IR disperser consists of a 36.5 mm × 36.5 mm grid of 45.5 μm square pixels, each spaced 45.5 μm from the neighboring pixel. The disperser topography is shown in Figure 6-3 of Chapter 6. The IR disperser works in the 3-5 μm

spectral range and is designed to diffract light into the higher diffraction orders. Figure 2-4(a) shows an image of a slit using the IR disperser. The diagonal orders are just barely visible in Figure 2-4(b).



(a) (b)

**Figure 2-4.** Spectral image of the exit slit of an IR monochromator. The input source of radiation is a 973-K blackbody. Part (a) shows a reverse contrast image taken with the IR disperser. Part (b) provides insight with respect to the signal levels (0-255) associated with the diffraction orders of the prototype MWIR disperser. (Data and processing courtesy of Tony Lin, University of Arizona.)

# CHAPTER 3

# DOE EFFICIENCY AND MASK LAYOUT

## 3.1 Efficiency vs. Number of Levels

The diffraction efficiency into the first order of a diffractive optic is directly related to the number of levels, or phase steps, created during fabrication. Adding levels creates a staircase pattern, which more closely approximates the spherical profile of a lens. Using N masks results in $2^N$ levels. The first diffraction order efficiency for a multi-level diffractive optic, with N levels can be calculated as follows:

$$\eta_1^N = \mathrm{sinc}^2\left(\tfrac{1}{N}\right) \qquad \text{where} \quad \mathrm{sinc}\left(\tfrac{1}{N}\right) = \frac{\sin\left(\frac{\pi}{N}\right)}{\left(\frac{\pi}{N}\right)} \text{ .}^{17} \tag{3}$$

As can be seen in Table 3-1, theoretical diffraction efficiency goes up substantially when 2 masks (N = 4) or 3 masks (N = 8) are used in fabricating the element. However the improvement in diffraction efficiency falls off rapidly as more levels are added. The gain in efficiency going from 32 to 64 levels is less than 0.25%.

| Number of Masks | Number of levels | 1st Order Efficiency | % improvement |
|---|---|---|---|
| 1 | 2 | 0.4053 | |
| 2 | 4 | 0.8106 | 100 |
| 3 | 8 | 0.9496 | 17.16 |
| 4 | 16 | 0.9872 | 3.96 |
| 5 | 32 | 0.9968 | 0.97 |
| 6 | 64 | 0.9992 | 0.24 |

**Table 3-1.** Theoretical 1st Order Diffraction Efficiency ($\eta$) for Multi-Level Diffractive Optics.

### 3.2 Mask Layout

Generation of the photomask is primarily a transformation of a phase profile $\phi(x, y)$ into a thickness profile $t(x, y)$. For a two-level binary optic the transformation consists of the following steps: (1) take the modulo $2\pi$ of the phase profile $\phi(x, y)$, (2) assign all points in the phase profile with phase values below $\pi$, to be transparent (i.e. transmit light) on the mask, and (3) assign all points in the phase profile with phase values above $\pi$ to be opaque on the mask. This resulting bright and dark pattern can then be converted, or fractured (i.e. broken up into tiny polygons), to MEBES (Moving Electron Beam Exposure System) format. MEBES is the file format used by electron beam writers, which write the photomasks.

### 3.3 Photomask Layout by Macro

The macro used to layout the lenslets was originally supplied by Mial Warren from Sandia National Laboratory.[18] The design macro, found in Appendix A, produces a 'quarter' lenslet in the first quadrant of the Cartesian plane. One anomaly encountered with the software/macro is the requirement that the element lie entirely within the first quadrant (i.e. not on the axis). The issue is trivial since the software allows the lower left corner of the element to be placed at $x = y = 0.01$ μm. However, it is important to remember to compensate for the offset when replicating the other three quadrants of the lenslet or the pattern will not meet in the center as illustrated in Figure 3-1.

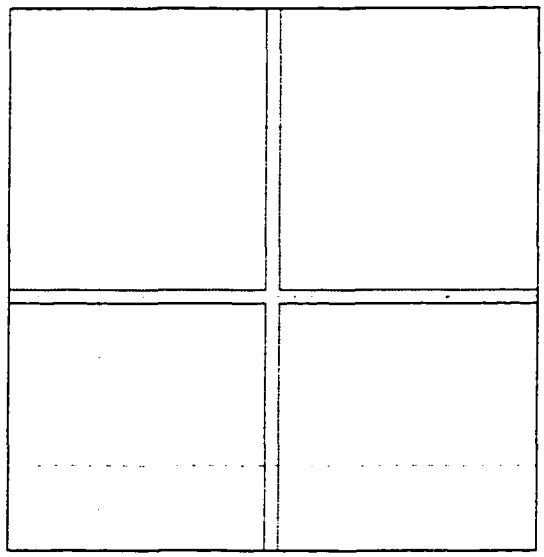


**Figure 3-1.** Magnified view of lenslet center where the 0.01 μm offset is not compensated.

Once the layout of the photomask is complete, it can be converted to a file format such as GDSII or MEBES which can be read by commercial photomask vendors.[19] See Appendix B for details on ordering a photomask. It is reasonable to expect a mask order can be filled in less than two weeks. It is relatively expensive if one is needed in less than a week. When the mask arrives, the patterning and fabrication can begin.

# CHAPTER 4

# FABRICATION

## 4.1 Patterning the Sample

Whether using a Reactive Ion Etcher (RIE) or an Ion Mill for the etching step, the substrate can be patterned by following the same steps. I will briefly highlight the important steps in patterning a sample. Additional details about spinning resist can be found in Appendix C. Operation of the mask aligner is described in Appendix D. All the patterning that I have done has been using Shipley 1813,[20] which is a positive resist (i.e. resist exposed to ultra-violet ($350nm < \lambda < 450nm$) is removed when developed). Future references to photoresist imply Shipley 1813. Since all photoresists have a slightly different chemistry, the reader should keep in mind that the following recipe is predicated on the use of Shipley 1813. We used ordinary microscope slides, made of soda lime glass, (3" × 1" × 1mm thick) for our visible elements and double polished gallium-arsenide wafers[21] (2" dia. × 0.5mm thick) for our infrared device. Both substrates were accommodated by the clean-room spinner, which can handle substrates up to 4" diameter. The first step is to spin the resist onto the sample.

- Set the spinner to spin for 5 seconds at 300 RPM and then for 30 seconds at 4000 RPM.
- Flood the sample with resist, completely covering the area of the sample where you plan to place your pattern, then engage the spinner.
- Remove sample and bake for 1 minute at 100°C.
- Put mask in mask aligner and set for a 4 second exposure. 3.5 seconds is sufficient for the highly reflective GaAs samples, because the resist will absorb additional UV reflecting off the substrate.
- Carefully position sample on the transport slide (especially important for multi-level diffractive optic designs) before inserting into alignment stage.

- Expose the sample.

Use Shipley 352 developer solution to develop (i.e. to remove the exposed resist).

- Submerge sample in the developer for 60 seconds (develop for 30 seconds if the sample is highly reflective like GaAs).
- Take sample out of the 352 developer and place in de-ionized water for at about 30 seconds.
- Remove and dry the sample.
- Place on hot plate for 1 minute at 100°C, to evaporate any remaining moisture. Finally place sample in the Plasma Preen II oven for 60 seconds.

This process will produce a pattern with a resist height between 1.3 μm and 1.4 μm deep where the mask was opaque and bare substrate where the mask was transparent.

### 4.2 Ion Milling

Although ion milling is generally slower than Reactive Ion Etching (RIE), it will work for any substrate. Both processes occur in an evacuated chamber. Ion milling works by physically impacting a substrate with a beam of energetic particles (which can be neutral in charge) that etch both the photoresist and the substrate (the rate of etch of the photoresist usually differs from that of the substrate). An RIE system similarly employs physical impact but also includes a chemical etch of the substrate to achieve a faster overall etch rate. Because of the chemical process involved not all substrates can be etched with this tool. For example, etching a sample containing sodium would result in sodium ions being deposited in the RIE's etch chamber, thus contaminating later etch

processes. As a result, samples such as microscope slides (made from soda-lime glass) that do contain sodium are not allowed in the RIE and must be etched with an Ion Mill. The attached Appendix E provides step by step instructions on running the Ion Mill, recently relocated to Lab 452 of the Optical Sciences Center. The mill appears ancient and sometimes requires undue attention to get it started, but we have found that it does etch consistently once it starts.

In theory the milling process is quite simple.

- Place a sample in the chamber.
- Evacuate the chamber.
- Introduce a small flow of the etch gas (Freon-116 provides a tolerable etch rate) into the chamber.
- Ignite a plasma steam directed at the sample and etch away.

In practice, all these steps are present but intermingled with numerous small adjustments to the pressure and current while establishing and maintaining a steady beam.

Evacuating the chamber is a two step process. First, a mechanical pump brings the pressure down from atmospheric pressure of 760 Torr to 0.1 Torr. Second, a diffusion pump brings the pressure down below $1x10^{-5}$Torr. The mechanical pump admits gas from the vacuum chamber into a relatively large volume of the pump, isolates the gas in the pump from the vacuum chamber, and compresses the gas, which then exits though an exhaust valve. The diffusion pump works by trapping gas molecules in a working fluid, usually an oil vapor. In order for this to work efficiently the oil is heated in the center of

the pump. Also in the central section gas molecules in the oil are allowed to exit the pump system. The heated oil is then sprayed into the main pump chamber as a jet of oil vapor. In the main chamber the oil condenses, cooled by the chilled outer pump walls, traps the gas molecules and the cycle repeats.[22]

Using Freon-116[23] as the etch gas, we have achieved etch rates of about 32 nm a minute, which means around 31 minutes per micron of etch depth desired. Using Argon as the etch gas, the rate was about 1/3 as fast, making it impractical for deep etches.

The ion beam passes through an aperture which is about 1¼ inches on a side, and we have recorded a slower etch rate (as much as 1/3 slower) toward the edge of the beam. Fortunately, the elements that we have etched fit in a relatively small area of the beam (less than 4 mm × 4 mm), so we have not had to deal with significant etch depth gradients across the element.

### 4.3 Reactive Ion Etching

In contrast to the Ion Mill, the Reactive Ion Etcher (RIE) is modern and does not require unusual attention.[24] Appendix F contains step by step instructions for operating the RIE. The RIE is computer controlled so the interface is through the software, except for placing the sample on the etch tray. There is a startup and a shutdown procedure that needs to be run at either end of an etch (or series of etches). These procedures add about 45 minutes of overhead to what might otherwise be a ten or fifteen minute etch. The etch

rate varies depending on the sample size: a 35 $mm^2$ GaAs wafer slice will etch about four times faster than a 50 mm diameter GaAs wafer given the same etch gas flow rates. In contrast to the Ion Mill, the RIE will etch a sample of large area (1200 $mm^2$) pattern on a 50 mm diameter GaAs wafer at a uniform rate (i.e. only 10% variation in etch depth from center to edge). When performing an etch with the RIE, the user should make sure that the Reflected Watts indicator remains less than 5% of the MW forward power. The process will shut down if the number climbs to 10%. I used a recipe developed by Penner[25] for etching GaAs with minor modifications. Specifically I used twice the gas flow rates that Penner describes and the higher RF forward power of 150 Watts. I etched the sample for 12.5 minutes to achieve a 1.08 μm +/- 0.05 μm etch depth across an infrared disperser pattern on a full 50mm diameter GaAs wafer.

Figure 4-1 contains an image of the *Status: Display* screen where you enter the process settings.

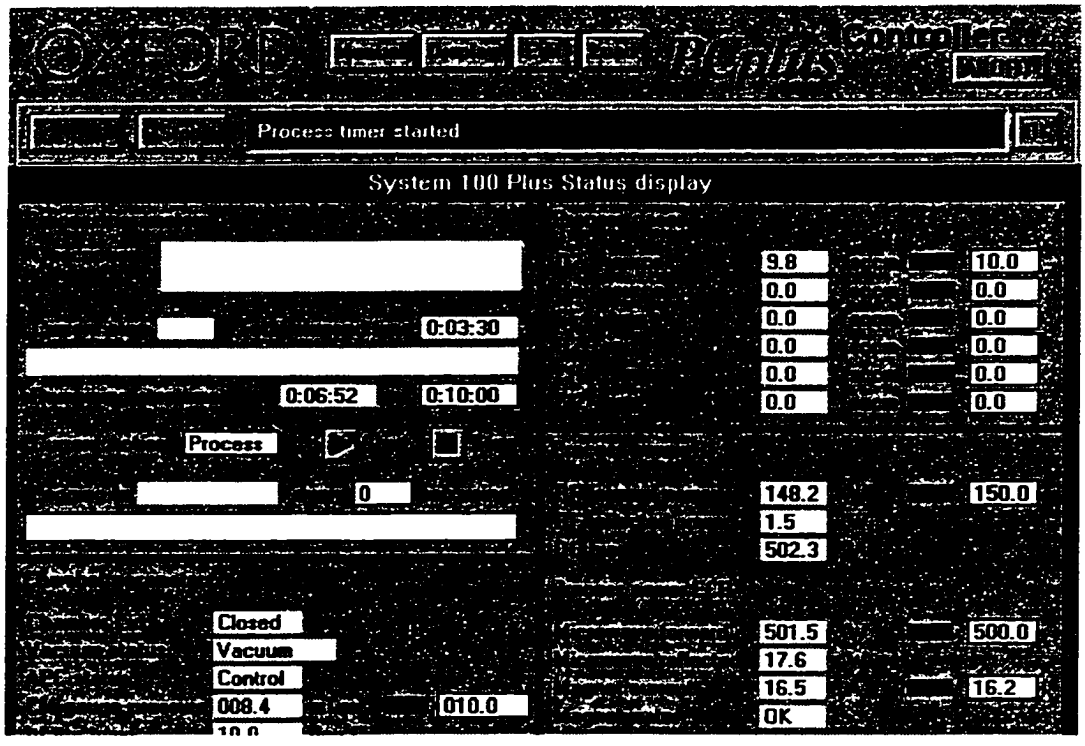



**Figure 4-1.** Screen capture of the display screen that is used to enter RIE etch process setting values, from the *Plasmalab 100 System*. Image used with permission of Oxford Instruments Inc.

Note that a high RF forward setting of 150 Watts was used to etch the infrared disperser.

Usually the RF forward setting is 100 Watts.

# CHAPTER 5

# CHARACTERIZATION OF ETCH DEPTH

## 5.1 Etch Depth for Lenslet Arrays

In general the object of the fabrication process is to transform every modulo $2\pi$ phase step of the original phase profile $\phi(x, y)$ into one design wavelength, $\lambda_0$, of optical path difference in the substrate. For a binary optic the etch depth thickness, $t_0$, depends on $\lambda_0$ and $n_0$, the index of the substrate at $\lambda_0$, in the following manner:

$$t_0 = \lambda_0 / (n_0 - 1) \tag{4}$$

Using the design wavelength of the *3-5mm block* lenslet array of $\lambda_0 = 0.6328$ μm and taking the index of the glass slide as $n_0 = 1.5$, the optimum etch depth is found to be $t_0 = 1.27$ μm.

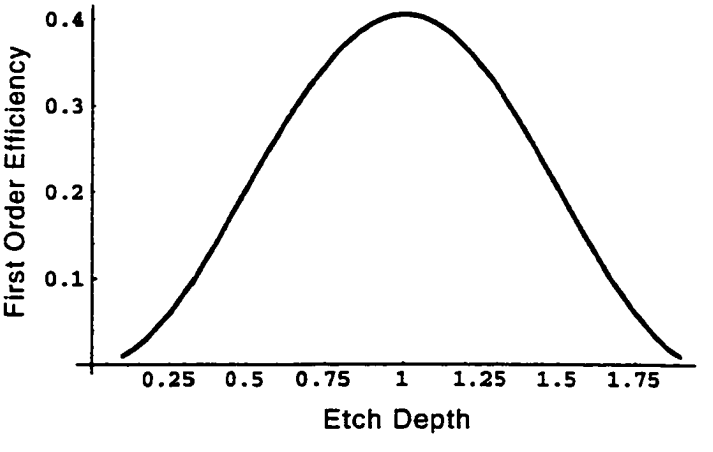



**Figure 5-1.** Plot of 1st Order Diffraction Efficiency vs. Etch Depth (in units of $\pi$) for a 2 level binary process.

From Figure 5-1 we see that when a 2 level process is used the highest diffraction efficiency into the 1st order occurs when the $2\pi$ phase step is approximated by a single $\pi$ phase step. A $\pi$ phase step corresponds to an etch depth of $t_0/2$ or 0.633 μm. This is obviously not a very good approximation, hence the low diffraction efficiency. Knowing the glass etch rate of 0.032 μm per minute, the etch time is easily calculated to be about 20 minutes. Figure 5-2 contains a three-dimensional view of the etched lenslet arrays, measured with a WYKO NT2000 optical profiler.[26] As can be seen from Figure 5-3, the lenslet array was fabricated to 2/3 of the optimum depth. Since the lenslet arrays use a 2 level process the desired etch depth was 0.633 μm or about 24% less than the actual depth.

If a multilevel diffractive optic is to be fabricated we again want one design wavelength, $\lambda_0$, of optical path difference, or a depth of $t_0$, etched in the substrate but we approach a depth of $t_0$ in a series of etches. The first etch is made half as deep as the desired depth and each subsequent etch will be half as deep as the preceding etch. In this manner the deepest etch depth approaches $t_0$ as additional etches are made. If $t_1$ is the thickness of the first etch, then

$$t_1 = t_0/2 \tag{5}$$

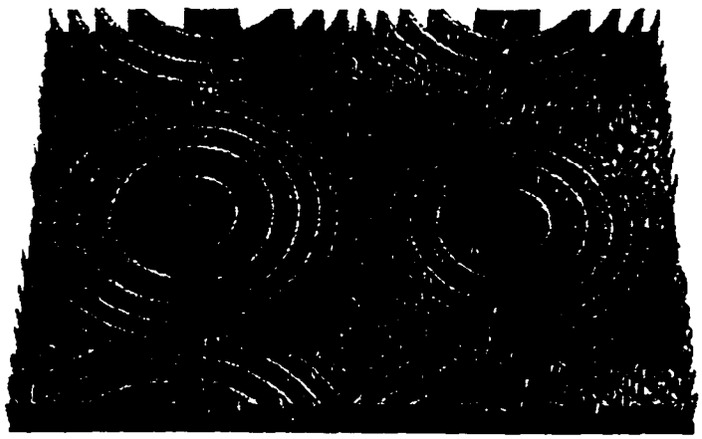


**Figure 5-2.** 460 μm × 600 μm view of etched 3 mm and 3.66 mm focal length lenslets, from *3-5mm block*. Etch depth is 0.83 μm +/- 0.025 μm.

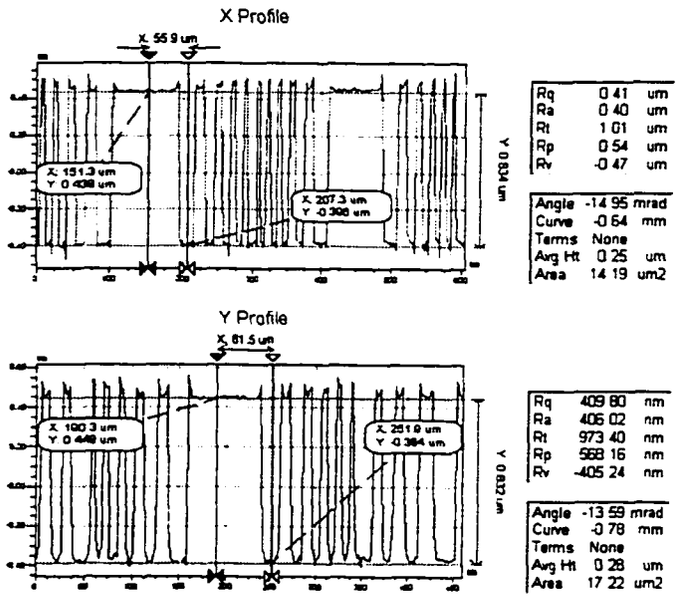



**Figure 5-3.** Depth profile of lenslets showing 0.834 μm and 0.832 μm etch depths.

## 5.2 Etch Depth for Infrared Disperser

In contrast to the lenslets, which are designed to focus light to a point, a disperser is designed to take incident light and disperse it with the same diffraction efficiency into a large number of diffraction orders. The efficiency with which light is diffracted into the higher diffraction orders depends on the etch depth and spatial etch uniformity. Based on experimental simulations, an optimal etch depth of 0.9 μm was determined. We experienced trouble maintaining a uniform etch over the relatively large area (36 mm × 36 mm) covered by the disperser, so several elements were etched. The best overall disperser was etched about 15% deeper than optimal but had good uniformity—less than 11% variation across the element, see Table 5-1.

| | Disperser Etch Depth (microns) | | |
|---|---|---|---|
| Location | Low | High | % Non uniformity |
| Center | 1.03 | 1.066 | 3.50 |
| Corner 1 | 1.103 | 1.141 | 3.45 |
| Corner 2 | 1.035 | 1.058 | 2.22 |
| Corner 3 | 1.014 | 1.038 | 2.37 |
| Corner 4 | 1.088 | 1.112 | 2.21 |
| Total | 1.03 | 1.141 | 10.78 |

**Table 5-1.** Measurement of high and low etch depths at various points on the disperser. Includes a measure of the % variation locally and across the element.

Figure 5-4 shows a surface profile taken of the IR disperser's central section.

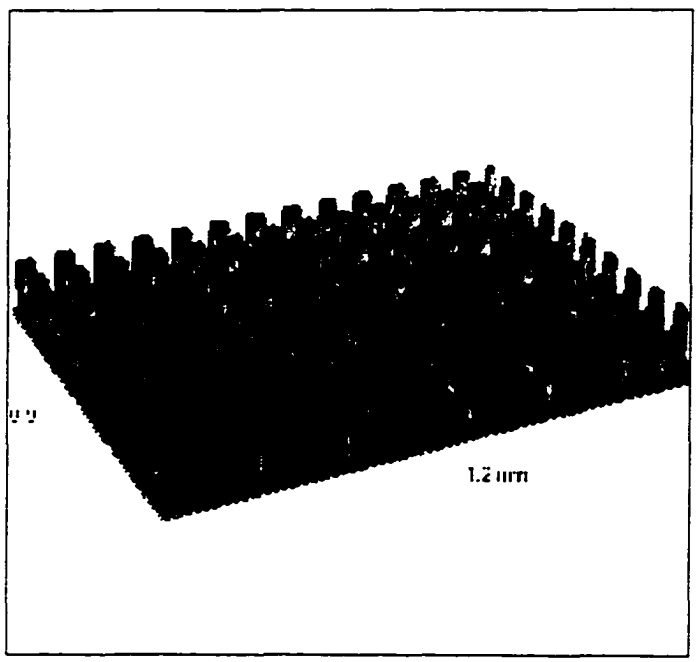


**Figure 5-4.** Center 0.9mm × 1.2mm section of Infrared disperser element. Etch depth 1.05 μm.

# CHAPTER 6

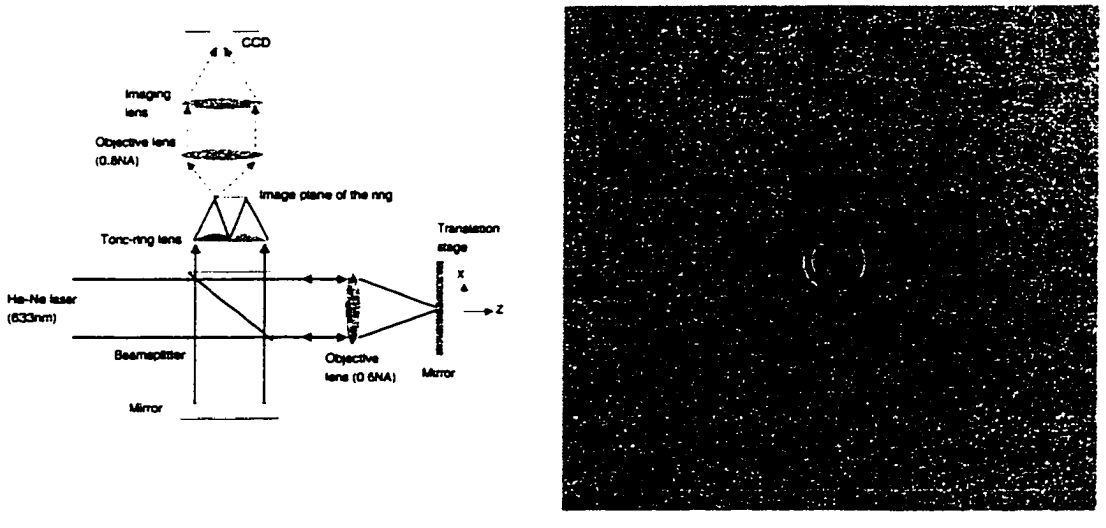
# DUAL-FUNCTION DIFFRACTIVE OPTICAL ELEMENT APPLICATION

## 6.1 Ring toric Concept

As mentioned earlier, one of the greatest advantages of diffractive optics (from a design perspective) is the ability to create an arbitrary phase profile. It is just as easy to fabricate a diffractive optic that produces an aspheric wavefront as one that produces a spherical wavefront. We have fabricated a two level, binary ring-toric lenslet using the same processes that were used to create the simple lenslet arrays. In general the primary challenge in creating an aspheric diffractive optic lies in the design and layout of the mask for fabrication. Because of the geometry involved in the case of the ring-toric lenslet, the design of this particular aspheric phase profile was greatly simplified.

The ring toric lenslet design is a result of work done by Mansuripur and Pons,[27] Bernacki and Mansuripur,[28] and Gerber.[29] In his work, Gerber describes how a ring lens, i.e. an annular lens capable of focusing light to a ring, can be used to perform focus- and track-error sensing in addition to reading data from an optical disk. One of the conclusions reached by Gerber was that a ring lens produces a steeper focus-error signal (FES) curve than the alternative astigmatic method of focus sensing. Despite this positive result, Gerber noted that the thermal process used to make the ring lens was not suitable for good quality lenses. Furthermore lenses with very small ring radii could not be produced using this method. A focused ring diameter of about 150 μm was recommended for optical disk applications.[29] Figure 6-1 (a) contains a schematic view of the test

configuration used to measure the performance of the ring toric lenslets. Figure 6-1 (b) shows the ring focus obtained using a ring toric lenslet with a 160 μm diameter ring.




(a) (b)

**Figure 6-1.** Ring toric testing. Part (a) schematic view of the ring toric test setup. Part (b) 160 μm diameter ring. View of the ring at focus through a ring toric lenslet.

## 6.2 Ring toric Photomask Layout

The essential difference between a traditional lenslet and a ring-toric lenslet is that the ring-toric lenslet will focus light to a ring instead of a point. But a point can be thought of as a ring with zero radius, so the problem becomes one of shifting the light out to a fixed radius. For a given radius, the 'origin' of the lenslet can be offset an amount equal to the given radius. The spacing of each zone relative to the others remains the same, but the zones are placed with an effective origin equal to the offset radius, see Figure 6-2. The pattern of decreasing radii is then mirrored into the center of the lenslet so that light

in the middle will also be focused out to the ring. Appendix G contains the macro used to layout the ring-toric lenslets.

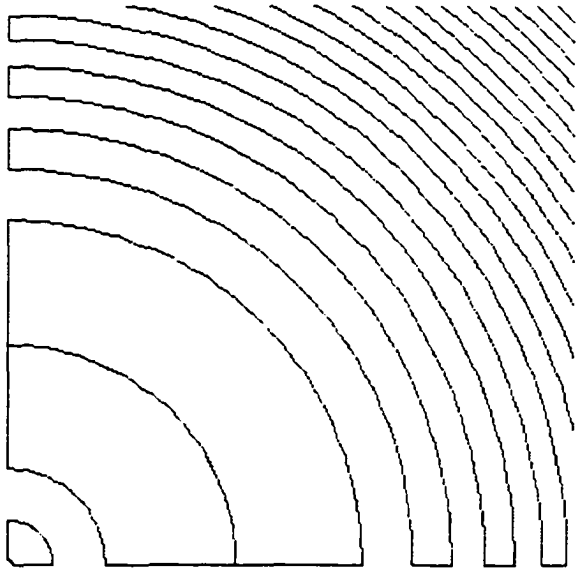


**Figure 6-2.** Example of a binary ring toric lenslet layout with a 400 μm diameter ring focus. Notice the shifted origin and how the pattern is mirrored towards the center.

### 6.3 Ring toric Fabrication

We have fabricated both reflective and transmissive ring-toric lenslets. Although the ring-toric lenslet is likely to be used in a transmissive configuration, the reflective element was made to verify the design at a time when the Ion Mill was not operational. The reflective ring-toric lenslet was etched into a ½ slice of a 50mm diameter GaAs wafer. The RIE settings were again those discussed by Penner.[25] The settings were basically the same as used for the IR disperser except a RF forward power of 100 Watts

was used. The etch time was 6 minutes. Notice that a slower etch rate compared to the IR disperser was achieved primarily because the RF forward power was set to 100 Watts.

The desired etch depth, $t_0$, of 0.159 μm can be calculated from

$$t_0 = \lambda_0/[2(n_0 - 1)] \tag{6}$$

where the design wavelength, $\lambda_0$, was equal to 0.635 μm. The index, $n_0$, for reflection is negative one. Figure 6-3 shows a surface profile of the etched reflective element. Figure 6-4 details the etch depth of the reflective element.

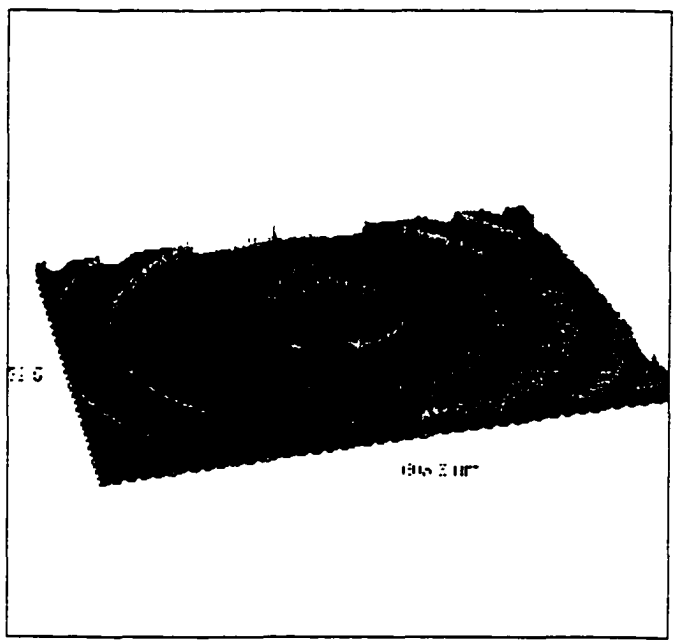


**Figure 6-3.** Center 460 μm × 600 μm section of 160 μm ring diameter, reflective ring toric lenslet.

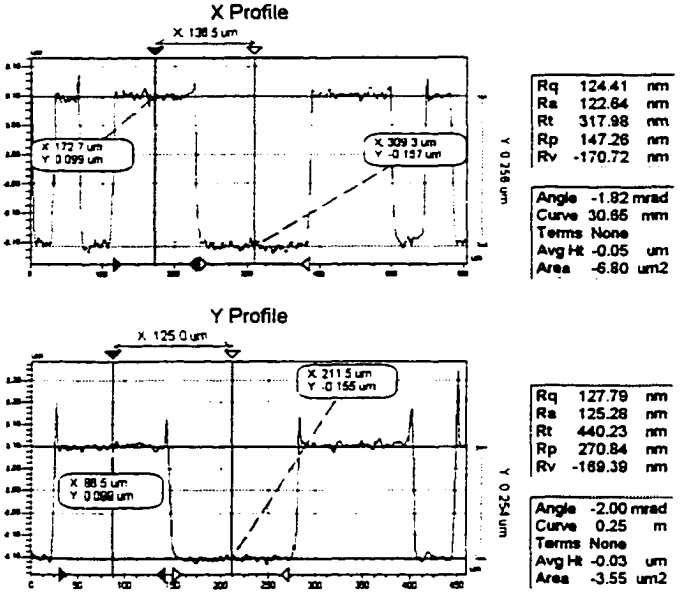



**Figure 6-4.** Depth profile of reflective ring toric lenslet etched in GaAs using RIE, showing an etch depth of 0.256 μm, about 0.1μm depper than desired. The spikes that appear at the 'corners' of the elements are an artifact of the measurement software.

Using the ion mill, we etched the ring-toric lenslet into a glass slide following the same process used for the lenslet arrays. The desired etch depth, $t_0/2$ (because this is a 2 level process), for the glass substrate is 0.635 μm, see Figure 6-5. The actual etch depth shown in Figure 6-6 is 0.8 μm or about 0.16 μm deeper than desired.

**Figure 6-5.** Center 460 μm × 600 μm section of 160 μm ring diameter, transmissive ring toric lenslet. Etch depth of 0.8 μm is about 26% deeper than desired.

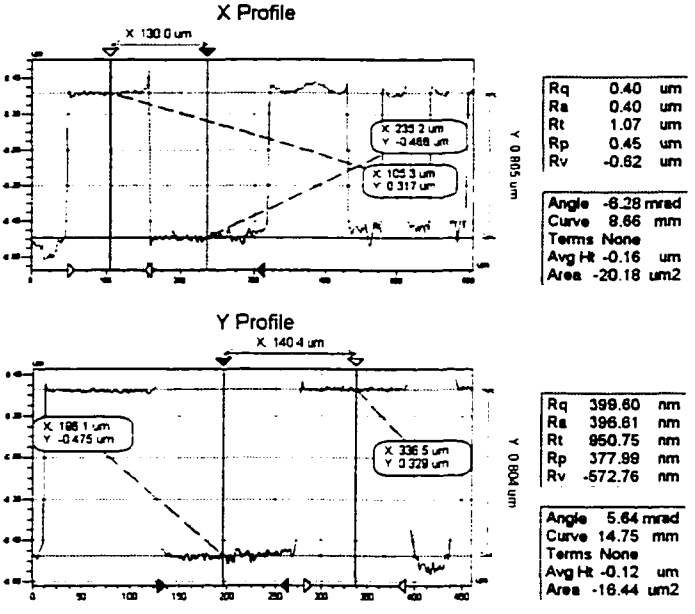
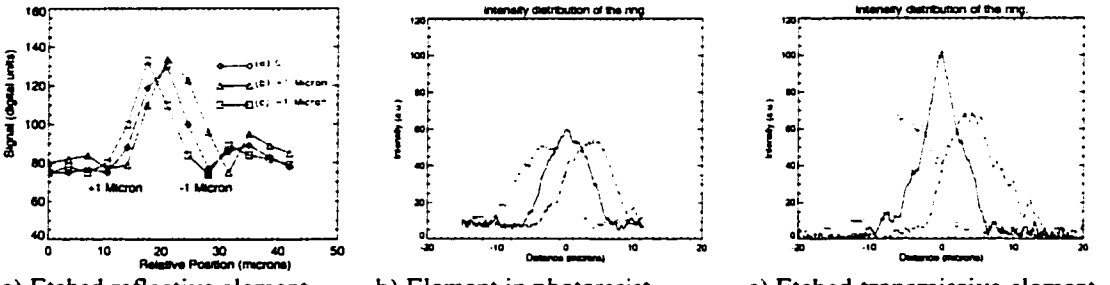



**Figure 6-6.** Depth profile of transmissive ring toric lenslet etched in soda lime glass showing an etch depth of 0.8 μm.

One measure of the performance of the ring toric lenslet is the peak intensity of the focused spot (higher is better), and how much the spot moves (more is better) for a given

amount of defocus. Figure 6-7 contains a series of graphs showing the evolution of the performance of the ring toric lenslet.



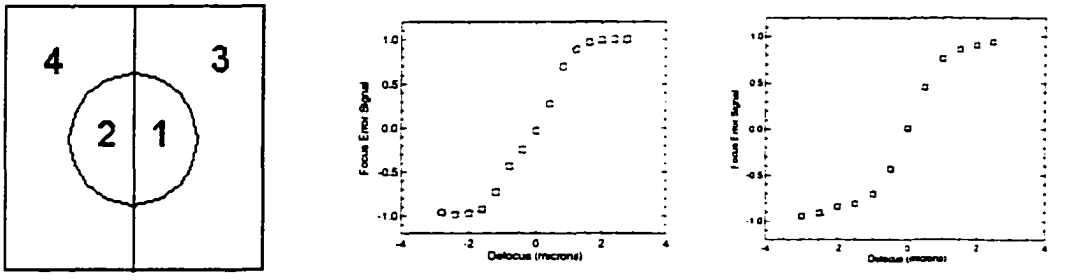

a) Etched reflective element b) Element in photoresist c) Etched transmissive element

**Figure 6-7.** Intensity distribution vs. defocus of the ring for $-1$ μm defocus (dotted line), at focus (solid line), and $+1$ μm defocus (dashed line). A sharper peak at focus, and a displacement of the peak for defocus is desirable.

By placing a phi detector, shown in Figure 6.8 (a), at the focal plane of the ring toric lenslet, the focus-error signal (FES)[30] may be computed as follows:

$$FES = \frac{(S_1 + S_2) - (S_3 + S_4)}{(S_1 + S_2 + S_3 + S_4)} \tag{7}$$

Where the subscript indicates the section of the detector, see Figure 6-8 (a), from which the signal was measured. For both the photoresist, see Figure 6-8 (b), and the etched ring toric lenslets, see Figure 6-8 (c), we calculated the slope of the experimental FES curve to be 0.63 $\mu m^{-1}$, which is about 25% better than the best number Gerber reported.




(a) (b) (c)

**Figure 6-8.** FES detector and curves. Part (a) end view of a phi detector showing the four locations where the focus-error signal is measured. Part (b) FES curve for ring toric in photoresist. Part (c) FES curve for etched transmissive ring toric. For both FES curves, squares indicate experimental results and the dotted line indicates theoretical values.

We measured the surface roughness in the central ring of the ring toric lenslet for both the reflective and transmissive elements after etching. We found the reflective element, had a rms surface roughness of 5.37 nm versus 9.96 nm for the transmissive element. This is consistent with anecdotal evidence that ion milling (used for the transmissive element) leads to a courser surface roughness than reactive ion etching (used for the reflective element).

# CHAPTER 7

# DIFFRACTIVE OPTICS WITH GRAYSCALE PHOTOMASKS

## 7.1 Design and Calibration

One very promising and relatively new technology for fabricating diffractive optics is using a grayscale photomask.[11, 12] A grayscale photomask is created using a special glass that darkens in proportion to the electron beam exposure dose. As a result, a multilevel diffractive optic can be written to a single mask by associating with each level a different exposure dose. Since multiple levels are written into the mask, a high diffraction efficiency diffractive optic can be patterned and etched in a single step.

The grayscale photomask process clearly affects both the design and fabrication of diffractive optics. By eliminating the incremental cost of using more levels, the designer may design elements with theoretical efficiencies approaching 100%. Moreover because multiple alignment and etch steps are collapsed into one, inefficiencies due to fabrication errors (i.e. misalignment of mask, etch depth variations, etc.,) can be virtually eliminated, allowing the real diffractive element efficiency to approach the theoretical limit.

The design of a grayscale photomask requires knowledge of both the substrate etch rate and the photoresist etch rate (sometimes referred to as selectivity), so the appropriate exposure dose can be assigned to the corresponding level. As a result, the grayscale photomask is process and substrate dependent. This is clearly a drawback if one wishes to reproduce an equivalent optic in a number of different materials or using a different

resist, patterning process or etching equipment, since a different grayscale mask would have to be written for each case.

I used Canyon Materials[31] as a vendor for the grayscale mask. They supply masks made from HEBS-glass (High Energy Beam Sensitive), a material that darkens when exposed to an electron beam. A higher dose corresponds to a higher optical density, i.e. darker point, on the mask. We began with a grayscale calibration mask, containing 100 gray levels, to determine what optical density (i.e. gray level) on the mask leads to what final etch depth. We processed several slides (4 second exposure, then developed for 52 seconds) and measured them before and again after etching to determine a photoresist etch rate and a substrate etch rate. See Table 7-1 for the etch rate results. From the measurements, we were also able to determine the dynamic range of gray levels (approximately 32) that we would need to obtain the proper etch depth. Our data indicated that the etch process was fairly linear for gray levels between 10 and 60. Below level 15 the calibration bars were sometimes completely removed during developing. Above level 60 the calibration bars were sometimes still coated with resist after etching for 50 minutes. We decided to use levels 20 through 51 for our design.

| Material Etched (ion mill) | Etch rate (nm/minute) |
|---|---|
| Shipley 1813 Photoresist | 13.5 |
| Glass slide (soda lime) | 35 |
| LAK 9 | 7.5 |
| LAK 8 | 6 |

**Table 7-1.** Material etch rates for resist, soda-lime glass slide, LAK 9 and LAK 8. Samples were etched using the ion mill.

The developing process appears to be non-linear. Small fluctuations in develop time (1-2 seconds) can lead to large changes in the resist height (as much as 0.2μm) for a given gray level. Therefore, we decided that is was better to underdevelop the samples and etch them longer since the etch process appears quite linear (at least over small areas (in the center of the beam)). The pattern was laid out in ten columns each containing ten sets of bars, with each set of bars corresponding to a single gray level. For example, the first column contained graylevels 1 to 10 in that order, and the second column contained graylevels 11 to 20. As a result, gray level 10 was located right next to gray level 20 at one edge of the sample and both were across the sample from gray level 11. The grayscale calibration pattern covered a significant potion of the ion beam area. As noted earlier the ion beam does etch points in the center of the beam faster than points near the edge of the beam. As a result all the points that we measured in the center of the pattern were etched more than those at the edges. Note the sawtooth pattern visible in the etch depth data of Figure 7-1.

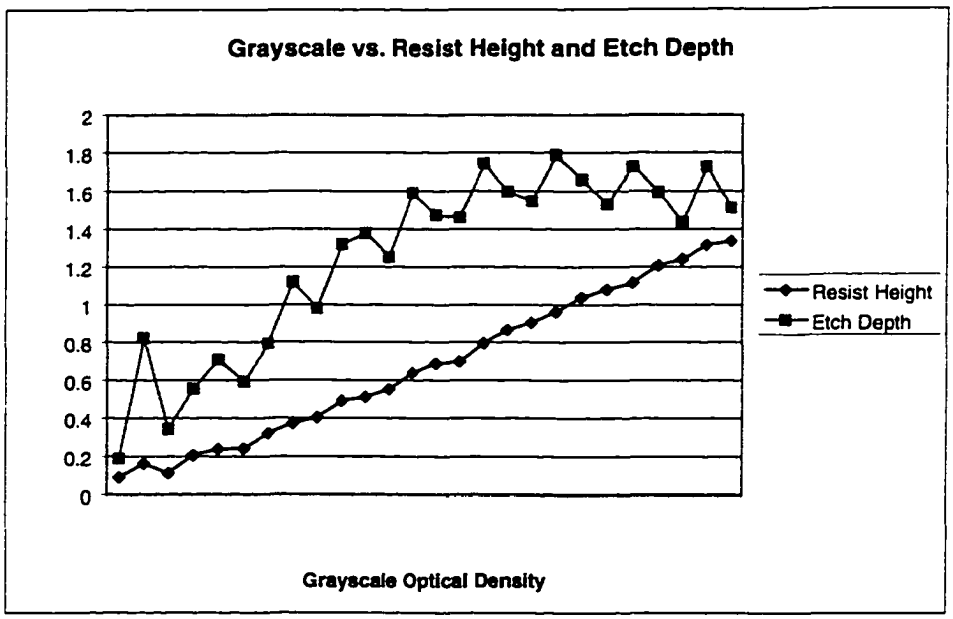



**Figure 7-1.** Grayscale vs. developed photoresist height and final etch depth. The sawtooth pattern is a result of a stronger ion beam at points in the center of the glass slide.

### 7.2 Ring-toric lenslet grayscale photomask

Using dw-2000 we designed a 32 level (i.e. equivalent to a 5 photomask design) ring toric lenslet with a 150 μm diameter ring focus. Figure 7-2 shows a number of these layers. In the 32 level design each zone period is divided into 32 zones. Unfortunately, the technology required to print features this small (i.e. F/#/64 in microns) simply does not exist for any but the slowest possible systems. The design of a reasonably fast system will require some compromise in the number of levels used to make the outer zones (i.e. leads to a reduction in diffraction efficiency over some portion of the lenslet area). We selected a minimum feature size of 0.5 μm as our threshold value.

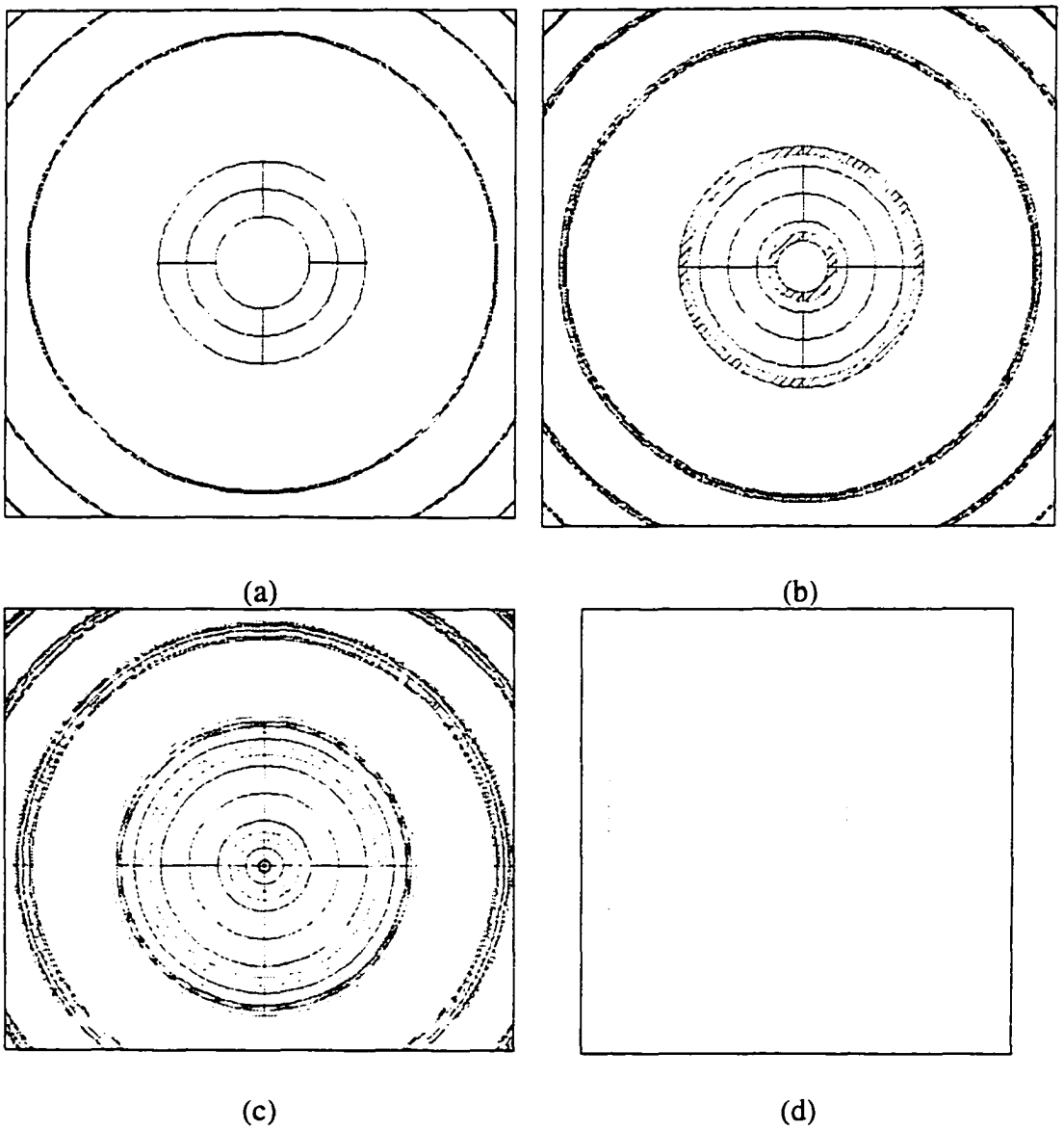



**Figure 7-2.** Several views of the grayscale ring toric lenslet layout. Part (a) shows the first layer. Part (b) shows the first three layers. Part (c) shows the first eight layers. Part (d) shows a transition from 32 levels to 16 levels with the central ring of the ring toric lenslet to the right. The zones become twice as wide after the transition.

Once a zone width became smaller than the threshold value we stopped laying out 32 levels per binary zone period and started laying out 16 levels. Laying out half the levels

leads to zones that are twice as wide (see Figure 7-2 (d)). Laying out 16 levels per binary zone works until the threshold value is again reached at which point we use only 8 levels.

We also included a series of 100 μm square boxes ranging from a gray level of 10 to 80, some are shown in Figure 7-3. The boxes help to determine how long to ion mill the samples. The macro used to lay out the grayscale ring toric lenslet is included in Appendix H. Each of the 32 levels of the ring toric design had to be placed on a separate layer and assigned an optical density. After making a list of which layer corresponds to what optical density, included in Appendix I, we converted the file to GDSII format and sent it along with the list to Canyon Materials for printing.

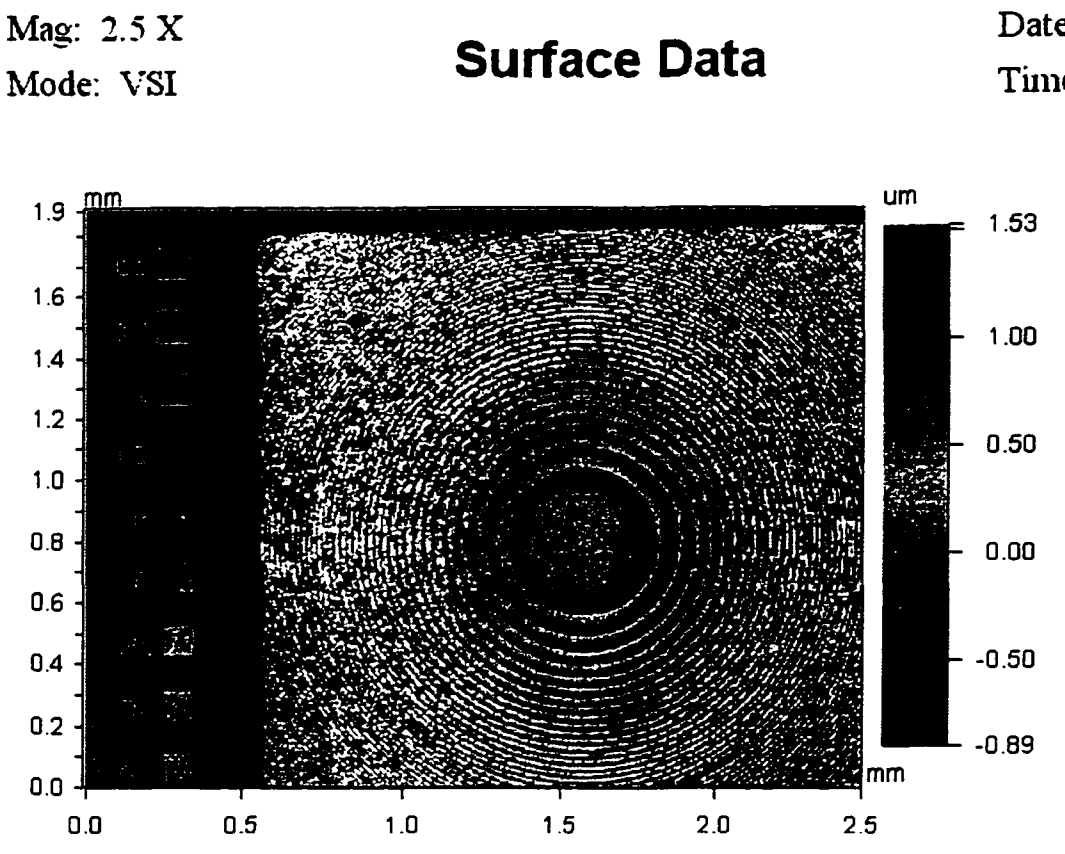



**Figure 7-3.** View of the ring toric lenslet with 'calibration' boxes. Boxes are used to determine etch time

### 7.3 Fabrication and Performance

Except for the development step, fabricating the grayscale ring toric element was rather straightforward. As noted above the developing process is not as linear as we would like it to be. When I used the grayscale calibration mask, I developed each sample for 52 seconds and graylevels in the 15 to 20 optical density range would be visible. When I developed the grayscale ring toric for 52 seconds, levels above 50 were removed. To get graylevels in the range of 10 to 15 (remember we wanted to underdevelop the sample), I

developed the grayscale pattern for 37 seconds. Measurements of the ring toric pattern in photoresist revealed a nicely blazed profile with a couple of unexpected features, see Figure 7-4 and Figure 7-5.

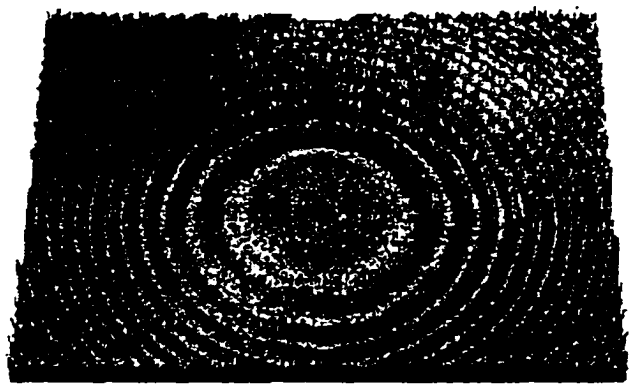


**Figure 7-4.** Center 0.9 mm × 1.2 mm section of the grayscale ring toric with a 150 μm diameter ring focus in photoresist.

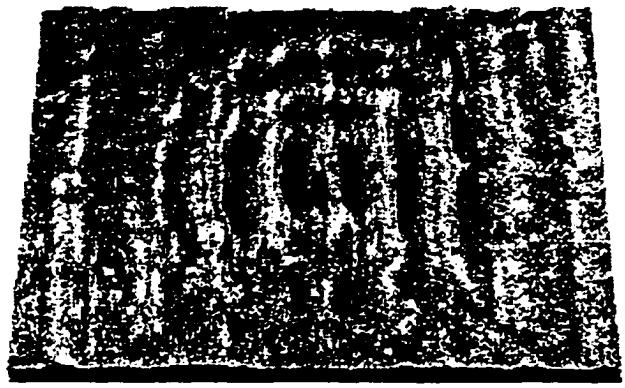


**Figure 7-5.** Close up view, 45 μm × 60 μm of central ring showing some linear artifacts of e-beam writing process.

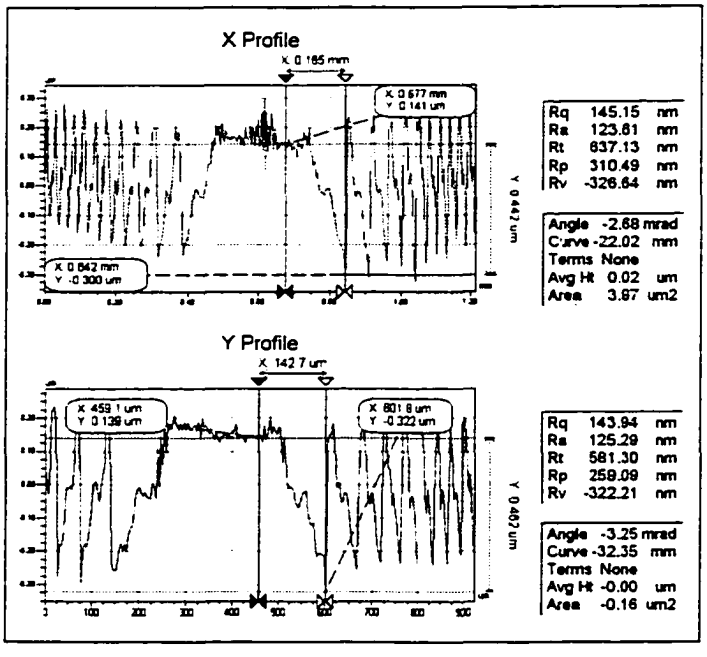



**Figure 7-6.** Profile of grayscale ring toric in photoresist. In the X profile, note the spikes at the very center of the element. Also note the apparent plateau near the middle of each ring.

In the very center zones (within the center 100 μm diameter area) of the element there is a pattern of unwanted spikes ranging up to 0.4 μm high, which we believe is an artifact of the mask writing process. It also appears that there is a plateau in the photoresist about halfway down the profile as shown in Figure 7-6. This apparent plateau puzzles us because it is not visible in the final etched element. We suspect it is an artifact of the measurement process with the optical profilometer, possibly caused by light reflected off the substrate from within the photoresist. To avoid this measurement ambiguity in the future, I suggest measuring the surface with a stylus profilometer before etching.

*Ion Mill Processing*

I etched the sample in the ion mill for 40 minutes. From our calculations this etch time should have led to a 1.2 μm maximum etch depth in the zones of the element. What we measured was a 1 μm maximum etch depth, as shown in Figure 7-7.

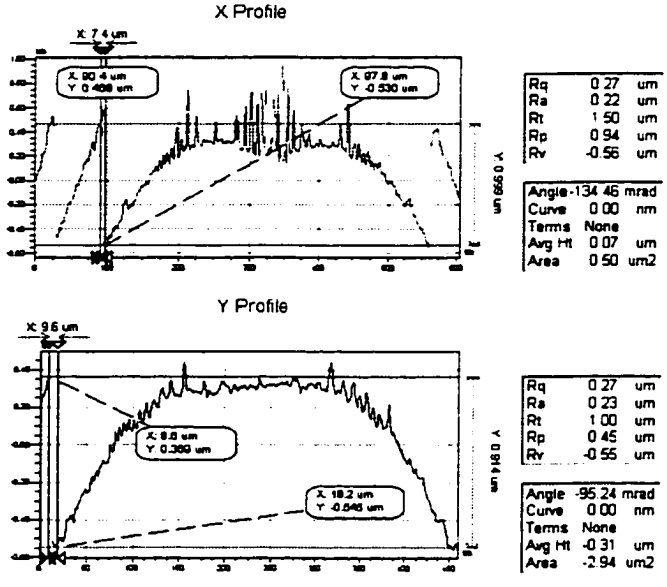



**Figure 7-7.** Profile of grayscale ring toric with 150μm ring focus etched in soda lime glass.

Nevertheless, we are happy with the smooth profile that we achieved in the grayscale ring toric element, shown in Figure 7-8.

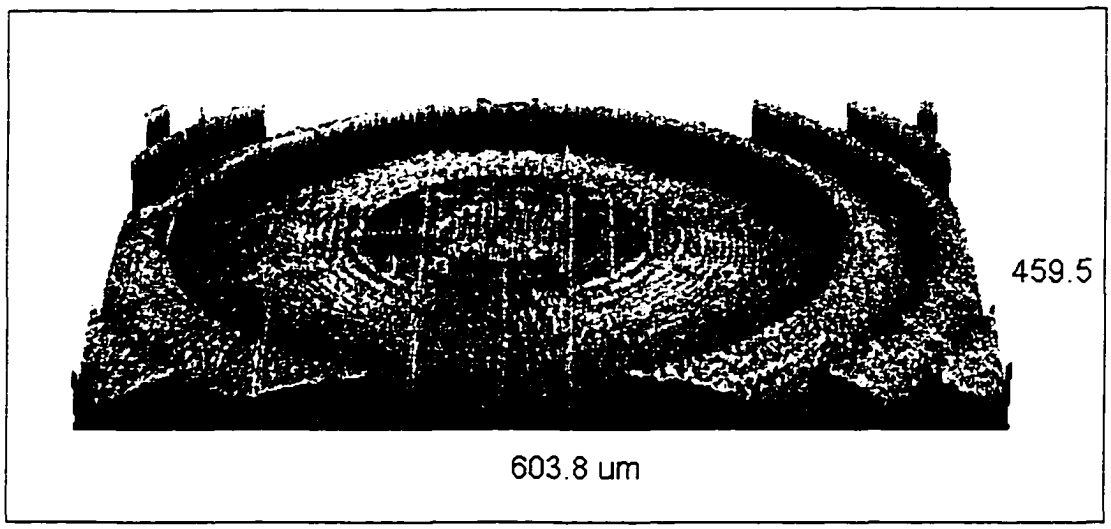



**Figure 7-8.** View of grayscale ring toric lenslet etched into soda lime glass using the OSC ion mill. The e-beam artifacts are present at the center of the element (little red spikes). Except for the e-beam artifact, the profile is smooth.

The plateau we noticed in the photoresist measurement is not apparent, although the center of the element still has the unexpected spikes. Since the rest of the pattern was transferred properly, we asked Canyon Materials to re-write the pattern without the spiky artifacts.

Canyon Materials was able to re-write the mask without the spiky artifacts in the center in time for me to fabricate one last element. I used the same develop and etch time described above and achieved the same etch depth. Since there are no spikes, the 'dip' in the center of the element can be seen in Figure 7-9. There does appear to be rectangular grid visible across the entire element (also present but less noticeable in the previous element). Canyon materials explained that this 'stitching error' is related to the mask writing process and cannot be eliminated.

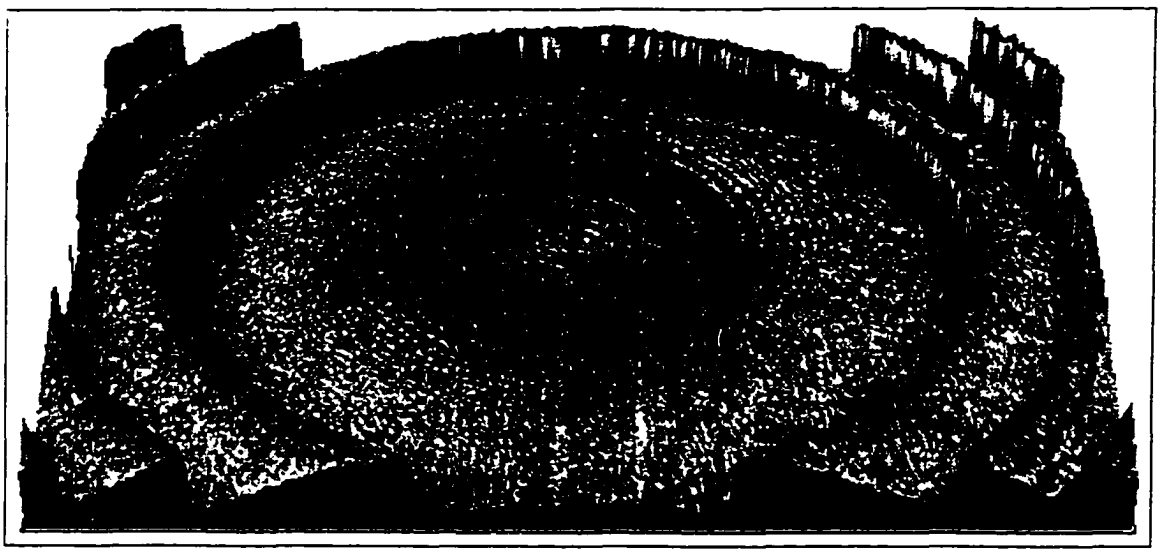


**Figure 7-9.** Center 460 μm × 600 μm section of the second grayscale ring toric lenslet. Lenslet was etched into soda lime glass using the OSC ion mill.

We reproduced the desired ring toric profile demonstrating the validity of the grayscale approach.

# CHAPTER 8

# CONCLUSIONS

Since beginning my studies at the Optical Sciences Center I have had a unique opportunity to design and fabricate a number of diffractive optics. In this thesis I have described the steps involved from the design of a simple lenslet through the fabrication of a relatively advanced grayscale ring toric element. I have included detailed descriptions on how to operate the equipment I have used, and discussed the results that I have achieved using the recipes provided. Hopefully this information will provide the reader with a useful starting point, from which they can quickly achieve meaningful results.

Despite the numerous uses that have been found for diffractive optics including wavefront multiplexing, beam shaping and steering, fiber-to-laser coupling, bifocal intraocular lenses, and microlens arrays for all wavelengths and sizes, the field can still be considered in its infancy. Driving the growth of diffractive optics will be the standard engine of technological advance, the demand for smaller, faster, cheaper optical systems that can be used to make and measure an ever growing array of products. As noted earlier diffractive optics are well suited to applications requiring 'small' optics especially so if only a single wavelength is required. More efficient and cheaper diffractive optics will emerge in parallel with advances in microlithography processes and perhaps more revolutionary advances can be achieved as such processes are modified specifically for optical fabrication (i.e. gray level photomasks). As designers strive to fit more functionality into a smaller space, the ability of diffractive optics to integrate the function

of multiple optical elements into a single element will lead to highly sophisticated systems on a chip.

## Appendix A: Lenslet layout macros

This macro and the following annrect1 procedure are used courtesy of Mial Warren.

```
\       RectFZlens2
\       macro provided by Mial Warren, Sandia National Labs.
\
\       Modifications:   Nov. 23, 1996   Incept date...
\       Daniel Simon     Feb 28, 1997    Replaced rmax and zmax calculations with minperiod
\
\
MENU
        "RectFZlens2"
ENDMENU

niladic procedure RectFZlens2

        external monadic function annrect1

        local focal; focalm; dia    \focal length of lens, diameter of lens
        local masks1; phasnum               \number of mask layers, number of phase
                                            \levels = 2 power (masks1)
        local lrad; fnum            \radius of lens, fnumber of lens
        local index; phasein                \loop index and loop number of phase

        local mradical; minperiod                   \ used for calculation
                                                    \ of smallest linewidth

        local layers                                \vector of layer#
        local layer1; layer2; layer3; layer4
        local zone; oddzone                         \zone number index

        local radius1; radius2; ring; flip      \these variables are used to write
                                                    \the zones into the data base...

        local radius1a; radius1b; radius2a; radius2b   \intermediate variables for above

        local minwidth                              \minimum width of a zone allowed
        local rectangle                             \matrix of corner coordinates of rectangle
        local rp1; rp2; rp3; rp4                \to make polygon of rectangle input
        local rectpoly                              \resulting polygon from rectangle
        local rectpolar                             \polar coord version of rectpoly
        local rectrad; minrectrad; maxrectrad       \min and max raddi for rectpoly
        local testring; testflip; testr1; testf1  \checking if inside rectangle

        private static lambda                       \design wavelength of lens in microns

\This part checks if program is currently busy or if structure is not open
```

```
        if ostruct = "" then
                error "A structure must be open."    \never returns
        endif
        if coords <> "" then
                error "Already digitizing."          \never returns
        endif

\Getting input values for lens parameters.

        while focal = "" do
                focal := EXPINPUT"Lens focal length in mm:"
                if focal leq 0 or focal gt 1000 then
                        focal := EXPINPUT "Focal length must be >0 & <1000mm. Try again:"
                endif
        enddo

        while lambda = "" do
                lambda := EXPINPUT "Design wavelength in microns:"
                if lambda leq 0 then
                        lambda := EXPINPUT "Wavelength must be >0. Try again:"
                endif
        enddo

\Getting corner coordinates of boundry rectangle

        while rectangle = "" do
                rectangle := WINDOWINPUT"Enter window coords in first quadrant only:"
        enddo
        rp1 := rectangle[1]
        rp2 := rectangle[1;1] ,[2] rectangle[2;2]
        rp3 := rectangle[2]
        rp4 := rectangle[2;1] ,[2] rectangle[1;2]
        rectpoly := rp1 ,[1] rp2 ,[1] rp3 ,[1] rp4
        rectpoly := polyclose rectpoly
        rectpoly
        rectpolar := polar rectpoly
        rectrad := MINMAX rectpolar[;1]
        minrectrad := rectrad[1]
        maxrectrad := rectrad[2]
        minrectrad
        maxrectrad

\ following to set minimum zone width allowed to control lithography requirements.
\ Minwidth is set by user before compilation in microns...

        minwidth := 1.0

\ following code to get number of mask levels and give user chance to
\ change if smallest feature is less than one micron...

        while masks1 = "" do
```

```
masks1 := EXPINPUT "Number of mask layers:"
if masks1 lt 1 or masks1 gt 4 then
        masks1 := EXPINPUT "Number of mask layers is 1 to 4.  Try again: "
endif

\ Calculate the smallest zone width of current design and prompt if zones
\ less than minwidth are going to be needed.  Formula for minperiod
\ of zones is from Nishihara "Progress in optics vol 24".

phasnum := 2 power masks1

focalm := focal * 1000
lrad := maxrectrad                          \largest extent of lens...
dia := 2.0 * lrad                           \diameter of equiv full lens...
fnum := focalm / dia
mradical := sqrt(1 + 4 * fnum * fnum)       \is 1/NA also from Nishihara
minperiod := 2*mradical*lambda/phasnum      \2/phasnum in a multiple layer factor

if (minperiod/2) lt minwidth then
        ALERT "warning"; "Zones are less than minwidth. Pattern will be truncated."
endif

enddo

\Get layers corresponding to the number of masks to be used. Routine does
\allow to use layers other than 1-20  if message is ignored.

if masks1 geq 1 then
        layer1 := ravel EXPINPUT "Layer from 1-20 for first (n =1) mask:"
        if layer1 lt 1 or layer1 gt 20 then
                layer1 := ravel EXPINPUT "Layer should be 1-20. Try again:"
        endif
else layer1 := ""
endif

if masks1 geq 2 then
        layer2 := ravel EXPINPUT "Layer from 1-20 for second (n =2) mask:"
        if layer2 lt 1 or layer2 gt 20 then
                layer2 := ravel EXPINPUT "Layer should be 1-20. Try again:"
        endif
else layer2 := ""
endif

if masks1 geq 3 then
        layer3 := ravel EXPINPUT "Layer from 1-20 for third (n =3) mask:"
        if layer3 lt 1 or layer3 gt 20 then
                layer3 := ravel EXPINPUT "Layer should be 1-20. Try again:"
        endif
else layer3 := ""
endif

if masks1 geq 4 then
```

```
            layer4 := ravel EXPINPUT "Layer from 1-20 for fourth (n =4) mask:"
            if layer4 lt 1 or layer4 gt 20 then
                  layer4 := ravel EXPINPUT "Layer should be 1-20. Try again:"
            endif
      else layer4 := ""
      endif

\Make vector "layers"

      layers := layer1 , layer2 , layer3 , layer4

\ Now start calculating the zone radii for each layer...

      index := 1

      WHILE index leq masks1 DO
            layer layers[index]
            phasein := 2 power index
            radius1 := 0
            radius2 := 0
            zone := 0
            oddzone := 1

            WHILE radius2 lt lrad DO

                  radius1a := ( 2 * zone * lambda * focalm / phasein )
                  radius1b := sqr ( zone * lambda / phasein )
                  radius1 := sqrt ( radius1a + radius1b )
```

The radius of the $m^{th}$ zone is determined as follows:

$r_m = \sqrt{2mf\lambda + (m\lambda)^2}$

where m is the zone #, f is the focal length, and $\lambda$ is the design wavelength.

As indicated earlier this equation is right out of the article "Micro fresnel lenses" by H. Nishihara and T. Suhara, which can be found in volume 24 of Progress in Optics edited by E. Wolf.

```
                  radius2a := ( 2 * oddzone * lambda * focalm / phasein )
                  radius2b := sqr ( oddzone * lambda / phasein )
                  radius2 := sqrt ( radius2a + radius2b )

                  if (radius2 - radius1) lt minwidth then
                        radius2 := lrad
                  endif

                  radius1
                  radius2

                  if radius1 lt maxrectrad and radius2 gt minrectrad then
```

```
                        if radius1 lt minrectrad then
                                radius1 := minrectrad
                        endif

                        if radius2 gt maxrectrad then
                                radius2 := maxrectrad
                        endif

                        radius1
                        radius2

                        ring := annrect1 radius1; radius2; rectpolar; rectpoly

                        if ring = "" then
                                ALERT "warning"; "annrect1 failed"
                        else

                                boundary
                                straight
                                ce ring
                                put

                        endif

                endif

                zone
                oddzone
                zone := zone + 2
                oddzone := oddzone + 2
        ENDDO
        index
        index := index + 1
ENDDO

endsub
```

The following procedure, Annrect1, breaks up the two quarter radii that make up the zone, into a bunch of small arc segments and calculates the Cartesian coordinates of each segment from polar coordinates.

```
\ a function to draw a quarter annulus given two radii
\ will draw inside rectpolar
\ the size of the segment can be altered

monadic function annrect := annrect1 arg
        local inrad; outrad; thetas; steps
        local thetastart; segs; inseg; outseg
        local thetaend; thetadif
```

```
        local rectpolar; rectpoly; r
        local r1; r2; r3; r4
        local xone; xtwo; yone; ytwo

        inrad := arg[1]
        outrad := arg[2]
        rectpolar := arg[3]
        rectpoly := arg[4]

        r := rectpolar[;1]
        r1 := r[1]
        r2 := r[2]
        r3 := r[3]
        r4 := r[4]

        xone := rectpoly[1;1]
        yone := rectpoly[1;2]
        xtwo := rectpoly[3;1]
        ytwo := rectpoly[3;2]

\doing inseg first
\check for closest corner

        if r2 leq r4 then

        \for inseg if r2 <= r4

                if inrad geq r1 and inrad lt r2 then
                        thetastart := arcsin (yone / inrad)
                        thetaend := arccos (xone / inrad)
                endif

                if inrad geq r2 and inrad lt r4 then
                        thetastart := arcsin (yone / inrad)
                        thetaend := arcsin (ytwo / inrad)
                endif

                if inrad geq r4 and inrad lt r3 then
                        thetastart := arccos (xtwo / inrad)
                        thetaend := arcsin (ytwo / inrad)
                endif

        else

                if inrad geq r1 and inrad lt r4 then
                        thetastart := arcsin (yone / inrad)
                        thetaend := arccos (xone / inrad)
                endif

                if inrad geq r4 and inrad lt r2 then
                        thetastart := arccos (xtwo / inrad)
                        thetaend := arccos (xone / inrad)
```

```
        endif

        if inrad geq r2 and inrad lt r3 then
                thetastart := arccos (xtwo / inrad)
                thetaend := arcsin (ytwo / inrad)
        endif

endif

thetadif := thetaend - thetastart
\ approx. 2 degree segments...

segs := ceiling ( thetadif / 2.0 )
thetastart
thetaend
thetadif
segs
if segs lt 1 then
        segs := 1
endif

thetas := thetadif / segs
inseg := thetas * iota (0, segs)
inseg := inseg + thetastart
inseg := transpose (inrad ,[1] inseg)

\ to fill corners...

if inrad lt r2 and outrad gt r2 then
        inseg := inseg ,[1] rectpolar[2]
endif

\ doing outseg next
\ check for closest corner...

if r2 leq r4 then
        \ for outseg if r2 <= r4

        if outrad gt r1 and outrad leq r2 then
                thetastart := arcsin (yone / outrad)
                thetaend := arccos (xone / outrad)
        endif

        if outrad gt r2 and outrad leq r4 then
                thetastart := arcsin (yone / outrad)
                thetaend := arcsin (ytwo / outrad)
        endif

        if outrad gt r4 and outrad leq r3 then
                thetastart := arccos (xtwo / outrad)
                thetaend := arcsin (ytwo / outrad)
        endif
```

```
        else

                if outrad gt r1 and outrad leq r4 then
                        thetastart := arcsin (yone / outrad)
                        thetaend := arccos (xone / outrad)
                endif

                if outrad gt r4 and outrad leq r2 then
                        thetastart := arccos (xtwo / outrad)
                        thetaend := arccos (xone / outrad)
                endif

                if outrad gt r2 and outrad leq r3 then
                        thetastart := arccos (xtwo / outrad)
                        thetaend := arcsin (ytwo / outrad)
                endif

        endif

        thetadif := thetaend - thetastart
        \ for now doing approx 2 degree segments
        segs := ceiling (thetadif / 2.0)
        thetastart
        thetaend
        thetadif
        segs
        if segs lt 1 then
                segs := 1
        endif

        thetas := thetadif / segs
        outseg := thetas * iota (segs, -1, 0)
        outseg := outseg + thetastart
        outseg := transpose (outrad ,[1] outseg)

        \ to fill corners
        if inrad lt r4 and outrad gt r4 then
                outseg := outseg ,[1] rectpolar[4]
        endif
        annrect := inseg ,[1] outseg
        annrect := cartesian annrect
        annrect := polyclose annrect
endsub
```

## Appendix B: Ordering a photomask

Listed below are some basic parameters that a commercial photomask shop will want to know in order to write a quote. From the designers point of view, perhaps the most important is the smallest e-beam spot size the shop can write because this sets the limit on the resolution of the diffractive optic design. Also important is how the smallest spot size selected translates into the cost of the mask.

Here are some of the parameters specified to order a photomask from Photronics Inc.

E-beam spot size: 0.5 micron (0.25 micron also available)
Final plate size: 4"x4" (depends on mask aligner used)
Glass type: White Crown (Quartz is also common)
Coating: Chrome coated
Field: Dark (vs Clear) (depends on the photoresist used, for positive resist use dark)
Parity: Pattern 'right sided' when viewed through glass
Defect tolerances: largest available (to keep cost down) depends on application
Delivery: 2 weeks (able to turn around an order in 24 hours for extra $$)

Our mask aligner has a 3" diameter printable area for a 4"x4" plate. Keep this in mind when designing the photomask.

A standard file format to send the design to the mask vendor is GDSII. Be aware that they will need to convert, or fracture (i.e. break up into tiny polygons), this to MEBES file format which is what the electron beam writer reads.

In some cases we were able to save extensive CAD charges from the mask vendor by converting the file to MEBES ourselves (since our software can do this) before sending it to them. Realize that MEBES files can get very large very quickly. For our largest design (with 5 10mm × 10mm arrays of lenslets) the vendor could not handle the 70+ MB file that resulted when we fractured the entire pattern. In the end we fractured one of the 10mm × 10mm patterns and the base lenslets for the other 4 arrays and provided them with instructions on how many to write and where to place them on the mask. This resulted in a more manageable 18 MB file (about 9 MB when zipped) which still took 2+ hours to ftp to the vendor.

## Appendix C: Spinning resist

This document, except for minor modifications, was provided by Scott Penner.

### Preparation of Shipley 1813 for Optical Lithography

### Spinning of Shipley 1813

- Turn off the non-filtered lights in the class 1000 area of the clean room.
- Place wafer on the chuck. The 2 inch diameter chuck actually works better than the O-ring chuck for small samples.
- Open green vacuum valve once sample is in position, verify that sample is vacuumed to the chuck.
- Use the dual speed function on the Headway Spinner when depositing the primer. Set the first speed to 300 RPM for 10 seconds and the main unit to 4000 RPM for 30 seconds. Load Shipley MicroPosit Primer into a syringe. Attach a 0.2 μm *Acrodisc* filter to the syringe. Start the spinner by depressing the foot pedal. Flood the sample while it is spinning at 300 RPM. After 10 seconds the spinner will automatically accelerate to 4000 RPM for 30 seconds.
  Note: I flooded the sample with resist before engaging the spinner, but only spun the sample for 5 seconds at 300 RPM.
- Close green vacuum valve and remove sample.
- Use MicroPosit EBR-10 or acetone to remove the edge bead and any resist on the back surface of the wafer. Use a Mini Alpha Swab to remove the edge bead. To clean the back surface, place a small amount of acetone on a Technicloth towel and drag the wafer across the wetted area.
- Soft bake on the hotplate for 1 minute at 100°C.

### Exposing the pattern

- Turn on Nitrogen and air flows to Mask Aligner. Turn on lamp controller and start the light source. Allow lamp to stabilize for 15 minutes before exposing.
- Select mask. Clean with soap and rinse in deionized water. Spray with acetone, rinse in deionized water and blow dry with nitrogen.
- Insert mask and sample.
- Align
- Expose. (Typical exposure around 4 seconds.)

### Developing

- Pour some Shipley MicroPosit 352 Developer into the designated beaker. The 352 Developer is used undiluted. If no 352 is available, 351 Developer can be used in 1:5 dilution with deionized water.
- Place the sample into the developer solution and gently move it around for 60 seconds.
- Submerge the sample into a beaker of deionized water for 60 seconds.
- Blow the sample with $N_2$.
- Bake on the hotplate for 1 minute at 100°C.
- Place in the Plasma Preen II-862 Asher for 1 minute. This will clean up the pattern and will remove about 0.1 μm of the resist.

### Cleaning (optional for 'clean' substrates i.e. new glass slides & new GaAs wafers.)

- Rinse sample with solvents: Acetone, Methanol, Isopropanol. The isopropanol is used to wash away the acetone residue.

- Use a Mini Alpha Swab (Qtip) moistened with acetone to remove larger particles. Gently rub the surface and push particles to one side. Repeat step 1.
- Rinse with de-ionized water to remove all of the solvents
- Blow off residual water with Nitrogen
- Bake on hotplate for 1 minutes at 100 °C
- Place sample in the Plasma Preen II-862 Asher for 1 minute

## Appendix D: Operating the Mask Aligner

This document, except for minor modifications, was provided by Scott Penner.

### Karl-Suss Mask Aligner

### Initial Setup

- Turn on the nitrogen supply: open valve on the tubing located to the left of the aligner behind the yellow chemical storage cabinet. Check the flow rate on the meter located on the right of the main unit. If there is no nitrogen flow, the lamp will not light. See if main nitrogen supply is on.
- Turn on the flow to the air table by opening the lever on the air line located on the wall directly behind the mask aligner.

### Starting Mercury Lamp

- Turn on the power switch on the lamp controller (black box located to the right of the mask aligner). The controller will perform a self diagnostic check. Press "start" to fire the lamp.
- The Mercury lamp should be on approximately 15 minutes before exposure in order for it to stabilize.
- Turn on electronics console by pressing the "power" button.
- Positioning of Mask
- Select the desired mask. This mask aligner is designed to accept 4 inch by 4 inch masks. A smaller plate with a 1 inch diameter exposable area can be used to accommodate smaller masks.
- Clean the mask with soap and/or solvents. Rinse with de-ionized water and blow dry with nitrogen.
- Remove the maskholder plate from the mask aligner by loosening the two clamping knobs located on the front of the unit and sliding the plate to the left. Be careful since the maskholder plate is surprisingly heavy. Place the maskholder on the bench with the O-ring surface facing upwards.
- Place the mask, with the chromed sided up, on the maskholder. Look at the edge of the mask in order to determine which side is coated with chromium. The chromed side is placed in contact with the sample in order to expose the pattern. This minimizes diffraction effects.
- Press the "Vacuum Mask" button to secure the mask to the maskholder. Try to move the mask to ensure that it is properly seated.
- Return the maskholder to the mask aligner and tighten the clamping knobs.

### Positioning the Sample

- Remove the transport slide from the mask aligner.
- Blow the sample with nitrogen to remove any particles that could scratch the mask.
- Place the sample on the chuck. One small and one large chuck are available. It may be necessary to cover the vacuum holes on the chuck. Insert the transport slide into the alignment stage.
- Bring the sample in contact with the mask by turning the contact lever counterclockwise. The maximum rotation is half a turn. The "contact" indicator on the front panel will light up when contact is achieved. Do not force the contact lever. Contact force (variable thickness adjustment) is controlled by using the dial on the front of front of the aligner (bottom most control). To increase the force turn the dial counterclockwise. Once the sample is in contact, adjust the contact force dial until snug.
- Caution: DO NOT FORCE THE DIAL. Too much force will break the mask or sample.
- Pull the separation lever towards the front of the machine in order to provide sufficient space to enable alignment of the sample without damaging the mask. The normal position of this lever is all the back (away from operator). The only time the lever should be in the forward position is to align the sample

after contact. With the lever in the forward position, the mask and sample are slightly separated. (Blue CONTACT light goes out and green SEPARATION is illuminated). After sample is properly aligned, place sliding lever in the back (contact) position.

- Use the X,Y, and ( alignment micrometers to position the sample. It may be necessary to remove and reposition the sample if the micrometers reach the limit of their travel. Use the microscope to view the alignment. The two buttons on microscope control arm are used to unlock the X and Y motions. The switch for the light is located on top of the mask aligner.
- Upon completion of the alignment procedure, return the separation lever to the contact position.

## Exposure

- Press the "Vacuum Chamber" button. The pressure gauge should read 0.5 to 0.6 ideally; however , 0.2 will suffice.
- Set the exposure time.
- Far right dial allows for seconds, minutes or hours (s,m,h)
- Black dials give the ones and tens digit while the 2 red dials are for decimal values.
- A typical exposure time is 4 seconds for Shipley 1813 resist.
- Press the "exposure" button to expose the sample. Do not look at the UV light.
- Removing the Sample after Exposure
- Rotate the contact lever to the forward position (you will hear the vacuum being broken).
- Remove the transport slide. Be careful when sliding out the sample as some pieces may still be stuck to the mask.

## Shutdown

- Remove the mask, clean it and place it back in its holder.
- Turn off the console power.
- Let the nitrogen flow for another 10 minutes so to cool the Mercury lamp.
- After 10 minutes, turn of the lamp, and close both the nitrogen and air lines. Look at the flow meter to ensure that the nitrogen is off.

RESISTS

Positive Resist: the exposed area is removed during development. The majority of resists that we use are positive resists.

Negative Resist: the unexposed area is removed.

LIGHT FIELD/DARK FIELD

Light (clear) Field Mask: the majority of the mask is not covered with chrome.

Dark Field Mask: the majority of the mask is chromed.

## Appendix E: Operating the ion mill

### How to etch a slide using the Ion Mill...

If the system is under pressure see instructions for venting chamber at the end of this section.

### Prepare vacuum chamber

- Glue sample(s) to translation stage using silver paste. Make sure all samples can 'see' the ion beam and translations stage does not run into bell jar.
- Arrange shutter so it covers the beam area.
- Lower bell jar and center—should be able to see about an eighth inch between bell jar skirt (black) and the edge of the vacuum chamber (metal) all the way around on the inside.
- Close air admittance vent.
- Turn off backing valve (middle indicator light off) and switch roughing valve open (rocker switch)
- When gauge A--on the left of the ion mill—gets to 100 millitorr, close roughing valve, open backing valve and open the high vacuum valve (butterfly valve at the base of the vacuum chamber). If the diffusion pump has been on for a while the pressure should drop quickly, otherwise give the pump some time to warm up.
- Let the chamber stabilize for about a half hour with diffusion pump on.

Do not leave the diffusion pump on for more than a couple hours with the backing valve off. If you do the diffusion pump oil can 'burn' and will need to be replaced (the oil is expensive and replacing it is involved).

One of the most time consuming elements of the etch process is getting the vacuum chamber to pump down to 100mTorr. Sometimes the rocker switch on the roughing pump gets 'stuck' due to a bad solenoid valve and needs to be turned off and then back on. So if the pressure indicator does not go below 1 Torr within 2 minutes try playing with the rocker switch.
Sometimes the pressure gets down to 500mTorr and then stalls. If this happens, close the roughing valve, vent the chamber and inspect the grease around the rim of the vacuum chamber. If the grease appears dry or the system has not been used for some time, apply a very thin coat of vacuum grease around where the skirt contacts the vacuum chamber.
Sometimes the pressure gets down to 200mTorr and then stalls. Flick the roughing pump switch off and on a few times to make sure the value is not stuck again. Let it pump for a while (at least 20-30 minutes) because often times the silver paste or the vacuum grease needs to outgas. If the pressure gauge has still not moved after 30 minutes vent the chamber and re-evacuate. Also check the vacuum grease, if you have not already done so. The roughing pump is capable of pulling the vacuum below 1 mTorr given enough time (say overnight) and down to 10mTorr in a few hours. I have seen it pull down to 100mTorr in about five minutes (that was a good day!).

We have had some success milling if we turn on the beam after the following steps. Pour two tanks of liquid nitrogen into the diffusion pump dewar. Pump down the chamber with the roughing pump only. When the pressure falls below 100 millitorr turn off the roughing valve. Next turn on the diffusion pump (but don't hit the reset switch yet) and the backing valve. Open the high vacuum valve and pressure should drop rather slowly. When the pressure drops down to 15-20 millitorr hit the reset switch and the diffusion pump will begin to heat up. While the pump is heating up experiment with the needle valve to find a setting for which the pressure gage on the ion mill reads about zero. After about 20 minutes you should have the range of setttings for the needle valve. Try igniting the beam at low current (i.e. < 100 mA) and play with

the pressure via the needle valve to achieve a steady beam. In ten or fifteen minutes you should be ready to etch.

## Turning on the Ion beam

- Open valves to let Argon or Freon into the line (needle valve should be closed)
- Bleed in gas with needle valve target $6 \times 10^{-4}$ Torr for Freon, $1\text{-}2 \times 10^{-3}$ Torr for Argon
- Make sure the shutter over sample is closed; hit green MAIN button on the ion power supply
- It may be helpful to start with a current between 100 and 120 mA and a voltage around 1.2 kV when first igniting the plasma and slowly increase the current to 160 mA as the beam stabalizes.
- Turn Hi Voltage button on (also green); it may be necessary to adjust the gas pressure (w/ the needle valve) to ignite the plasma. 270 +/- 5 reading on the needle valve is a good starting point.
- For a good etch the voltage indicator should read 1.9 kV and the current at 160 mA; let the source warm up for about 15 min before milling sample. As the source warms up it should flicker less often (and spark less). Adjusting the gas pressure up tends to bring the voltage down and vice versa.
- Move shutter to the side once a good beam is stable (i.e. there should be no arcing/sparking and the beam may still flicker but it should be infrequent) for a few minutes and begin etch.

Do not increase current above the 160 mA set point (there is a tick mark on the power supply-do not go above this) it is possible to 'blow' a cable at higher currents (cables are expensive and the source could be damaged as well).

## Turning off the Ion beam

- Turn Hi Voltage off using the red button
- Turn Main power off using red button on right
- Close needle valve and valve to gas tank.
- Let source cool for about 15 min

## Venting Chamber

- Close Hi Vacuum valve (between diffusion pump and chamber)
- Make sure roughing valve is closed and turn of ionization gauge (filament then power)
- Vent chamber using air admittance valve
- After a couple minutes the bell jar can be lifted

## Appendix F: Operating the Reactive Ion Etcher (RIE)

This document, except for minor modifications, was provided by Scott Penner.

### Start up

- Turn on the monitor. Note that the CPU should never be turned off. From the load screen, check that the Penning pressure is below the base pressure. Look at the Nitrogen Flow Meter (located above the roughing vacuum line) to make sure the nitrogen is flowing. If the nitrogen is not flowing DO NOT USE THE EQUIPMENT. Contact the lab personnel.

- Turn on the ECR (electron cyclotron resonance) power supply. Wait about 10 seconds and then turn on the microwave source, located below the power supply. Check to see that the Reflected Watts reading is not significantly above zero. If it does read above zero, the reading is erroneous and the microwave source should be turned off for a few seconds and then on again.

### Conditioning the Chamber

Prior to running your process, the chamber must first be conditioned and cleaned with Oxygen. A trial run with the gasses that you will be using is also recommended.

- Open the oxygen bottle all the way.
- Select *Return to Process Control* followed by *Display: Status.*
- Click on the **Select** button and open the **startup.rec** file located in the public directory. This will start a 5 minute cleaning.
- Once the pressure is below $10^{-5}$ mbar press **Start** to begin the process.
  Note: 1 bar of pressure is equal to 750 Torr, approximately 1 atmosphere.
- The software will ask if you want to perform a second process on the wafer, say **Yes**. (Chamber is empty)
- When the oxygen flow has stabilized to 50 sccm (standard cubic centimeters), the RF and microwave source will start. For this cleaning process, a reflected power of less than 50W is fine. If it is greater then 50W then tune the microwave source (see below for tuning specifics).
- When the process is done, prepare a test run with the gasses that you will be using. Either select the appropriate file or enter the parameters from the *Manual: Status* screen.
- Open the gas bottles that you will use.
- Start the process.
- Ensure that the gas flow thermometer (on the computer screen) ramps up to green—this should take about 12-15 seconds.
- Once the microwave source has started, check to see that the Reflected power indicator is less than 5% of the forward power. If the microwave source does not start within 10-15 seconds after the RF power starts (also the start of the process time clock) then press the **Stop** button to cancel the process. Check variables and restart once the system has reached base pressure.

## Tuning the microwave source

There are three black dials on the microwave source. Left: fine Center: coarse Right: medium
In most cases the source is close to optimum and small adjustments of the left knob (i.e. a few notches—a $1/8^{th}$ turn would be considered a large adjustment) or slight adjustment of the right knob will bring the Reflected Watts reading back into process parameters. For long etches (i.e. 10 minutes) there is a good chance the source will need to be tuned at least once.

## Loading the Sample

- Click on the **Load** button to enter the load screen.
- Select **Unload**, and follow the loading instructions on the screen. Make sure that the status of the Slit Valve is OPEN, before moving the transfer arm. Be careful when removing the susceptor plate from the chamber. Move the transfer arm in a slow, smooth manner to prevent the plate from falling off the arm.
- When the loadlock has vented, the loadlock door may be opened.
- Wear gloves when loading the sample and make sure the sample is clean. Do not place samples containing sodium (i.e. glass slides) in the chamber. Loadlock door should be open for the shortest possible time to prevent moisture and dust from entering the loadlock.
- Select the *wafer in loadlock*, radio button on the screen and the computer will ask you to **confirm** that the wafer is in the loadlock.
- Press **Evacuate** to evacuate the loadlock.
- Once the *'Ready to Load'* message appears, click **Load** to load your sample into the chamber. Follow the instructions given by the system.
- Select **Return to Process Control**
- Select the desired recipe either from a file or enter it from the *Manual: Display* screen.
- When the pressure is below $10^{-5}$ mbar, start the process by clicking on the **start** arrow.
  Note: Although the process will start timing before the base pressure ($10^{-5}$ mbar) is reached, it is advantageous to wait until the chamber is below base pressure for several reasons. If you are creating a datalog file, it will prevent logging the pump down parameters which otherwise increase the file size. Second if you wait there is a direct correspondence between the *Total elapsed time* and the *Remaining step time*. (This is good if the process shuts down prematurely which it sometimes does for long etches.) It normally takes 20 to 25 seconds for the gasses to stabilize and the RF power to turn on, which starts the process timer. There is a 5 to 10 second delay before the microwave power begins.
- Once the etch is complete and the pressure has returned to the mid $10^{-5}$ mbar, unload you sample following the instructions given above.

If there is a several minute delay between removing one sample and loading the next, evacuate the loadlock and turn off the microwave power generator.

If for some reason you want to stop the process once you have started it, click on the **stop** arrow. Do not select Abort as this will shut down the pumps and the whole system will need to be reset.

It is a good idea to keep track of how long you have been etching (as well as watch the reflected watts) because the system can stop etching before the process timer finishes its count down. Do not leave the machine unattended during an etch.

## Shutdown

If you are finished using the RIE you need to 'pump back' the lines. This is an important step that must be done before leaving every night. This step pulls the gases out of the system (especially important for corrosive gases) so they do not damage the equipment.

- Once you have removed your final sample from the chamber, close the loadlock and select **Wafer in Loadlock** followed by confirm (even though chamber is empty).
- Evacuate the loadlock and load the susceptor plate. If the process used either $Cl_2$ or $CF_4$, the line must be pumped back.

  Pumping back the $Cl_2$ or $CF_4$ lines.
  - Turn off the microwave power generator
  - Close all the gas bottles except for oxygen.
  - From the *Manual: Process* menu, enter the following target values.
    - **CM gauge pressure**: 0 mTorr
    - **$Cl_2$ ring**: 80 sccm (if you ran a $Cl_2$ process)
    - **$CF_4$ ring**: 40 sccm (if you ran a $CF_4$ process)
    - **Remaining step time**: 30:00
    - All other setpoints should be set to zero
    - Click on the **Start** arrow to begin evacuating the lines. Ideally the process never starts. If $Cl_2$ process starts make sure the gas bottle is closed. For $CF_4$ the process may start anyway.
    - After about 40 minutes the gas flow should reach 0.2 sccm and the CM gauge pressure 0.8 mTorr at this point stop the process.
- Select the *cleanup.rec* file (the same way you did the startup.rec file) which will clean the chamber with a 10 minute oxygen process.
- Turn on the microwave source generator.
- Press **Start**.
- After the cleanup process is finished, turn off the microwave source and power supply, close the oxygen bottle and turn off the monitor. DO NOT shut down the computer, it should always be left on.

## Appendix G: Ring Toric Macros

**This macro was modified from the 'standard' lenslet macro provided by Mial Warren.**

**The modifications include shifting the 'focus' of the lenslet out from the center to a user specified distance and mirroring the zones in towards the center.**

```
\       RectFZlens2
\       macro provided by Mial Warren, Sandia National Labs.
\
\       Modifications:  Nov. 23, 1996   Incept date...
\       Daniel Simon    Feb 28, 1997    Replaced rmax and zmax calculations with minperiod
\       Daniel Simon    July 30, 1997   Changed RectFZlens to make a 'ringlens'
\
\
MENU
        "Ringlens"
ENDMENU

niladic procedure Ringlens

        external monadic function shiftfocus

        local focal; focalm; dia    \focal length of lens, diameter of lens
        local masks1; phasnum               \number of mask layers, number of phase
                                            \levels = 2 power (masks1)
        local lrad; fnum            \radius of lens, fnumber of lens
        local index; phasein                \loop index and loop number of phase

        local mradical; minperiod                   \ used for calculation
        local temp                                          \ of smallest linewidth

        local layers                                        \vector of layer#
        local layer1; layer2; layer3; layer4 ;layer5 ;layer6
        local zone; oddzone                                 \zone number index

        local radius1; radius2; ring; flip      \these variables are used to write
                                                            \the zones into the data base...

        local radius1a; radius1b; radius2a; radius2b    \intermediate variables for above

        local minwidth                                      \minimum width of a zone allowed
        local rectangle                                     \matrix of corner coordinates of rectangle
        local rp1; rp2; rp3; rp4                        \to make polygon of rectangle input
        local rectpoly                                      \resulting polygon from rectangle
        local rectpolar                                     \polar coord version of rectpoly
        local rectrad; minrectrad; maxrectrad               \min and max raddi for rectpoly
        local testring; testflip; testr1; testf1  \checking if inside rectangle
        local shiftfocusr; dummy; dummy2
```

## shiftfocusr; dummy; dummy2 added to make ring lens

```
        private static lambda                                   \design wavelength of lens in microns

\This part checks to see if program is currently busy or if structure is not open

        if ostruct = "" then
                error "A structure must be open."    \never returns
        endif
        if coords <> "" then
                error "Already digitizing."          \never returns
        endif

\Getting input values for lens parameters.

        while focal = "" do
                focal := EXPINPUT"Lens focal length in mm:"
                if focal leq 0 or focal gt 1000 then
                        focal := EXPINPUT "Focal length must be >0 & <1000mm. Try again:"
                endif
        enddo

        while lambda = "" do
                lambda := EXPINPUT "Design wavelength in microns:"
                if lambda leq 0 then
                        lambda := EXPINPUT "Wavelength must be >0. Try again:"
                endif
        enddo
                \shiftfocusr = ""\for some reason this variable was set to null

while shiftfocusr = "" do
                shiftfocusr := EXPINPUT "Enter radius of ring in microns:"
                if shiftfocusr leq 0 then
                        shiftfocusr := EXPINPUT "radius must be >0. Try again:"
                endif
        enddo

\Getting corner coordinates of boundry rectangle

        while rectangle = "" do
                rectangle := WINDOWINPUT"Enter window coords in first quadrant only:"
        enddo
        rp1 := rectangle[1]
        rp2 := rectangle[1;1] ,[2] rectangle[2;2]
        rp3 := rectangle[2]
        rp4 := rectangle[2;1] ,[2] rectangle[1;2]
        rectpoly := rp1 ,[1] rp2 ,[1] rp3 ,[1] rp4
        rectpoly := polyclose rectpoly
        rectpoly
        rectpolar := polar rectpoly
        rectrad := MINMAX rectpolar[;1]
```

```
        minrectrad := rectrad[1]
        maxrectrad := rectrad[2]
        minrectrad
        maxrectrad

\ following to set minimum zone width allowed to control lithography requirements.
\ Minwidth is set by user before compilation in microns...

        minwidth := 1.0

\ following code to get number of mask levels and give user chance to
\ change if smallest feature is less than one micron...

        while masks1 = "" do
                masks1 := EXPINPUT "Number of mask layers:"
                if masks1 lt 1 or masks1 gt 6 then
                        masks1 := EXPINPUT "Number of mask layers is 1 to 6.  Try again: "
                endif

\ Calculate the smallest zone width of current design and prompt if zones
\ less than minwidth are going to be needed.  Formula for minperiod
\ of zones is from Nishihara "Progress in optics vol 24".

        phasnum := 2 power masks1

        focalm := focal * 1000
        lrad := maxrectrad                              \largest extent of lens...
        dia := 2.0 * lrad                           \diameter of equiv full lens...
        fnum := focalm / dia
        mradical := sqrt(1 + 4 * fnum * fnum)           \is 1/NA also from Nishihara
        minperiod := 2*mradical*lambda/phasnum          \2/phasnum in a multiple layer factor

        if (minperiod/2) lt minwidth then
                ALERT "warning"; "Zones are less than minwidth. Pattern will be truncated."
        endif

        enddo

\Get layers corresponding to the number of masks to be used. Routine does
\allow to use layers other than 1-120  if message is ignored.

        if masks1 geq 1 then
                layer1 := ravel EXPINPUT "Layer from 1-120 for first (n =1) mask:"
                if layer1 lt 1 or layer1 gt 120 then
                        layer1 := ravel EXPINPUT "Layer should be 1-120. Try again:"
                endif
        else layer1 := ""
        endif

        if masks1 geq 2 then
                layer2 := ravel EXPINPUT "Layer from 1-120 for second (n =2) mask:"
                if layer2 lt 1 or layer2 gt 120 then
```

```
                    layer2 := ravel EXPINPUT "Layer should be 1-120. Try again:"
            endif
        else layer2 := ""
        endif

        if masks1 geq 3 then
            layer3 := ravel EXPINPUT "Layer from 1-120 for third (n =3) mask:
            if layer3 lt 1 or layer3 gt 120 then
                    layer3 := ravel EXPINPUT "Layer should be 1-120. Try again:"
            endif
        else layer3 := ""
        endif

        if masks1 geq 4 then
            layer4 := ravel EXPINPUT "Layer from 1-120 for fourth (n =4) mask:"
            if layer4 lt 1 or layer4 gt 120 then
                    layer4 := ravel EXPINPUT "Layer should be 1-120. Try again:"
            endif
        else layer4 := ""
        endif

        if masks1 geq 5 then
            layer5 := ravel EXPINPUT "Layer from 1-120 for fifth (n =5) mask:"
            if layer5 lt 1 or layer5 gt 120 then
                    layer5 := ravel EXPINPUT "Layer should be 1-120. Try again:"
            endif
        else layer5 := ""
        endif

        if masks1 geq 6 then
            layer6 := ravel EXPINPUT "Layer from 1-120 for sixth (n =6) mask:"
            if layer6 lt 1 or layer6 gt 120 then
                    layer6 := ravel EXPINPUT "Layer should be 1-120. Try again:"
            endif
        else layer6 := ""
        endif

\Make vector "layers"

        layers := layer1 , layer2 , layer3 , layer4 , layer5 , layer6

\ Now start calculating the zone radii for each layer...

        index := 1

        WHILE index leq masks1 DO
            layer layers[index]
            phasein := 2 power index
            radius1 := 0
            radius2 := 0
            zone := 0
            oddzone := 1
```

```
WHILE radius2 lt lrad DO

        radius1a := ( 2 * zone * lambda * focalm / phasein )
        radius1b := sqr ( zone * lambda / phasein )
        radius1 := sqrt ( radius1a + radius1b )
```

**The radius of the m$^{th}$ zone is determined as follows:**

$$r_m = \sqrt{2mf\lambda + (m\lambda)^2}$$

**where m is the zone #, f is the focal length, and λ is the design wavelength.**

**As indicated earlier this equation is right out of the article "Micro fresnel lenses" by H. Nishihara and T. Suhara, which can be found in volume 24 of Progress in Optics edited by E. Wolf.**

```
        radius2a := ( 2 * oddzone * lambda * focalm / phasein )
        radius2b := sqr ( oddzone * lambda / phasein )
        radius2 := sqrt ( radius2a + radius2b )


        if (radius2 - radius1) lt minwidth then
                radius2 := lrad
        endif


        if radius1 lt maxrectrad and radius2 gt minrectrad then
                if radius1 lt minrectrad then
                        radius1 := minrectrad
                endif

                if radius2 gt maxrectrad then
                        radius2 := maxrectrad
                endif

                \shiftfocusr

                dummy := radius2 + shiftfocusr
                if dummy lt lrad then
                ring := shiftfocus radius1; radius2; rectpolar; rectpoly; shiftfocusr
                endif
                if ring = "" then
                        ALERT "warning"; "shiftfocus failed"
                else

                        boundary
                        straight
                        ce ring
                        put
```

```
                endif

            \add lines here to mirror ring towards center...
                \radius2

                if shiftfocusr gt radius2 then
                    dummy2 := radius1
                    \dummy2
                    radius1 := - radius2
                    radius2 := - dummy2
                    \shiftfocusr
                    \radius1

                    ring := shiftfocus radius1; radius2; rectpolar; rectpoly;
shiftfocusr

                    boundary
                    straight
                    ce ring
                    put
                endif \mirror shift

            endif

            zone
            \oddzone
            zone := zone + 2
            oddzone := oddzone + 2
        ENDDO
        \index
        index := index + 1
    ENDDO

    endsub
```

**The following procedure takes the inner and outer radii of the current 'fresnel zone', the 'focus shift' (or ring radius) and the coordinates of the arc segment that need to be filled in. This procedure is not very interesting since its main purpose is to break up the ring radii passsed to it into small segments and translate those segments from polar coordinates back to Cartesian coordinates.**

```
\ Shiftfocus
\ a function to draw a half annulus given two radii
\ will draw inside rectpolar
\ the size of the segment can be altered

monadic function shiftfocus2 := shiftfocus arg
    local inrad; outrad; thetas; steps; shiftrad
    local thetastart; segs; inseg; outseg
    local thetaend; thetadif
```

```
        local rectpolar; rectpoly; r
        local r1; r2; r3; r4; r5; r6
        local xone; xtwo; yone; ytwo

        inrad := arg[1]
        outrad := arg[2]
        rectpolar := arg[3]
        rectpoly := arg[4]

        shiftrad:= arg[5]

        r := rectpolar[;1]
        r1 := r[1]
        r2 := r[2]
        r3 := r[3]
        r4 := r[4]

        xone := rectpoly[1;1]
        yone := rectpoly[1;2]
        xtwo := rectpoly[3;1]
        ytwo := rectpoly[3;2]

\doing inseg first
\check for closest corner


        inrad := inrad + shiftrad   \modified to make ring lens

        if r2 leq r4 then



        \for inseg if r2 <= r4

                if inrad geq r1 and inrad lt r2 then
                        thetastart := arcsin (yone / inrad)
                        thetaend := arccos (xone / inrad)
                endif

                if inrad geq r2 and inrad lt r4 then
                        thetastart := arcsin (yone / inrad)
                        thetaend := arcsin (ytwo / inrad)
                endif

                if inrad geq r4 and inrad lt r3 then
                        thetastart := arccos (xtwo / inrad)
                        thetaend := arcsin (ytwo / inrad)
                endif

        else

                if inrad geq r1 and inrad lt r4 then
```

```
                thetastart := arcsin (yone / inrad)
                thetaend := arccos (xone / inrad)
        endif

        if inrad geq r4 and inrad lt r2 then
                thetastart := arccos (xtwo / inrad)
                thetaend := arccos (xone / inrad)
        endif

        if inrad geq r2 and inrad lt r3 then
                thetastart := arccos (xtwo / inrad)
                thetaend := arcsin (ytwo / inrad)
        endif

endif

thetadif := thetaend - thetastart
\ approx. 2 degree segments...

segs := ceiling ( thetadif / 2.0 )
\thetastart
\thetaend
\thetadif
\segs
if segs lt 1 then
        segs := 1
endif

thetas := thetadif / segs
inseg := thetas * iota (0, segs)
inseg := inseg + thetastart
inseg := transpose (inrad ,[1] inseg)

\ to fill corners...

\if inrad lt r2 and outrad gt r2 then
\       inseg := inseg ,[1] rectpolar[2]
\       inseg
\endif

\ doing outseg next
\ check for closest corner...

outrad := outrad + shiftrad \modified to make ring lens

if r2 leq r4 then
        \ for outseg if r2 <= r4


        if outrad gt r1 and outrad leq r2 then
                thetastart := arcsin (yone / outrad)
                thetaend := arccos (xone / outrad)
```

```
        endif

        if outrad gt r2 and outrad leq r4 then
                thetastart := arcsin (yone / outrad)
                thetaend := arcsin (ytwo / outrad)
        endif

        if outrad gt r4 and outrad leq r3 then
                thetastart := arccos (xtwo / outrad)
                thetaend := arcsin (ytwo / outrad)
        endif

else

        if outrad gt r1 and outrad leq r4 then
                thetastart := arcsin (yone / outrad)
                thetaend := arccos (xone / outrad)
        endif

        if outrad gt r4 and outrad leq r2 then
                thetastart := arccos (xtwo / outrad)
                thetaend := arccos (xone / outrad)
        endif

        if outrad gt r2 and outrad leq r3 then
                thetastart := arccos (xtwo / outrad)
                thetaend := arcsin (ytwo / outrad)
        endif

endif

thetadif := thetaend - thetastart
\ for now doing approx 2 degree segments
segs := ceiling (thetadif / 2.0)
\thetastart
\thetaend
\thetadif
\segs
if segs lt 1 then
        segs := 1
endif

thetas := thetadif / segs
outseg := thetas * iota (segs, -1, 0)
outseg := outseg + thetastart
outseg := transpose (outrad ,[1] outseg)

\ to fill corners
if inrad lt r2 and outrad gt r2 then
        inseg := inseg ,[1] rectpolar[2]
        \inseg
endif
```

```
        if inrad lt r4 and outrad gt r4 then
                outseg := outseg ,[1] rectpolar[4]
                \outseg
        endif

        shiftfocus2 := inseg ,[1] outseg

        shiftfocus2 := cartesian shiftfocus2
        if inrad lt r4 then
                shiftfocus2 := polyclose shiftfocus2
        endif

endsub
```

## Appendix H: Grayscale Ring Toric Macros

**This macro was modified from the 'standard' lenslet macro provided by Mial Warren.**

**The modifications include shifting the 'focus' of the lenslet out from the center to a user specified distance and mirroring the zones in towards the center.**

```
\       RectFZlens2
\       macro provided by Mial Warren, Sandia National Labs.
\
\       Modifications:  Nov. 23, 1996   Incept date...
\       Daniel Simon    Feb 28, 1997    Replaced rmax and zmax calculations with minperiod
\       Daniel Simon    July 30, 1997   Changed RectFZlens to make a 'ringlens'
\       Daniel Simon    March 23, 1998  Modified to layout 32 levels on 32 layers
\
MENU
        "Ringlens"
ENDMENU

niladic procedure Ringlens

        external monadic function shiftfocus
```

**no modifications need to be made to the shiftfocus procedure**

```
        local focal; focalm; dia    \focal length of lens, diameter of lens
        local masks1; phasnum               \number of mask layers, number of phase
                                            \levels = 2 power (masks1)
        local lrad; fnum            \radius of lens, fnumber of lens
        local index; phasein                \loop index and loop number of phase

        local mradical; minperiod                   \ used for calculation
        local temp; comp                                \ of smallest linewidth
        local test1; test2; test3
        local layers                                    \vector of layer#
        local layer1; layer2; layer3; layer4 ;layer5 ;layer6
        local zone; oddzone                             \zone number index

        local radius1; radius2; ring; ring2; flip       \these variables are used to write
                                                        \the zones into the data base...

        local radius1a; radius1b; radius2a; radius2b; radius3  \intermediate variables for above

        local minwidth                                  \minimum width of a zone allowed
        local rectangle                                 \matrix of corner coordinates of rectangle
        local rp1; rp2; rp3; rp4                    \to make polygon of rectangle input
        local rectpoly                                  \resulting polygon from rectangle
        local rectpolar                                 \polar coord version of rectpoly
        local rectrad; minrectrad; maxrectrad           \min and max raddi for rectpoly
        local testring; testflip; testr1; testf1  \checking if inside rectangle
```

```
        local shiftfocusr; dummy; dummy2        \added to make ring lens
        local curlayer                          \added to layout ring toric truncated

        private static lambda                   \design wavelength of lens in microns

\This part checks if program is currently busy or if structure is not open

        if ostruct = "" then
                error "A structure must be open."   \never returns
        endif
        if coords <> "" then
                error "Already digitizing."         \never returns
        endif

\Getting input values for lens parameters.

        while focal = "" do
                focal := EXPINPUT"Lens focal length in mm:"
                if focal leq 0 or focal gt 1000 then
                        focal := EXPINPUT "Focal length must be >0 & <1000mm. Try again:"
                endif
        enddo

        while lambda = "" do
                lambda := EXPINPUT "Design wavelength in microns:"
                if lambda leq 0 then
                        lambda := EXPINPUT "Wavelength must be >0. Try again:"
                endif
        enddo
                \shiftfocusr = ""\for some reason this variable was set to null

while shiftfocusr = "" do
                shiftfocusr := EXPINPUT "Enter radius of ring in microns:"
                if shiftfocusr leq 0 then
                        shiftfocusr := EXPINPUT "radius must be >0. Try again:"
                endif
        enddo

\Getting corner coordinates of boundry rectangle

        while rectangle = "" do
                rectangle := WINDOWINPUT"Enter window coords in first quadrant only:"
        enddo
        rp1 := rectangle[1]
        rp2 := rectangle[1;1] ,[2] rectangle[2;2]
        rp3 := rectangle[2]
        rp4 := rectangle[2;1] ,[2] rectangle[1;2]
        rectpoly := rp1 ,[1] rp2 ,[1] rp3 ,[1] rp4
        rectpoly := polyclose rectpoly
        \rectpoly
        rectpolar := polar rectpoly
        rectrad := MINMAX rectpolar[;1]
```

```
        minrectrad := rectrad[1]
        maxrectrad := rectrad[2]
        \minrectrad
        \maxrectrad

\ following to set minimum zone width allowed to control lithography requirements.
\ Minwidth is set by user before compilation in microns...

        minwidth := 0.5

\ following code to get number of mask levels and give user chance to
\ change if smallest feature is less than one micron...

        while masks1 = "" do
                masks1 := EXPINPUT "Number of mask layers:"
                if masks1 lt 1 or masks1 gt 6 then
                        masks1 := EXPINPUT "Number of mask layers is 1 to 6.  Try again: "
                endif

\ Calculate the smallest zone width of current design and prompt if zones
\ less than minwidth are going to be needed.  Formula for minperiod
\ of zones is from Nishihara "Progress in optics vol 24".

        phasnum := 2 power masks1

        focalm := focal * 1000
        lrad := maxrectrad                              \largest extent of lens...
        dia := 2.0 * lrad                       \diameter of equiv full lens...
        fnum := focalm / dia
        mradical := sqrt(1 + 4 * fnum * fnum)           \is 1/NA also from Nishihara
        minperiod := 2*mradical*lambda/phasnum          \2/phasnum in a multiple layer factor

        if (minperiod/2) lt minwidth then
                ALERT "warning"; "Zones are less than minwidth. Pattern will be truncated."
        endif

        enddo
```

**The following section contains the adjustments needed to write the ring toric zones to 32 levels with each level placed on its own layer. This code is specific to the 2mm diameter lenslet designed for lambda = 0.635μm that I was designing. The big if then else statement allows the macro to skip every other zone (by changing the value of phasein) if the zonewidth would otherwise be less than minwidth.**

\ Now start calculating the zone radii for each layer...

```
index := 0

        radius1 := 0
        radius2 := 0
        radius3 := 0
        zone := 0
        oddzone := 1
        test1 := 0
        test2 := 0
        test3 := 0
```

**The radius of the $m^{th}$ zone is determined as follows:**

$$r_m = \sqrt{2mf\lambda + (m\lambda)^2}$$

**where m is the zone #, f is the focal length, and λ is the design wavelength.**

**As indicated earlier this equation is right out of the article "Micro fresnel lenses" by H. Nishihara and T. Suhara, which can be found in volume 24 of Progress in Optics edited by E. Wolf.**

```
WHILE radius2 lt lrad DO
        index
        index:= index + 1
        comp := 1
        if radius2 lt 760 then
          phasein := 32
        elif radius2 lt 1500 then
           phasein := 16
                comp := 2
                test1 := test1 + 1
                if test1 lt 2 then
                zone:= zone/2
                oddzone := zone + 1
                endif
        elif radius2 lt 3000 then
           phasein := 8
                comp := 4
                test2 := test2 + 1
                if test2 lt 2 then
                zone:= zone/2
                oddzone := zone + 1
                endif
        else phasein := 4
                comp := 8
                test3 := test3 + 1
                if test3 lt 2 then
                zone:= zone/2 + 1
```

```
            oddzone := zone + 1
            endif
endif

radius1a := ( 2 * zone * lambda * focalm / phasein )
radius1b := sqr ( zone * lambda / phasein )
radius1 := sqrt ( radius1a + radius1b )

radius2a := ( 2 * oddzone * lambda * focalm / phasein )
radius2b := sqr ( oddzone * lambda / phasein )
radius2 := sqrt ( radius2a + radius2b )

radius1a := ( 2 * (zone+2) * lambda * focalm / phasein )
radius1b := sqr ( (zone+2) * lambda / phasein )
radius3 := sqrt ( radius1a + radius1b )

if (radius2 - radius1) lt minwidth then
            radius2 := lrad
endif


if radius1 lt maxrectrad and radius2 gt minrectrad then
            if radius1 lt minrectrad then
                        radius1 := minrectrad
            endif

            if radius2 gt maxrectrad then
                        radius2 := maxrectrad
            endif

            \shiftfocusr

            dummy := radius2 + shiftfocusr
            if dummy lt lrad then
            ring := shiftfocus radius1; radius2; rectpolar; rectpoly; shiftfocusr
            ring2:= shiftfocus radius2; radius3; rectpolar; rectpoly; shiftfocusr
            endif
            if index lt phasein then
            curlayer:= index * comp
            else
            index := 1
            curlayer:= index * comp
            endif

            if ring = "" then
                        ALERT "warning"; "shiftfocus failed"
            else
```

**curlayer specifies the layer on which to place the zone**

```
                        layer curlayer
```

```
                                boundary
                                straight
                                ce ring
                                put

                                index:= index + 1
                                curlayer:= index * comp

                                layer curlayer
                                boundary
                                straight
                                ce ring2
                                put
\                               index:= index - 1
                        endif

\                       \add lines here to mirror ring towards center...
\                               \radius2

                                if shiftfocusr gt radius2 then
                                        dummy2 := radius1
                                        \dummy2
                                        radius1 := - radius2
                                        radius2 := - dummy2
\                                       \shiftfocusr
\                                       \radius1

                                ring := shiftfocus radius1; radius2; rectpolar; rectpoly; shiftfocusr


                                        radius2 := radius1
                                        radius3 := - radius3


                                ring2:= shiftfocus radius3; radius2; rectpolar; rectpoly; shiftfocusr
                                        curlayer := curlayer - (1 * comp)
                                        layer curlayer
                                        boundary
                                        straight
                                        ce ring
                                        put

                                        curlayer := curlayer + (1 * comp)
                                        layer curlayer
                                        boundary
                                        straight
                                        ce ring2
                                        put
                                endif \mirror shift

                        endif
                                radius2 := sqrt ( radius2a + radius2b )
```

```
                \zone
                \oddzone
                zone := zone + 2
                oddzone := oddzone + 2
            ENDDO
endsub
```

## Appendix I: List of Optical Density for each Design Layer

The following is the list of layers and optical densities I sent to Canyon Materials for the Grayscale ring toric design.

Conversion/Mapping binary levels to grey levels for ring toric

| | | |
|---|---|---|
| Item code | rtl | ring toric lenslet--pattern of concentric circles of varying radii looks like a fresnel zone plate |
| | step | Narrow step--test pattern made up of 250x0.2 micron rectangles |
| | box | Grey level box--100 micron square box to guide develop/etch time |
| | text | Numbers corresponding to the grey level of the adjacent box |

Name of complete element in Dw2k final32gl75mrtl

| Binary layers(levels) | Grey Level | Optical Density | Item |
|---|---|---|---|
| 1 | 51 | 0.412294 | rtl |
| 2 | 50 | 0.404787 | rtl & box |
| 3 | 49 | 0.397407 | rtl |
| 4 | 48 | 0.39015 | rtl |
| 5 | 47 | 0.383013 | rtl |
| 6 | 46 | 0.375991 | rtl |
| 7 | 45 | 0.369081 | rtl |
| 8 | 44 | 0.362279 | rtl |
| 9 | 43 | 0.355582 | rtl |
| 10 | 42 | 0.348987 | rtl |
| 11 | 41 | 0.34249 | rtl |
| 12 | 40 | 0.336089 | rtl & box |
| 13 | 39 | 0.329781 | rtl |
| 14 | 38 | 0.323564 | rtl |
| 15 | 37 | 0.317434 | rtl |
| 16 | 36 | 0.31139 | rtl |
| 17 | 35 | 0.305428 | rtl |
| 18 | 34 | 0.299547 | rtl |
| 19 | 33 | 0.293745 | rtl |
| 20 | 32 | 0.288019 | rtl |
| 21 | 31 | 0.282368 | rtl |
| 22 | 30 | 0.276789 | rtl & box |

| | | | |
|---|---|---|---|
| 23 | 29 | 0.271281 | rtl |
| 24 | 28 | 0.265842 | rtl |
| 25 | 27 | 0.260471 | rtl |
| 26 | 26 | 0.255165 | rtl |
| 27 | 25 | 0.249923 | rtl & box |
| 28 | 24 | 0.244743 | rtl |
| 29 | 23 | 0.239625 | rtl |
| 30 | 22 | 0.234566 | rtl |
| 31 | 21 | 0.229566 | rtl |
| 32 | 20 | 0.224622 | rtl & box |

| Narrow step layer | Grey level | Optical Density | Item |
|---|---|---|---|
| 33 | 20 | 0.224622 | step |
| 34 | 24 | 0.244743 | step |
| 35 | 28 | 0.265842 | step |
| 36 | 32 | 0.288019 | step |
| 37 | 36 | 0.31139 | step |
| 38 | 40 | 0.336089 | step |
| 39 | 44 | 0.362279 | step |
| 40 | 48 | 0.39015 | step |
| 41 | 52 | 0.419933 | step |
| 42 | 56 | 0.45191 | step |
| 43 | 60 | 0.48643 | step & box |
| 44 | 64 | 0.523933 | step |
| 45 | 68 | 0.564982 | step |
| 46 | 72 | 0.610321 | step |
| Remaining boxes and text | | | |
| 47 | 70 | 0.58706 | box |
| 48 | 10 | 0.178054 | box |
| 49 | 15 | 0.200714 | box |
| 50 | 80 | 0.718271 | box & text |

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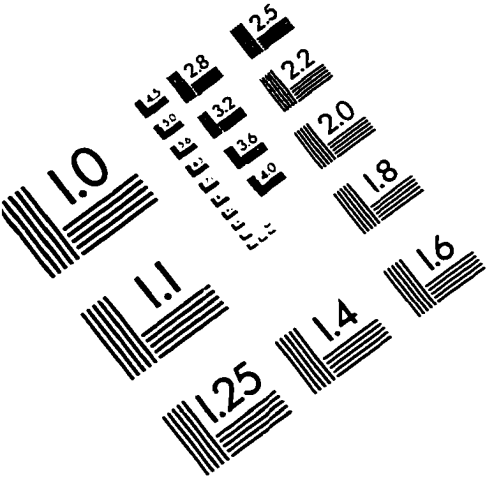
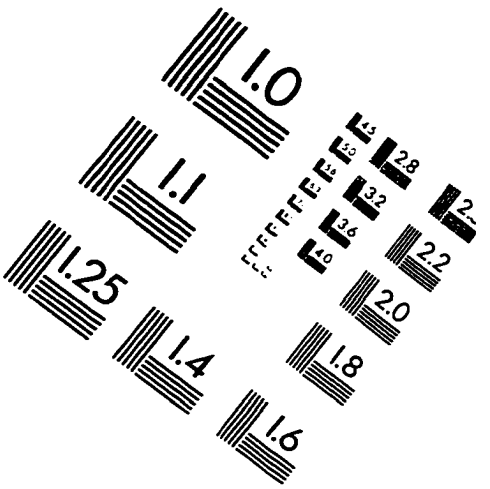
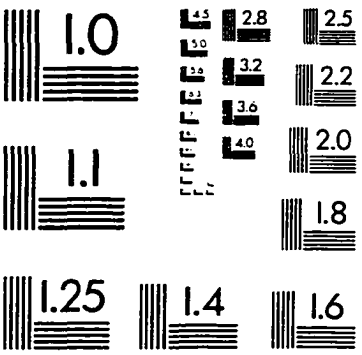
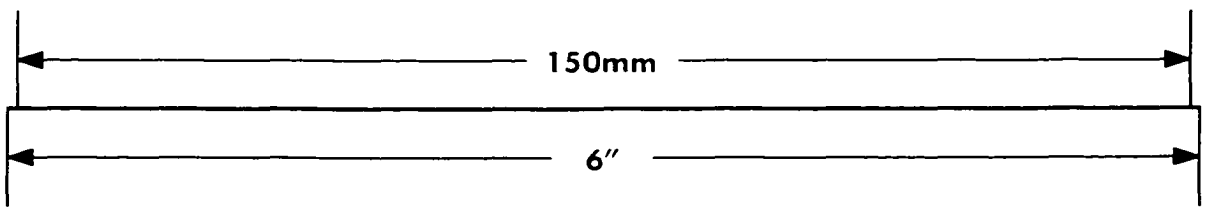
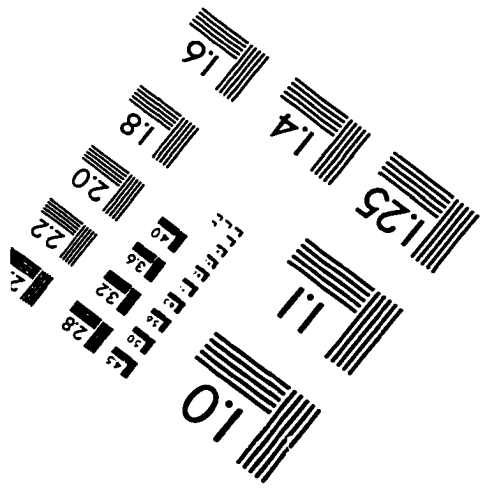
# IMAGE EVALUATION
# TEST TARGET (QA-3)

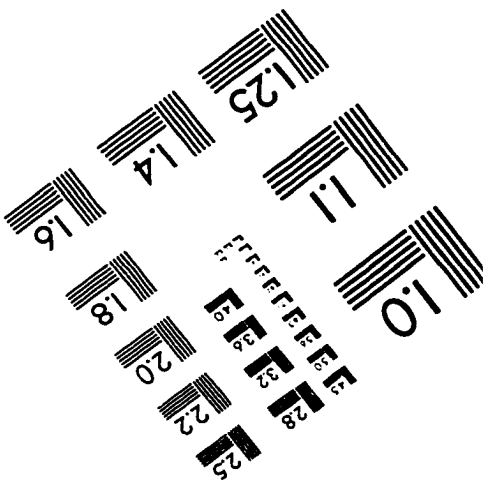



APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989