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Maskless Projection Lithography

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Maskless Projection Lithography

Submitted in partial fulfillment of the requirements for the degree of
Batchelor of Arts in Physics, Pomona College by:

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May 7th, 2003

Advised by: Dr. David Tanenbaum

Maskless Projection Lithography

J. David Musgraves

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Chapter 1: Introduction

Photolithography is a key element of the modern integrated circuit process. It is photolithography, combined with metal deposition, that allows a three dimensional circuit to be built up on a two dimensional surface. Since it is such an important part of the semiconductor manufacturing industry, a massive base of research in this area already exists. The problem with this pre-existing research is that it is geared solely toward industrial purposes, as opposed to more academic research areas. The goal of my research is to move this industrial process into the academic setting of Pomona College.

Photolithography generally consists of 3 steps: spinning on a photoresist, exposing the resist to light to pattern it in the desired way, and finally developing the exposed resist. The step that is generally prohibitive to academic research is the exposure step. It is often difficult because industrial exposure processes are done using a series of masks to properly expose the photoresist. These masks can cost on the order of $100 each, and must be ordered months in advance. A typical integrated circuit design makes use of 15 to 20 masks.

Because Pomona College is not in the business of mass-producing integrated circuits, taking the same approach as industry seems impractical. An academic setting requires much more flexibility than is provided using the standard methodology. To this end, it seemed logical to develop a system in which a student or professor could design a pattern on the fly and still be able to use it in the photolithography system. The most practical way to do this was to design a system that circumvented the masks in the standard process.

Since single unit maskless systems already exist, ours was not a project of checking to see if the process itself could be done; it was rather a project of trying to make it work at Pomona. To do this, we envisioned assembling a system from its constituent parts. This would give us maximum control over the system and would allow us also to upgrade the individual parts as we saw fit.

Such a maskless system is not only useful for the purpose of creating integrated circuits; it has uses in many situations in which students wish to pattern something on a substrate. Indeed, our project was to have immediate benefits. As I write this, two other seniors are currently using this projection system in the course of their thesis work. Just as an example, Matt Ferguson is using this process to pattern catalyst pads for growing carbon nanotubes on a silicon substrate.

In a broad strokes picture, I created a system that works by taking a pattern created on a computer, and projecting it through a DLP projector. The projected image is then reduced and sent through the camera port of a trinocular microscope. The optics of the microscope work to focus this image on the stage and allow the image to be magnified or reduced. The setup is shown below in Figure 1.1.

I purchased a light projector (2 lbs) so that it could be mounted on top of the microscope, facing downward. This allows me to leave the microscope in its intended position, which saves a lot of effort in manipulation. Another reason for the purchase of this particular projector was its projection chip. The PLUS V-1080 has a resolution of 1024 x 768 pixels, which is generated by a Texas Instruments DLP chip. This chip is really an array of microscopic mirrors, each 16μm on a side. The chip works by angling

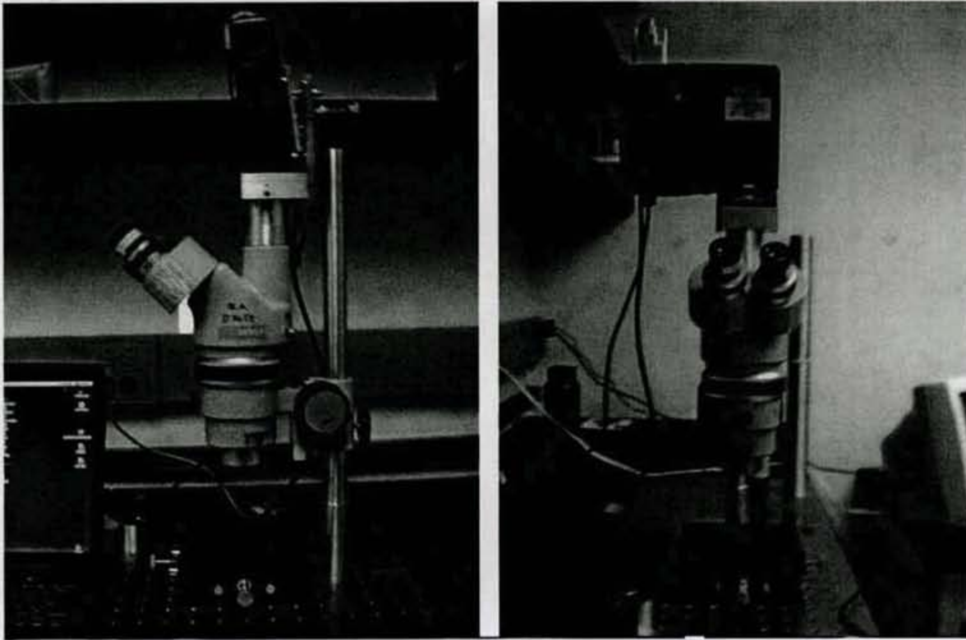

Figure 1.1: Experimental Setup

these mirrors either towards or away from the light source. Those mirrors that are angled towards are turned on, and those that are away are turned off. By angling these mirrors very rapidly, the DLP chip is able to generate a grayscale image with one mirror per pixel. The light from the mirrors then passes through a color wheel giving an image with up to 16.7 million colors.

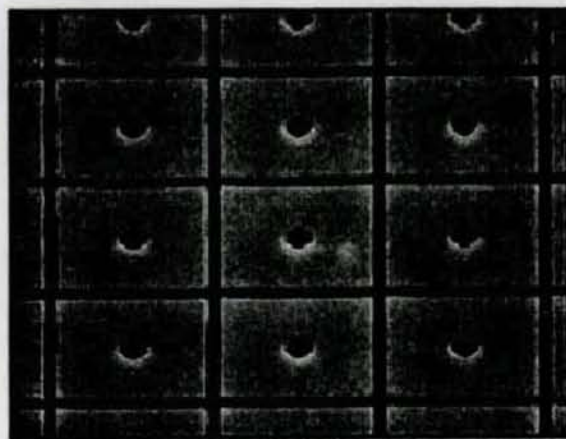

Figure 1.2: DLP Mirror Array[i]

After finalizing construction of the maskless system, I spent the remainder of my time trying to characterize what it was capable of producing. The steps involved in both the creation and characterization can be seen in Chapter 3, Experimental Procedure. Chapter 2 provides a more in depth look at the two main elements of an exposure system: optics and photoresists. The final chapters will discuss the results of my attempts at characterization, including suggestions for exposure and development times, smallest printable lines, and smallest printable spaces.

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[i] Sampsell p.3

Chapter 2: Theory

There are two major elements that must be considered in the discussion of the capabilities of a photolithographics system: optics and photoresist chemistry. These two things dictate the time that exposures take, the resolution of the patterned image, the resulting line sizes, and many other salient features. The photoresist chemistry that I used was similar to that used in integrated circuit fabrication several years ago, and for this reason the chemistry is well understood. On the other hand, the optical train that I used was different for the maskless system than it would be in a projection mask system. I will lay out the how the optics are understood in the previous systems, and how my optics differ.

Optics

There are three possible methods of exposure using a mask for photolithography; these are contact, proximity, and projection. Contact printing is the simplest of these three techniques, and was developed first in the history of fabrication; it is done simply by pressing the mask firmly against the photoresist and shining the light through it. The major benefit of this type of exposure is that there is no issue with diffraction of the light through the mask because the by the time the light has passed through the mask it is already in the photoresist. The major problem with contact lithography is that the contact between the mask and the photoresist tends to damage both, and results in a large number of defects in the resulting pattern.

The problem of contact was solved by the introduction of proximity printing. In this technique the mask is held approximately 10 μm from the photoresist surface during

the exposure. The major downfall of proximity printing is that the gap between the mask and the resist provides room for diffraction. Because of these diffraction issues, proximity printing cannot resolve features smaller than a few micrometers. When the fabrication industry needed feature sizes in the sub-micron range, proximity exposure was discarded for this reason.

The final technique, projection exposure, is almost universally used in manufacturing today, and is the only one of the systems that reduces the size of the features on the mask. A typical mask feature used in projection is reduced 4 to 10 times in the projection process. As projection is the most widely used technique and is the most similar to that used in my thesis, I will focus only on the optical issues associated with it, and when I refer to exposure in the remainder of this section it should be assumed that I am referring to projection exposure.

Projection exposure systems are generally characterized by a number of parameters regarding their optics. The two most important of these parameters are resolution and depth of focus. I will begin by describing the issues associated with projection resolution and will give a brief derivation of the theoretical resolution limits of this type of exposure. A ray diagram of the optics in a projection system can be seen in Figure 2.1. As we can see, the light from a point source is collimated by the first lens and then sent through an aperture. Let's assume for now that the aperture is circular and represents a feature on the mask that we would like to pattern on the resist. Light diffracts through this aperture according to Huygen's principle and is collected by the focusing lens and concentrated on the resist.

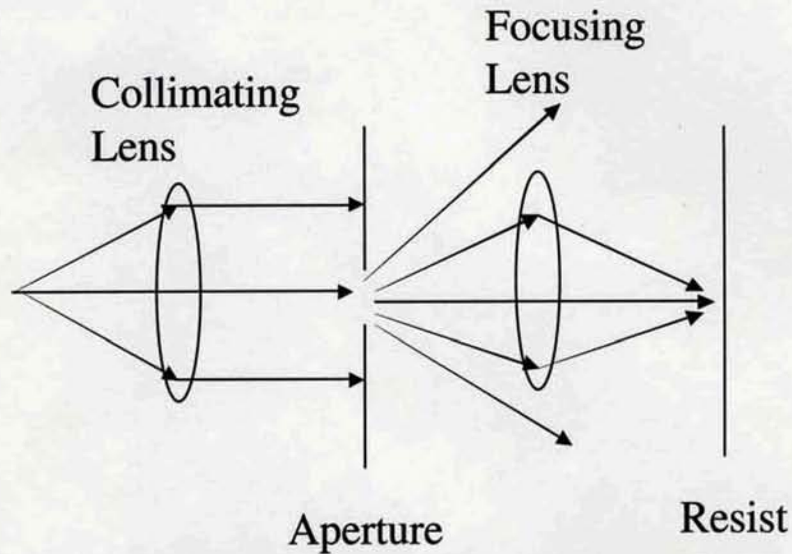

Figure 2.1: Projection Exposure with Mask[i]

The image generated by a point source using this projection system is an Airy disk, which we know from optics has a central maximum diameter of given by:

$$D = \frac{1.22\lambda f}{d} \tag{2.1}$$

where λ is the wavelength of the impinging light, d is the diameter of the focusing lens, and f is the distance from the focusing lens to the resist on the image plane. The universally accepted definition of the resolution of this system is that the maxima generated by one point must not be closer than the first minima of the second point. Using this definition we have a resolution, R, given by:

$$R = \frac{1.22\lambda f}{d} \tag{2.2}$$

or

$$R = \frac{0.61\lambda}{NA} \tag{2.3}$$

where NA is the numerical aperture of the focusing lens.

$$NA = \sin\left(\arctan\left(\frac{d}{2f}\right)\right) \tag{2.4}$$

Equation (2.3) relies on Fraunhofer diffraction and thus only applies to point sources. In standard exposure systems we are not working with point sources, so we generally replace the constant 0.61 with k_1 to indicate that the resolution is affected by various engineering techniques[ii]. Using Equation (2.3) we can get a feeling for the sort of resolution available in a projection system. If we assume that we are working with g-line light from an Hg lamp (436 nm) and have a lens with numerical aperture of 0.6, and a k_1 value of 0.7 our resolution is:

$$R = \frac{0.7(436nm)}{0.6} = 0.51\mu m \tag{2.5}$$

As we will see later, even this simple projection system that we have been looking at has a much higher resolution capability than a maskless system.

Next I would like to discuss the second major issue in the optical portion of the exposure process, namely depth of focus. Depth of focus is a function of the path length difference between light rays passing through the center of the lens and those passing through the edge of the lens. A ray diagram illustrating this issue can be seen in Figure 2.2. The commonly accepted restriction is that the difference in path length of these two rays can be no more than $\lambda/4$. This restriction has a direct effect on Equation (2.3). If we wanted to decrease our resolution limit, one way to do it would be to make a very large lens with a high numerical aperture. But if we did this we would violate the Rayleigh criteria for the depth of focus. Physically speaking, the depth of focus is a description of

the distance over which the image will be on focus from the image plane. The larger the lens, the smaller the depth of focus, which explains why finding focus on microscope objectives of high magnification, is so much more difficult than on lower magnifications.

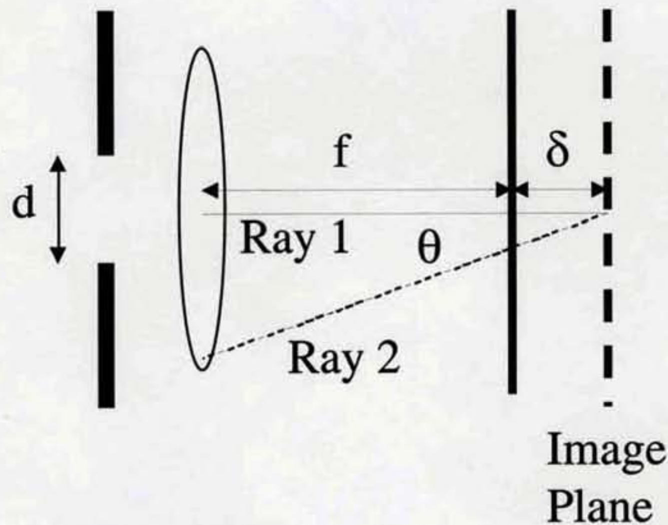

Figure 2.2: Depth of Focus[iii]

Thus we can see that the Rayleigh criterion requires that:

$$\frac{\lambda}{4} = \delta - \delta \cos\theta \tag{2.6}$$

If we assume that θ is small, in our case it was approximately 10 degrees, we can use the approximation:

$$\frac{\lambda}{4} = \delta\left[1 - \left(1 - \frac{\theta^2}{2}\right)\right] \cong \delta\frac{\theta^2}{2} \tag{2.7}$$

$$\theta \cong \sin\theta = \frac{d}{2f} = NA \tag{2.8}$$

$$DOF = \delta = \pm\frac{\lambda}{2(NA)^2} \tag{2.9}$$

Again, we generally replace the constant of 1/2 by k_2 to indicate that the depth of focus can be altered using different engineering techniques.[iv]

Now I would like to examine the differences between this projection system and my maskless system. The main variation between the two optical systems has to do with where the information is inserted. In the projection system, the information was inserted by the aperture on the mask midway through the train, whereas in my system the information is present from the beginning of the optics. A diagram of this can be seen in Figure 2.3.

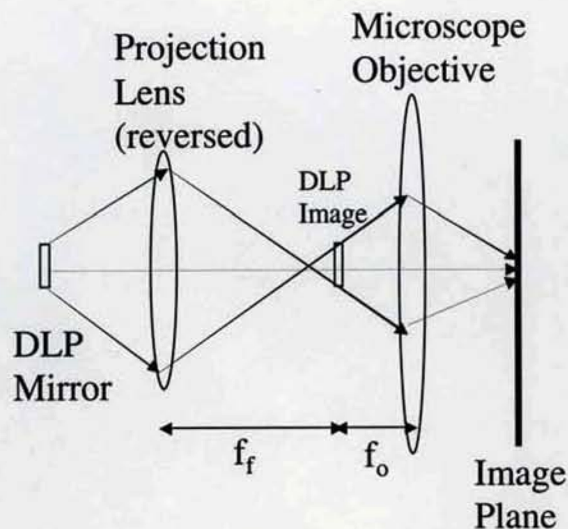

Figure 2.3: Maskless Projection System

As it turns out, diffraction is only one of the factors affecting the resolution of this system. I described earlier the setup of the DMD chip that is inside of the PLUS projector. The mirrors in this array each represent one pixel on the screen, and are each 16μm on a side[v]. In the lab, I work with a magnification of 3.5X, which means that each

pixel corresponds to a 4.5μm width. Thus the best possible resolution that I can get working at this magnification is 4.5μm, regardless of other effects. However, the resolution can be improved by moving the projector to a microscope with a different magnification and numerical aperture. The effects of this transition will be seen at the end of Chapter 4.

We can make an assumption about this optical system that will allow us to look at the effects of lens diffraction on the resolution, so that we might compare this effect to the limit based on mirror size. The assumption that we can make is that the initial focusing lens is simply creating an image the exact same size of the chip at its focal length. This allows us to look at only the right half of Figure 2.3 when interested in diffraction effects. For this situation, the resolution of the lens is given by Equation (2.3)[vi], where our lens has a numerical aperture on the order of 0.1 according to distributor specifications. Therefore our resolution is given by:

$$R = \frac{0.61(440nm)}{0.1} = 2.7\mu m \qquad (2.10)$$

So we see that while our resolution limited by diffraction at this wavelength is much higher than for a projection system using a mask, the resolution is in fact governed by the size of the mirrors in the projector. If we were to use a microscope with numerical aperture of 0.4, this resolution becomes 0.7μm.

We can also look at the depth of focus of the maskless projection setup. The depth of focus is given by Equation (2.9) using the same approximation as above:

$$DOF = \frac{440nm}{2(0.1)^2} = 22\mu m \qquad (2.11)$$

Compare this to the DOF of an Excimer laser stepper with a KrF light source: 0.34μm. This value is on the same order as the thickness of the photoresist layer, which is about 0.2μm. So lithography involving this setup requires that the photoresist layer be extremely flat, so that it does not fall over the DOF limit. This is not an issue for the maskless system. With a DOF of 22μm there is no concern that the resist be particularly level. However, if we again change our numerical aperture to 0.4, the depth of focus becomes 1.4μm.

Photoresist Chemistry

I would now like to look at the second major portion of the exposure system, the resist chemistry. Photoresists are formed from organic polymers that have been photosensitized by the addition of small molecular chains. The function of these photoresists is to undergo a chemical change when bombarded with photons. There are two basic types of photoresists: positive and negative. Positive resists are the most widely used in manufacturing, and become more soluble when exposed to light. A simple diagram of the reaction of a positive resist can be seen in Figure 2.4.

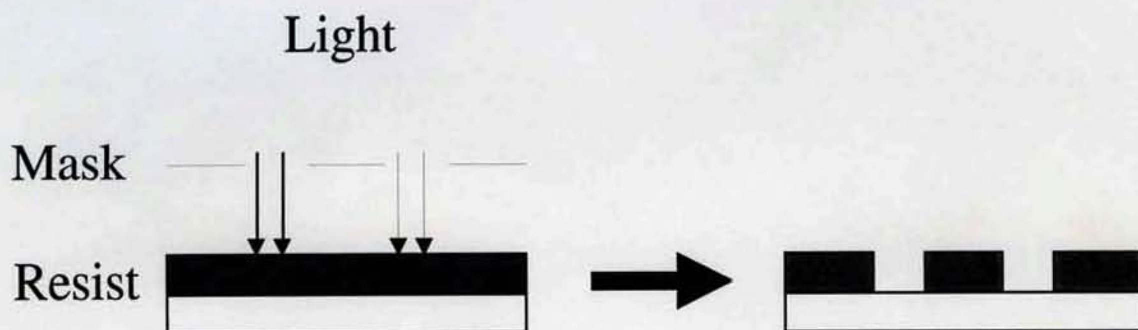

Figure 2.4: Positive Photoresist Process

I used a positive novolac resist for my work. This means that I had a mixture that contained a photoactive compound (PAC), namely diazonaphthoquinone, a novolac

resist, and a solvent used to control the viscosity of the liquid. Novolac is the organic polymer that serves as a base for the photoresist, and can be seen below in Figure 2.5.

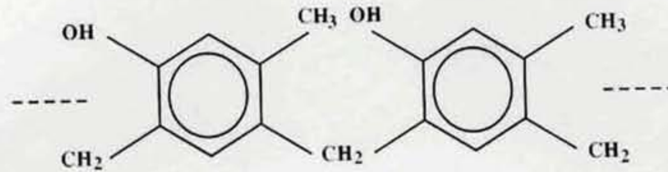

Figure 2.5: Novolac Structure[vii]

This chain can be repeated to form an extended polymer. By itself novolac is very easily dissolved in NaOH, and is removed at a rate of approximately 15 nm/s.[viii]

More important to the exposure process is the PAC; in my case I used diazonaphthoquinone. This is the portion of the liquid that changes by exposure to photons. This PAC absorbs the 365, 405, and 435nm lines from an Hg lamp, and thus was widely used in the early stages of IC manufacturing. After spinning and soft bake, this molecule is insoluble in NaOH, and will not etch at a rate higher than 1-2 nm/s. But after being exposed to light, it is highly soluble and can be developed at a rate of 100-200 nm/s. The mechanisms of this change are discussed below. A diagram of the PAC is shown in Figure 2.6.

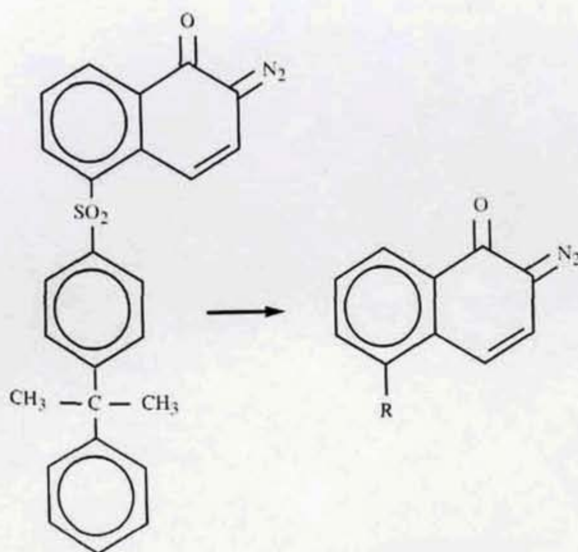

Figure 2.6: Diazonaphthoquinone Structure

The photosensitive portion of the molecule is the top group, which is abbreviated as shown to the right. A major drawback to diazonaphthoquinone-novolac resists is their poor adherence to silicon, which can cause adhesion failures as seen in Figure 2.7. To avoid this, it is necessary to prime the substrate; there are numerous techniques for doing this including oxidizing in $KmnO_4$, treating the surface with cyanocrylate, or polymerization of silanes via e-beam among many others. I did not end up using any of these techniques in my exposure trials because I did not have a high rate of adhesion failure.

Figure 2.7: Adhesion Failure of Novolac Resist

Upon exposure to light, the diazonaphthoquinone undergoes a chemical change known as a Wolff rearrangement. The N_2 in the PAC is very loosely bound to the rest of the structure and is freed when a photon is absorbed. The resulting carbene rearranges to a ketene when one of the carbon atoms leaves the ring. The OH is absorbed from the water in the surrounding resist and creates indene acid. The resulting structure is extremely hydrophilic and easily developed in a weak NaOH solution[ix].

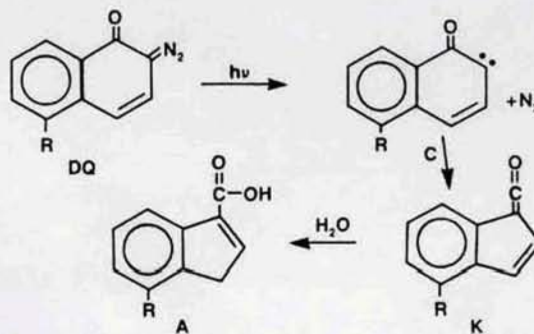

Figure 2.8: Wolff Rearrangement in Diazonaphthoquinone

There are two major factors used to characterize photoresists: contrast (γ) and critical modulation transfer function (CMFT). The contrast describes the resist's ability to distinguish between light and dark. In other words, it is a description of how well a resist resists in areas where there is not a perfect binary value of either light or dark. The modulation transfer function is an optical function of light passing through the mask. It deals with how diffracted straight lines on the mask become on the substrate. The critical modulation transfer function is a description of the reaction of the resist to this diffraction.

We would like to be able to describe how the resist dissolves in terms of optical parameters such as wavelength and numerical aperture. We can start this description with the following equation:

$$\frac{dR}{dZ} = \left(\frac{dR}{dE}\right)\left(\frac{dE}{dZ}\right) \qquad (2.12)^{x}$$

where R is the rate of dissolution of the resist, Z is the depth of the resist, and E is the energy absorbed. The term $\left(\frac{dR}{dE}\right)$ is known as the developer term and $\left(\frac{dE}{dZ}\right)$ is referred to as the energy absorbed term. Now we can introduce the concept of contrast to help us understand equation (2.11) a little more in depth. Mathematically, contrast is defined as:

$$\gamma = \frac{1}{\log(Q_f / Q_o)} \qquad (2.13)$$

where Q_0 is the exposure does at which the resist first begins to dissolve and Q_f is the exposure dose at which the resist is completely dissolved.

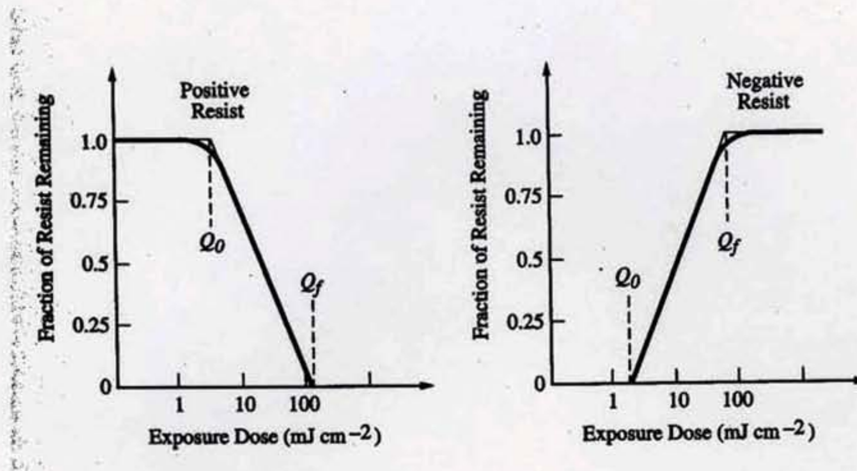

Figure 2.9: Contrast for Positive and Negative Resists[xi]

Figure 2.9 also shows a related feature of a given resist, the sensitivity. The sensitivity is different for different resists and is the exposure dose at which the resist begins its chemical change. The sensitivity can be read off of the contrast graph, it is the elbow on the positive resist curve, and is given as Q_0.

The developer term can then be written in terms of the contrast of the resist:

$$\frac{dR}{dE} = -\frac{\gamma}{Q_0} \tag{2.14}$$

and the energy absorption term in terms of optical properties:

$$\frac{dE}{dZ} = \frac{NA}{\lambda}\left[(1-k)\left(\frac{\Delta X(NA)^2}{\lambda}\right)\right]^2 \tag{2.15}$$

which lets us describe the rate of dissolution at a given height in terms of constants and properties of the optics and resists[xii]:

$$\frac{dR}{dZ} = \frac{NA}{\lambda \log\left(\frac{Q_f}{Q_0}\right) Q_0}\left[(1-k)\left(\frac{\Delta X(NA)^2}{\lambda}\right)\right]^2 \tag{2.16}$$

Finally, it should be noted that the CMTF can also be expressed in terms of the contrast function. Namely:

$$CMFT = \frac{Q_f - Q_0}{Q_f + Q_0} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1} \tag{2.17}$$

If the CMFT for the resist is greater than the MFT for the mask, the resist will be unable to reach the resolution being produced by the mask.

In practice, the aerial image of a grating has a modulation transfer function of about 0.6. If the MTF of the mask goes below the CMTF of the photoresist, or below 0.5, the resist will be unable to resolve the grating image.

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[i] Plummer. p 237.
[ii] ibid. p 213.
[iii] ibid. p 214.
[iv] ibid. p 214.
[v] Yoder. p 2.
[vi] Pedrotti. p 336.
[vii] Plummer p 223.
[viii] ibid. p 224.
[ix] Moreau p 44.

[x] ibid p 29.
[xi] Plummer p 227.
[xii] Moreau p 31.

Chapter 3: Experimental Procedure

I began this project with a proof of concept, to show that the principles that I was using could in fact be applied to this setting. The test was to set up an optical train that included a projector and various lenses that could take an image and project it down to an area of approximately 20 mm^2. To do this I used the department's Sharp XG-NV2U Notevision projector. In addition, I was given a set of lenses from the optics storeroom. These included an 85 mm, 55 mm, 35 mm, and 25 mm lens. The idea was to arrange these lenses in a sort of reverse beam expander, as shown in Figure 3.1.

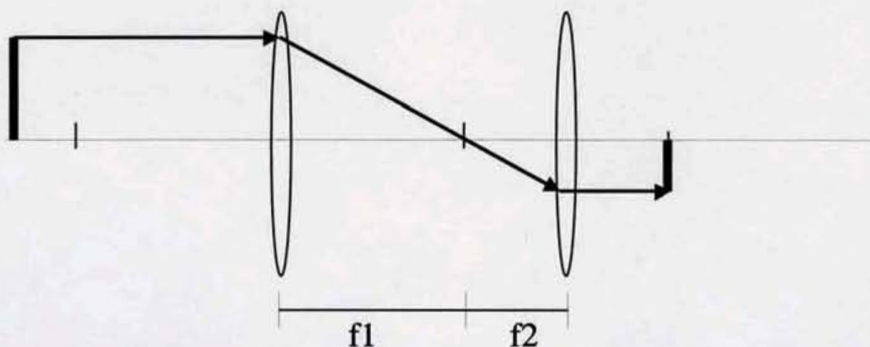


Figure 3.1: Proof of Concept Ray Diagram

This system reduces the size of the projected image by $\frac{f_1}{f_2}$ where f_1 and f_2 are the focal lengths of the lenses and are given in the above Figure. At the end of this optical train I placed a departmental microscope. I secured this microscope to an aluminum base, to which I attached two "arms". Using these arms to prop up the microscope such that the eyepieces were parallel to the tabletop, I projected the reduced image through a hole where I had removed the eyepiece.

The internal optics of the microscope work in such a way as to focus parallel beams of incident light down to the stage. Using these three pieces: the projector, the lenses and the microscope, I attempted to project an in-focus image on the stage of the microscope. The goal of the proof was to project an image that was no more than 5mm by 4mm. I was able to prove to myself that this setup was feasible using an 8.5cm focal length lens closest to the projector, followed by a lens with a 25 cm focal length in front of the microscope eyepiece. This setup generated an image that was 8mm by 6mm on the stage of the microscope.

Having completed this proof, I proceeded to purchase a new microscope and projector. The projector I purchased was a PLUS V-1080. My first goal was to replace my old projector with the new one and recreate the conditions of the proof of concept to see if the optics needed modification. As it turned out, the PLUS projector was completely incompatible with the lenses that I had been using. This was because the projection lens for the new projector was much stronger than that in the Notevision. Using a similar optical train did not work because the first lens was unable to focus the rapidly diverging light beams coming from the projection lens. After having exhausted the possible lens combinations, I decided that it would be necessary to remove the projection lens from the projector.

Removing this lens was beneficial in several respects, the first being that it made the experimental situation closer to the theoretical. In Figure 3.1 we assumed that the impinging light beams were parallel to each other, which was only an approximation. But using the projection lens made our beams very divergent. The projection lens is designed to increase the size of the small image generated inside the projector to a size of

30 or 40 square feet by the time that it reached the wall, up to 10 feet away. This condition meant that the beams coming out of the projection lens diverged rather quickly, so by removing it we came much closer to our approximation.

The second reason is that the size of the image being generated inside the projector was much more on the size scale that we were hoping to pattern. The Digital Micromirror Device (DMD) that is the heart of the PLUS projector is about 13mm on a side. Thus by removing the projector lens, I was able to work with a much smaller image by the time that it reached the first lens.

I finally had success, not by using the two-lens setup shown in Figure 3.1, but by simply inserting the projection lens backwards into the projector. Because the projection lens is a compound lens like those found in cameras, this was not an intuitive answer. The projection lens was designed to create an image from 36 to 200 inches diagonal on a wall at least 6 feet away, but when working with the projection lens in backwards I found that I could see a very sharp, and contracted image on a surface placed 2.5 inches from the lens. This image was 14 mm (0.551 in) across, almost exactly the same size as the DMD chip inside the projector. I should note that this is an experimental distance. I was not able to calculate this distance using any optical laws or knowledge of the lens.

One last consideration that had to be resolved before attempting to couple the projector to the microscope: the projection angle. In its standard mode, the projector was designed to throw its image up at an angle of 17 degrees. Even with the lens placed in backwards, I found that the projector continued to throw up at this angle. This angle had to be compensated for in the device used to couple the two together.

The schematics for the individual parts that I machined to mount and control the projector can be seen in Appendix 1. There were several constraints in the creation of this attachment. First, the cooling fan for the V-1080 projector was on the front. Because of this, I was unable to build a setup in which the projector simply rested on a flat surface. Blocking this cooling fan would have overheated the projector and caused it to fail. Secondly, I created pieces such that the in focus image at 2.5 inches from the projector lens was inside of the microscope tube so that the rays could be focused by the microscope optics. As I have also just mentioned, the design had to be such that I could angle the projector in the mount to compensate for the 17-degree throwing angle.

Projector Usage

The first step in using the projection system is to establish that the surface and the image are in focus at the same time. In order to do that, I attached a camera to one of the eyepieces of the Nikon microscope. With the camera set to focus at infinity I found the point at which the surface of the stage was in focus. I then used the projector to project a standard image, a red box in a white field. Using the camera again, I changed the focus of the projector until I could see that the image was in focus as well as the surface. This focusing process is necessary in order to assure that the patterns to be etched into the resist are in focus when they reach the surface, and requires that the relative position of the projector and microscope be adjusted precisely.

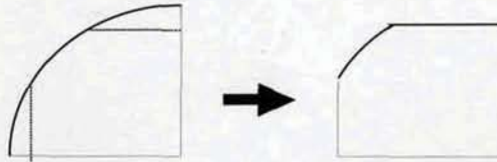
The next step in the process is to spin on the photoresist. The Novolac resin resist is stored in a large stock bottle in the refrigerator in room B12 in Millikan. After mixing the contents of the bottle thoroughly, I decanted some into a small amber bottle. The

resist is highly sensitive to white light, so precautions must be taken during the decanting. The reason that the resist is stored in the refrigerator is that it has a shelf life of about 6 months when sitting in a warm light environment, even in an amber bottle. After this time the resist becomes much more viscous, and begins to strip away completely in the developer solution.

For my resist spinning, I found it adequate to use the blender setup in Professor Tanenbaum's lab. This consists of a food processor that has the blades removed and replaced with a vacuum chuck. The vacuum is not high powered, it is provided by a fish tank bubbler that is attached to the blender. To ensure that there is a good seal between the substrate and the blender during the spin, I used various O-rings that had been covered in vacuum grease. From this point on in the procedure it is important to work under yellow or red light. The photoresist is extremely sensitive to some of the wavelengths contained in the white light from the fluorescent bulbs. To this end, amber light covers were installed in the labs, and should be used to prevent exposure.

As I progressed, I found it easier to spin larger pieces of silicon as a time saving technique. The largest pieces that I felt comfortable sinning were quarter sections of silicon wafers. Because these pieces tend to be more asymmetrical than small sample pieces, they have a large tendency to jump off the chuck shortly after the spin has begun. There are two ways to resolve this problem that I have found. The first is to simply remove the largest asymmetrical parts of the wafer. If a quarter of a wafer is trimmed in the way shown in Figure 3.2, it stays on the chuck much more easily. The second technique that can be used if trimming the wafer is out of the question is to put a few

drops of the resist on the chuck, under the O-ring. After drying, the resist is extremely



sticky and keeps good contact between the ring and the chuck surface.

Figure 3.3: Trimming Wafers for Spinning

When wafers did come off of the chuck during a spin, I was able to salvage them if they had not been broken in the process. Because the disruption in the spin greatly affects the quality of the resulting resist, it is necessary to begin the spin again. To clean the wafer I washed it in acetone, followed by a rinse in isopropyl alcohol. The isopropyl should be applied almost immediately after the acetone, and should be allowed to air dry. I found that the wafer cleaned best when I held it by a corner during the process and allowed the chemicals to run to another corner. The drips on the edge can be blown off with a dust gun or with dry nitrogen. I should note here that whenever I refer to the drying off of samples, it is important to use either of these two gasses as opposed to compressed air. The compressed air in Millikan often contains small particles of oil and other impurities that are detrimental to the lithography and to any subsequent processes.

Immediately following the spin on resist, it is important to soft bake the wafers. Initially I was not baking my wafers at all and found that because of the intensity of the projector, some areas outside of those I wished to pattern were being exposed. After trying many combinations of bake, expose, and develop times, I found that 30 seconds of

bake time at 90 degrees Celsius was optimal. The samples can be placed directly on the heating plate, and when the heat has removed the excess moisture from the resist it changes colors slightly. This occurs after three seconds and is the minimum bake time.

For my exposures I used the program Power Point, from the Microsoft Office suite. I chose Power Point because I believe that it is a fairly accessible program for people to learn, and has several components that are useful in the lithographic process including finely maneuverable line positions and slide timers. A typical run in my process was a series of 9 slides alternating between exposures and safe slides during which I could reposition my sample.

I began each run with a slide of pure red background. In the RGB picker in Power Point pure red is setting G and B to 0% and R to 100%. This red has very little intensity in the 400-450 nm region as can be seen in Figure 4.3. This is helpful because it allows for an alignment slide. This slide can either be pure red, or can be a black background with red features if alignment of these features is necessary. The exposure slide is then blue features on a black background. The "black" that is put up by the projector is not the same as having those pixels turned off; the projector is in fact putting out light. The effects of this ambient light may be grounds for further investigation.

For my attempts at characterizing this system I worked almost exclusively with rectangles and bars. An example of a slide that I used for exposure is shown below in Figure 3.4 where the white areas would be blue in the exposure.

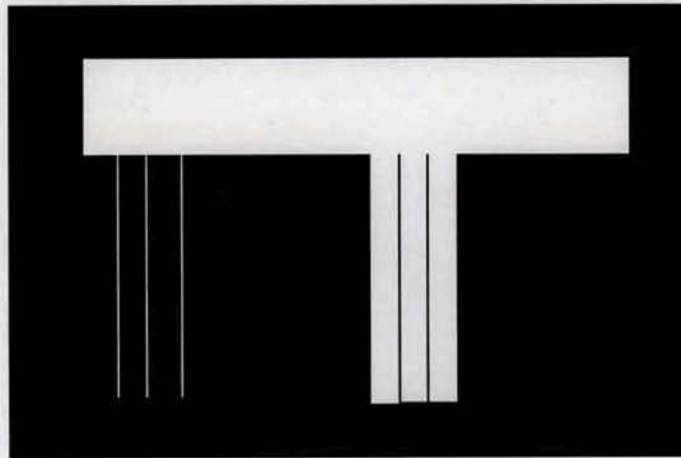


Figure 3.3: A Sample Exposure Slide

I used this type of slide to test both fine lines and fine spaces to see how the soft bake, expose and develop times could be optimized to pattern each. The discussion of these times can be found in Chapter 4. The large bar at the top of the screen was useful in terms of locating the areas that I patterned when it came time to make observations in the microscope. One operational note: the placement of the lines to be patterned in the center of the screen was very intentional. I was unable to capture the top corners of the screen in my projections. The usable projected area was over 90% of the total projected area, but it is extremely important to note the positions that do not get projected and avoid patterning in them.

After patterning the resist, I immediately developed in an NaOH solution. For my purposes, a relatively weak solution of 0.2M NaOH was strong enough. Every two to three weeks I mixed a new bottle of developer. The reason for this is that I found that the developer tended to concentrate over time. If I did not use the bottle for a long period the concentration at the bottom was much higher than 0.2M. The result of this concentration was that when I went to develop, the NaOH stripped away all of the resist, exposed or

not. To avoid this situation I found it useful to shake the bottle for 1 minute before pouring a 50 ml aliquot into a beaker.

It is also important to use a fresh aliquot of developer for each day. I found that 50 ml was enough to develop 12 samples over the course of 2 hours, but when left over night the developer lost its potency. It is also very important to keep the beakers well cleaned. When it evaporates the NaOH leaves a residue on the beaker that adversely affects the molarity of the new developer solution.

After soaking in the developer for one minute, I removed the samples and rinsed them with deionized water. Special care should be taken in drying the samples. As always, I used a dust gun instead of the compressed air in the building, but the angle and duration of the drying spray is also extremely important; too direct or too long of a spray can detach features from the surface due to the poor adhesion of novolac resist to the silicon. One must also rinse and dry the samples immediately after removing them from the developer. If left exposed to the air for more than 5 seconds without rinsing, crystals begin to form on the surface of the resist. These crystals completely degrade the remaining pattern.

While it is possible to examine samples using the Nikon SMZ-10 microscope, I found it much easier to transfer them to the Nikon ME-600 microscope for observation. This microscope has a translatable stage and magnification from 5X to 50X. This range of magnifications was very helpful for examining samples. Using the 50X objective it is possible to make out the details of where very fine lines had burned through the resist. This is not possible for some lines even using objectives of 20X.

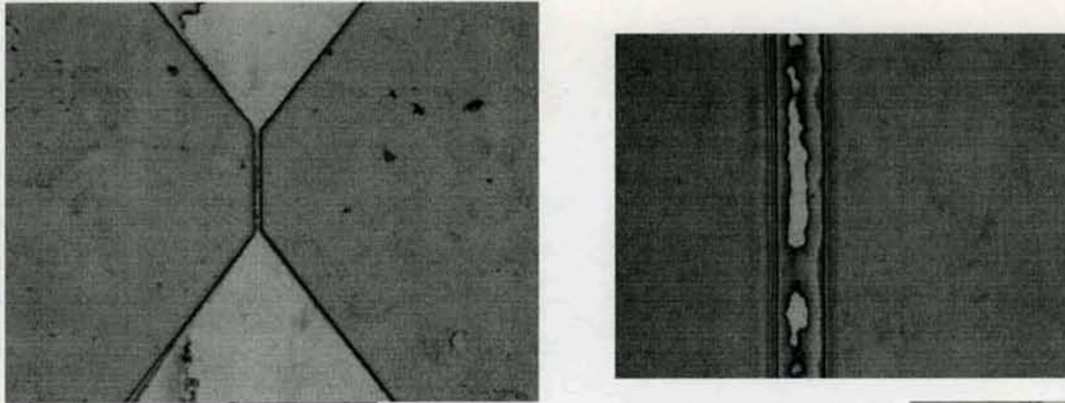


Figure 3.5
A line that looks burned through at 5X is shown to be incomplete at 50X

Both microscopes have ports for digital cameras. I made extensive use of several Nikon cameras. These cameras have threads around the lenses for attaching extra features such as zoom lenses. Professor Tanenbaum acquired a 10X microscope eyepiece with threads that match those on the camera. By attaching this eyepiece onto the front of the camera, we were able to adapt the camera to the microscopes. On the SMZ-10 microscope, I machined an extra adapting piece to which I attached a neutral density filter. I found that the intensity of the projector overwhelmed the circuits of the digital camera, which made the image flicker and change color rapidly. To combat this, I installed a neutral density filter that reduced the intensity of the light reaching the camera 1000 times.

Chapter 4: Results

Projection Spectra

One of the first aspects of the maskless projection system that had to be characterized was the spectrum of the light impinging on the resist. As we saw in Chapter 2, the novolac resist that I am using responds strongly to the wavelengths between 350 and 450nm that are generated by an Hg lamp. Thus, it was crucial that my exposure light have a strong peak in this range. Conversely, it was also very important that the light that I was using as a "safe" light have no strong peak in this range.

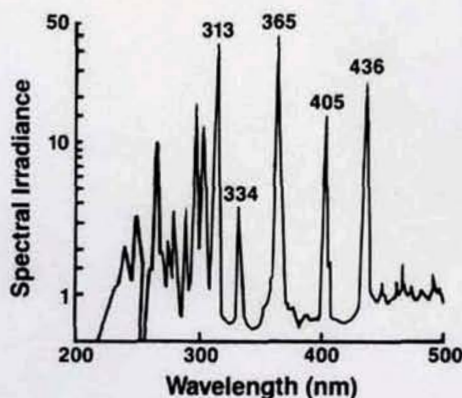


Figure 4.1: Spectrum of Hg

I used pure blue light to expose the resist; this definition of pure refers to the use of the RGB color picker in the Power Point program, and is given simply by Red 0%, Green 0% and Blue 100%. In my proof of concept I used an Ocean Optics spectrometer to take spectra of the exposure and safe light. These spectra can be seen in Figures 4.2 and 4.3 respectively. I captured this data using the 001Base32 software that can be downloaded from www.oceanoptics.com.

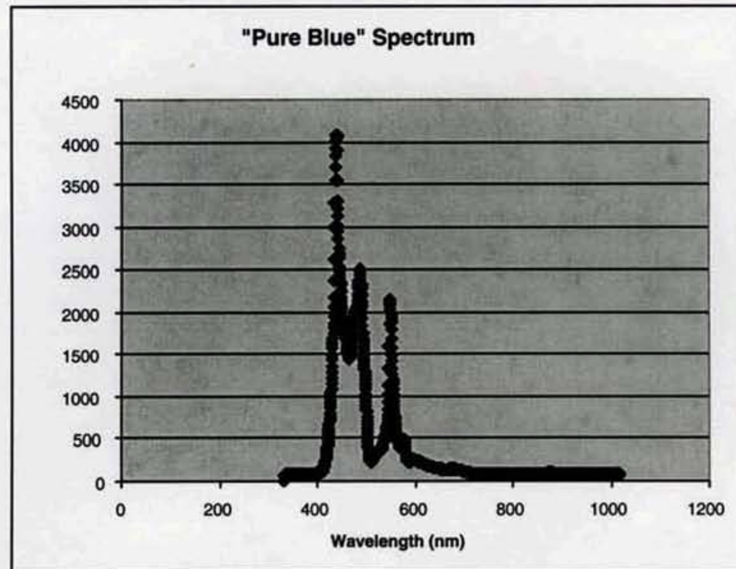


Figure 4.2

We can see from the spectra in the above figure that the pure blue has its strongest peak at 440.7nm, although there are additional peaks at 488 and 550nm. This wavelength of light works well for exposing the novolac resist, as we will see below. But we must be careful, especially in examining the optical effects of the system, to keep in mind that the light is not compromised of single wavelength.

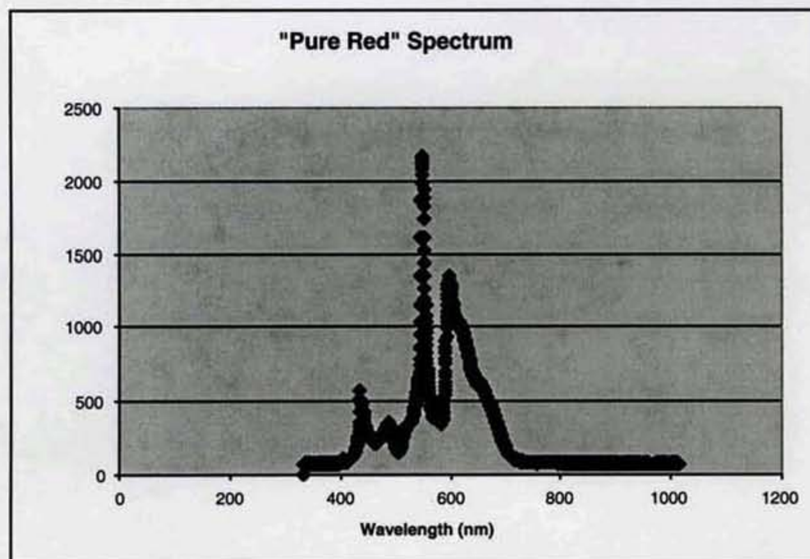


Figure 4.3

The pure red spectrum has a strong peak at 550nm, with a subsidiary peak at 600nm, as an extremely small peak at 437.1nm. This last peak is in the reactive area for the novolac resist, but the peak is so small that any exposure to the red light has negligible effects on the resist.

Pattern Timing

The next step in the characterization of the system was to understand the various timings involved with a patterning. These timings include: spin time, bake time, exposure time, and develop time. The first of these, spin time, was fairly independent of the others, and as such was the easiest to calculate. But the other three times are somewhat dependent on each other as well as on various outside variables meriting further consideration below.

The spin time is most easily found by observing the spinning process. As the resist is spread out over the substrate it changes thickness; because of the thin film interference generated by the light in the room interacting with the changing film thickness, the reflected light varies in color. This "fringing" is an easy indicator of the relative thickness of the spun film. To make sure that my films were of similar thickness, I allowed the resist to spin until the fringing had stopped, and then let it spin an additional 10 seconds to make sure that the fringing had not simply slowed. This fringing process, with the additional 10-second safety, took a total of 40 seconds each time.

Next I investigated how the bake time interacted with the exposure and develop times. The intention of baking is to remove the excess solvent from the resist before

exposure. A resist that is exposed without this "soft bake" tends to overexpose, i.e. patterned lines tend to bleed out and become larger than they were intended if the resist is unbaked. However, if the resist is baked for too long, or at too high of a temperature, it begins to decompose and cannot be properly exposed. The resist is mostly dry after 3 seconds, but I found the optimal soft bake time for this system to be 30s at 90 C. Any temperature above 150 C causes the resist to decompose.

I arbitrarily set the developer time to 1 minute. This time is completely dependant on the type and molarity of the developer used. In my characterization process I used 0.2M NaOH to develop slides after exposure. I chose 1 minute as the developer time because I found that shorter developer times did not allow some of the less exposed areas to fully develop, while any time over 1 minute 30 seconds began to strip unexposed resist from the substrate.

By far the most delicate of the timings was the exposure time. As I discovered during the course of my characterization, the timing for exposures depends heavily on the features being exposed. To pattern the finest lines that I could using this setup, I needed exposure times of 3.5 minutes. For larger features, anything greater than 20 pixels across, exposure times are on the order or 10 to 15 seconds. This fact will become important when trying to pattern usable features in the resist. Features larger than 20 pixels should be placed on the same slide, and should be patterned for 13 seconds. Features smaller than 6 pixels have to be exposed for more than 3 minutes, with the time increasing to 3 minutes 30 seconds for features smaller than 4 pixels.

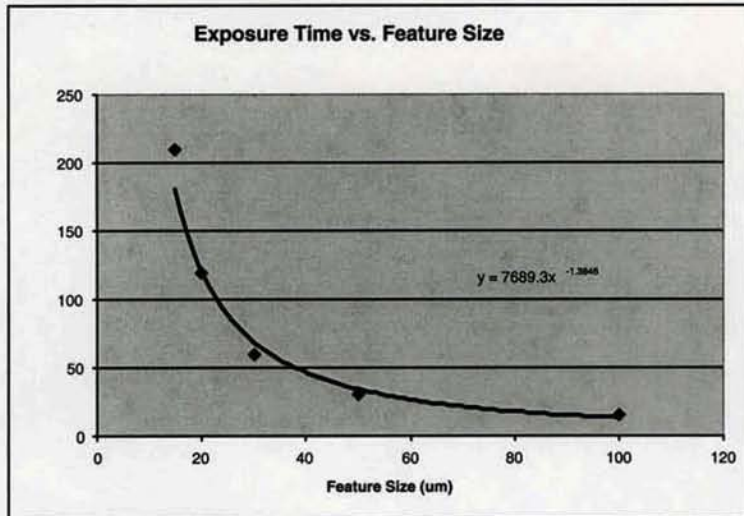


Figure 4.4: Graph of Empirical Exposure Times

Feature Sizes

Finally, I would like to show the smallest features that I was able to pattern using this particular setup. My initial intention was to characterize the smallest line, the smallest space, and any grids that I could pattern. The smallest line can be seen in Figure 4.5a and b at 20X zoom and at 50X zoom, and has a width of 15μm. As we can see the edges of this line are not very well defined, the gradient that can be seen along the edges indicates the slope of the resist down to the substrate. Because I am interested in how the impinging light affects the resist, I chose to measure the width of the line as the places where the resist began to slope down. Obviously this method of measurement would be less than useful if I was interested in the area of the substrate that was exposed by the removal of the resist.

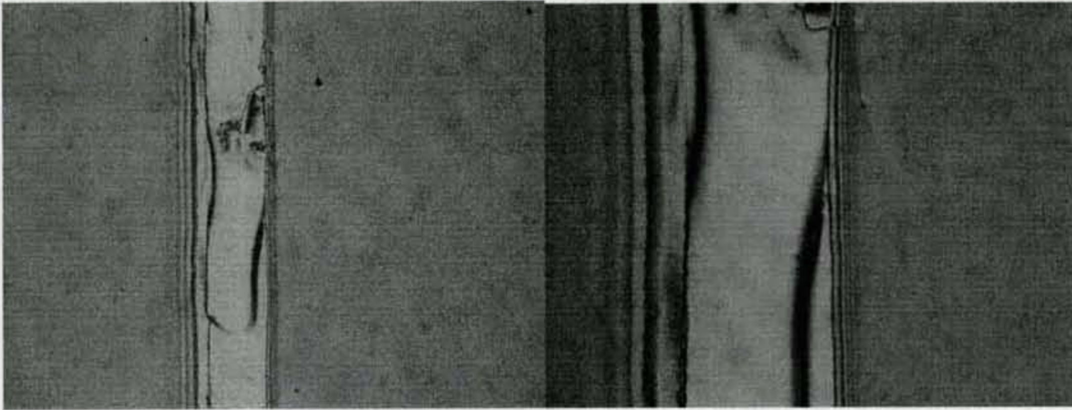


Figure 4.5 a (left) and b (right):
15 μm line at 20X and 50X magnification

The debris that can be seen in the center of the line is remaining resist. This problem becomes increasingly larger as the line size decreases. Possible solutions to the problem are slightly longer exposure times and more evenly distributed resist. There are slight variations in the resist thickness at the edges of a wafer because the resist tends to pool there during the spin process. Because I was not very concerned about overall resist thickness during my characterization, I spun larger samples and worked around the obviously thicker resist areas. But in a more delicate setting, it may be necessary to spin smaller substrates to avoid this pooling.

Next I attempted to characterize the smallest possible space that I could pattern. To do this, I created a series of slides that varied the distance between 2 20 pixel wide lines. I found that the smallest on-screen space that I could pattern was 20 pixels, but that this did not correspond to 200μm as it would have for patterning lines. Instead, I found that the 20-pixel space was actually 50μm wide on the surface of the resist.

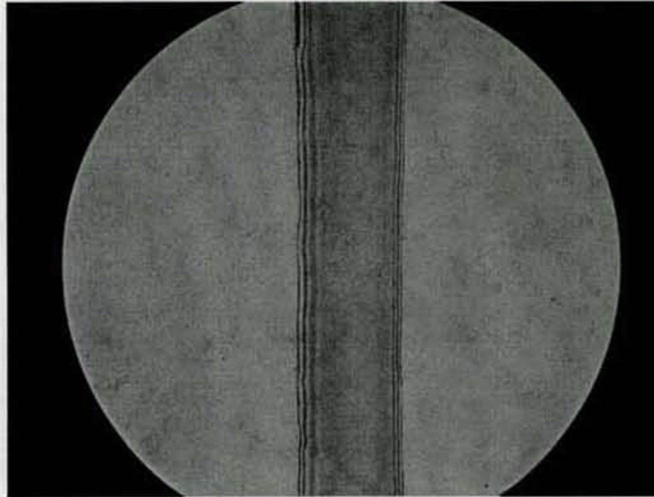


Figure 4.5: 50μm space at 50X magnification

Though the smallest patternable space is over 3 times the size of the smallest patternable line, it does have the benefit of being much cleaner. Because the actual patterned area is so large, all of the resist is removed inside, leaving a very clean edge.

Finally I attempted to pattern a grid of lines. This was an extremely difficult process because of the timing issues that I discussed above. I found that in order to expose the grid long enough to reach the substrate beneath the lines, I had exposure times on the order of 3 minutes. But with exposure times this long with a high number of features, we begin to see the effects of adhesion failure in the novolac resist. The areas began to be overexposed and experience adhesion failure at times as low as 60 seconds. At this exposure time, however, the lines of the grid were not patterned all the way through.

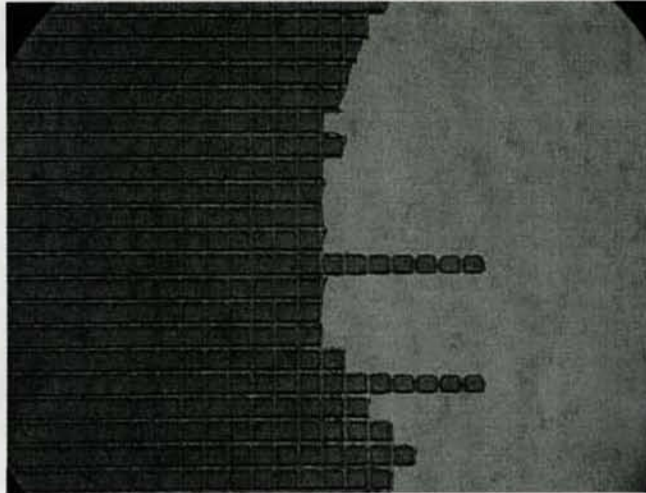


Figure 4.6:
60s grid exposure at 20X magnification
Each box is 60μm across

The maskless photolithography system is at its best when it is patterning very large (0.1mm scale) features. As we can see below, for these types of features we have extremely sharp edges and very clean interior areas.

Figure 4.7: Lines are 100μm wide

One last characteristic of the resist that should be discussed is the thickness. Using the AFM, I was able to take images of the profiles of a patterned area and of a scratch.

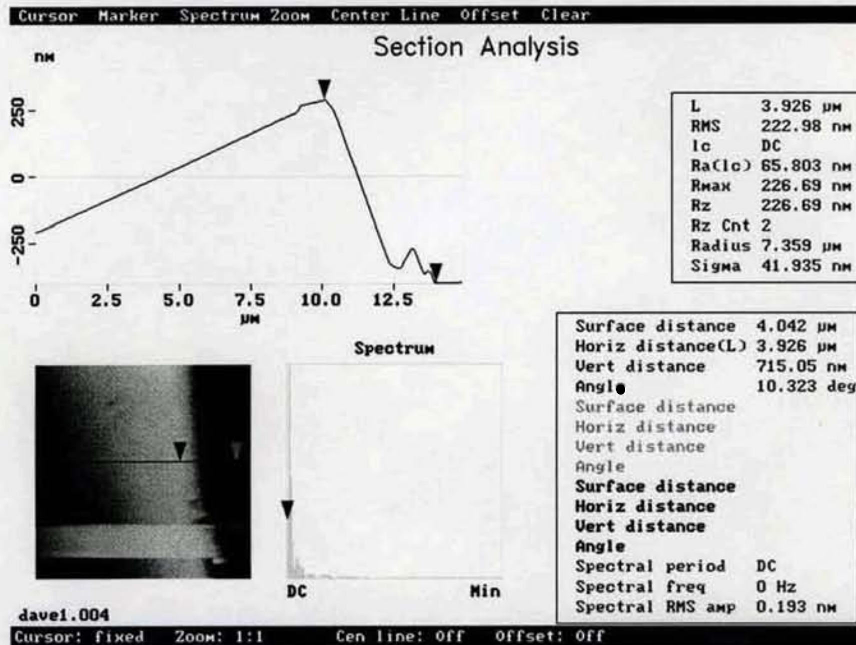


Figure 4.8

Figure 4.8 shows the profile of a scratch through the resist. We can see that the resist depth is 715 nm. This image was taken in the center of the sample, to avoid the thickness variations we find at the edges of the samples. This thickness variation is easily detectable with the naked eye and should be avoided in patterning.

<u>Changing Microscopes</u>

As we saw in Chapter 2, changing the numerical aperture and magnification can have drastic effects on the resolution of the projection system. We would like to maximize this resolution so as to approach the theoretical limits of the system. We can do this by moving the projection system onto the ME-600 microscope, which has a range of

magnifications from 5X to 50X. I have plotted the theoretical resolution of the system as governed by the mirror size and by the optical diffraction in Figure 4.9. As we can see, the mirror resolution approached the diffraction limit only when the numerical aperture reaches 0.8, which corresponds to a magnification of 50X for the ME-600.

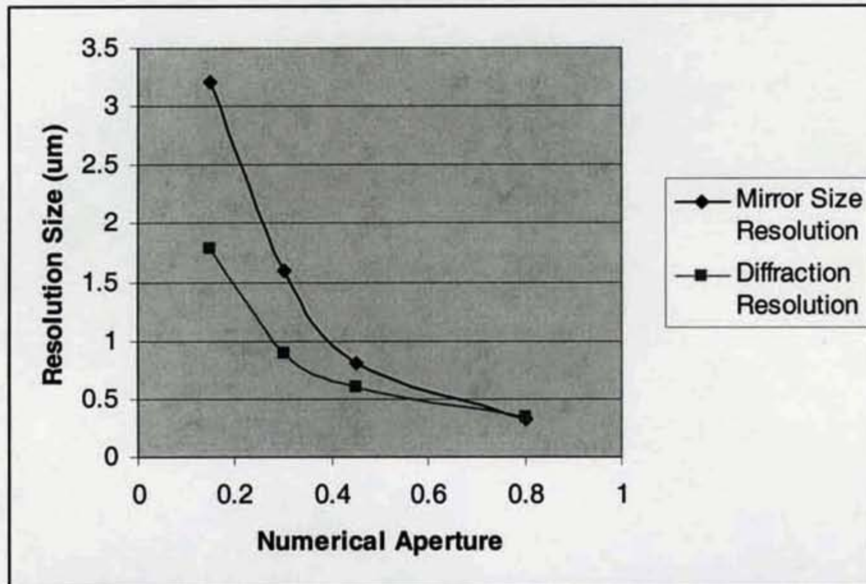


Figure 4.9: Resolution Effects of Various Magnifications

The major difficulty with working with a system that is at 50X magnification is that the depth of focus is reduced to 0.4μm. This would require an exceedingly thin and uniform resist in order to pattern. As we saw above, we are capable of spinning crude resists of a thickness of 715nm, so any work done with a more powerful microscope would require a different approach to resists.

Chapter 5: Conclusions

Maskless photolithography proved to be a viable process in an academic setting. As we have seen, the components are easy to make and relatively inexpensive to purchase. For my demonstration I used a fairly expensive PLUS projector, but this need not be the case in other systems. One of the most appealing things about this system is the flexibility involved; if monetary constraints dictate a larger projector, a similar setup can be created with the same ease. Similarly, the microscope used need not be of the same specifications as the Nikon SMZ-10. Indeed, one of the next steps in the lifetime of this project is to transfer the projector to the Nikon ME-600.

Specifically, this system has proved itself to be a valuable tool for academic research at Pomona College. Already two other senior physics majors, Matt Ferguson and Cory Forsyth, have used it in the course of their thesis work, and several freshmen are now learning how to pattern. One of the most attractive aspects of the patterning process is how easy it is to learn. In the course of one afternoon a person can become acquainted with how to spin resist, how the exposure process works, and the necessary steps for developing a pattern.

Hopefully this report can serve as a guide to the use of the maskless projection system, both for those at Pomona College and elsewhere. I have included instructions on how to use the existing system in Millikan basement, as well as directions for how a similar system can be created at other institutions. In addition to these instructions, I have also left some challenges for those continuing this research. These challenges include more in depth investigation of the optics of the projector and the microscope, an investigation into the effects of multi-wavelength light in the exposure process, and a

challenge to see if the resolution of the system can be pushed closer to the theoretical limit imposed by the size of the DLP mirrors.

Acknowledgements:

I would like to thank Izzy Smith and Alan Tarr for their work calibrating the Nikon ME-600. I would like to thank Matt Ferguson for his help with the AFM and various other problem solving advise. I would like to thank Glen Flohr for his expertise and trust in the machine shop. Finally, I would like to thank my advisor Professor David Tanenbaum for all his help.

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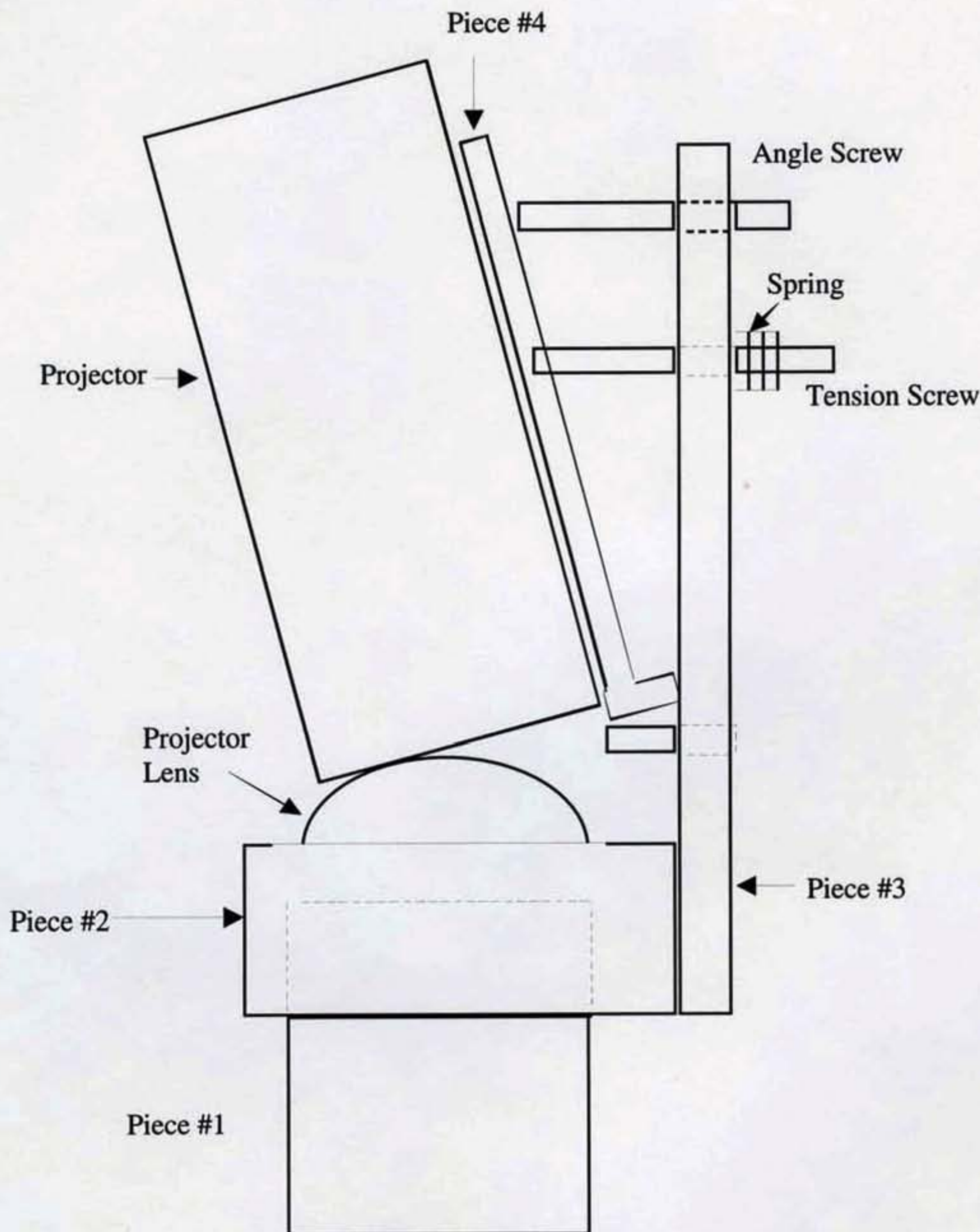
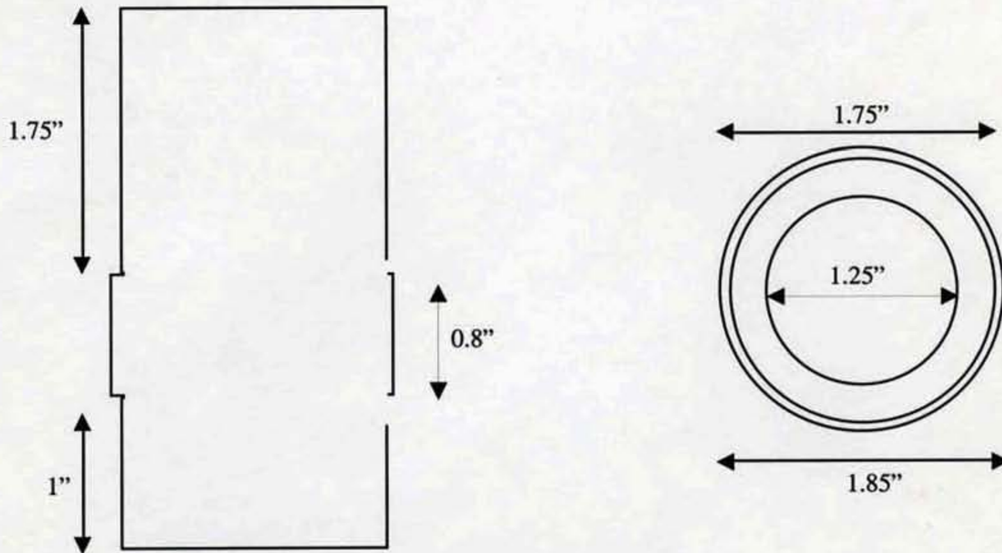
Apendix 1: Machined Parts

Overview



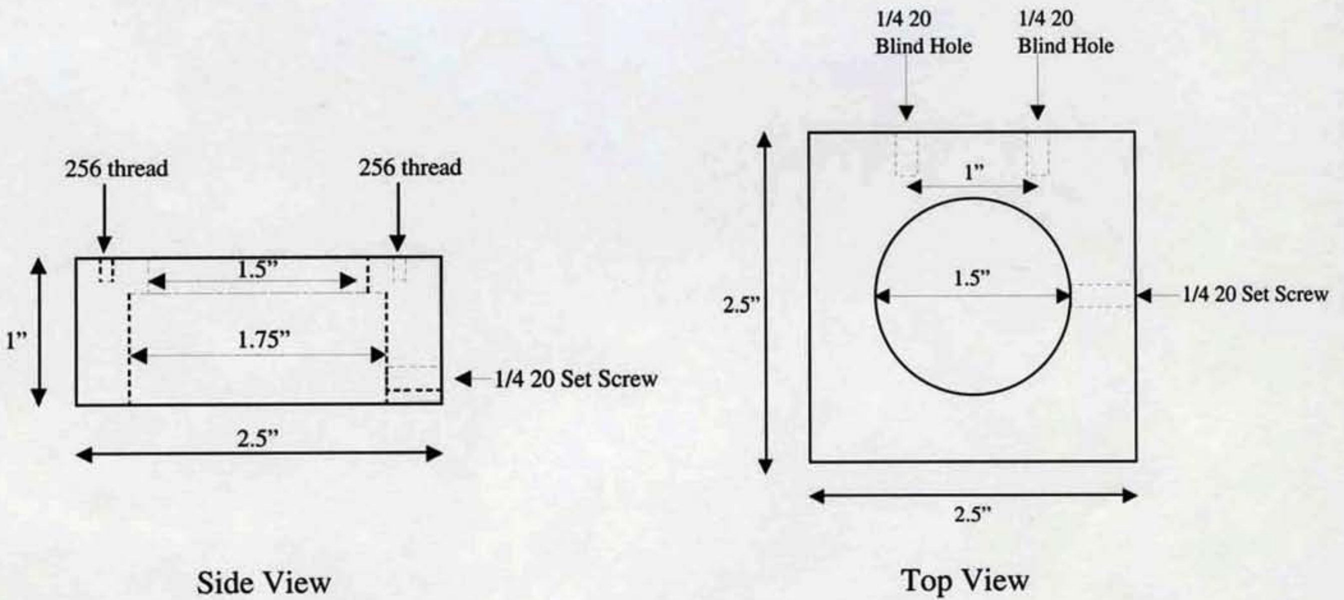
The projector is attached via 3mm screws to piece 4, the holes in the projector were there when purchased. Piece 4 is attached at several points to piece 3. It is suspended above the focusing lens by posts in piece 3. Additionally there are two screws attaching the pieces; the angle screw is used in concert with the tension screw to adjust piece 4 to the angle of 17.2 degrees to account for the throwing angle of the projector.

Piece 1

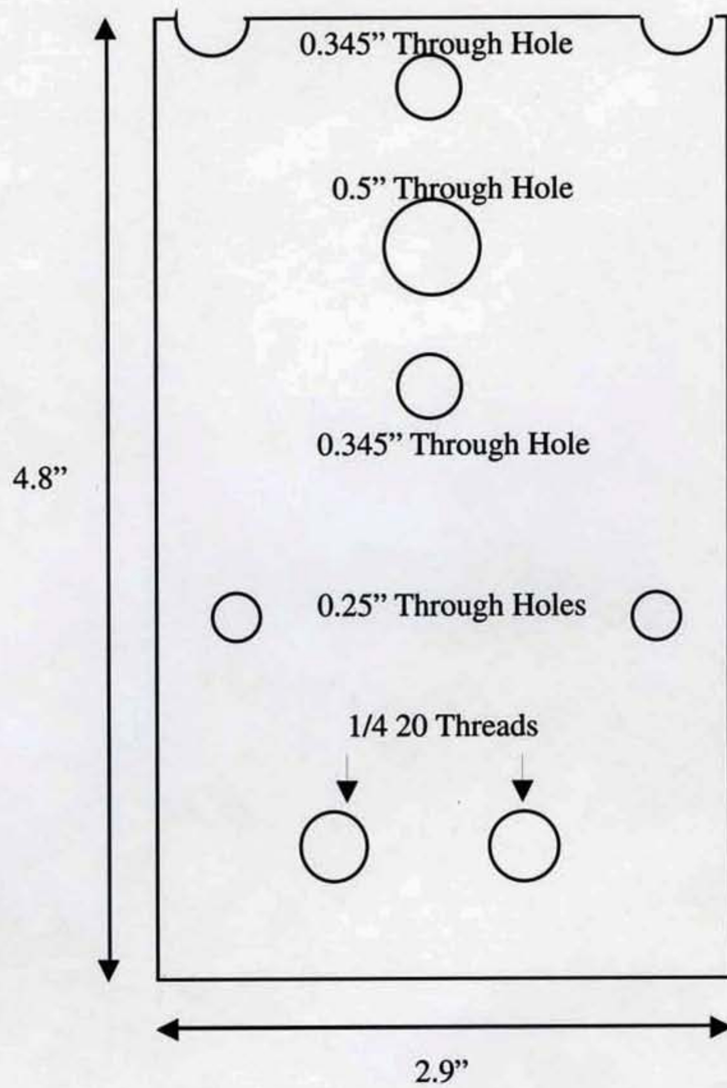


An adaptor piece between the microscope and the projector mount.

Piece 2



Piece 3



Piece 4