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Optical Lithography - Nanotechnology Lab

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Contents

1 ABSTRACT

The word lithography comes from the Greek lithos, meaning stones, and graphia meaning to write. It means quite literally writing on stones. In the case of semiconductor lithography, our stones are silicon wafers and our patterns are written with a light sensitive polymer called a photoresist.

Optical lithography is the basic technology used in the exposure of microchips: it is the key to the age of micro- and nano-electronics. The fabrication of circuits on a wafer requires specific patterns of various materials to be deposited on or removed from the wafer's surface. The process of defining these patterns on the wafer is known as lithography. Optical lithography refers to a lithographic process that uses visible or ultraviolet light to form patterns on photoresist material. This is done by projecting the image of the patterns onto the wafer surface using a light source and a photo mask.

Our aim in this lab is to fabricate some given patterns onto glass samples using optical lithography and to study the effects of different exposure times on the produced sample dimensions.

2 INTRODUCTION

Optical lithography is a photographic process by which a light sensitive polymer, called a photoresist, is exposed and developed to form three-dimensional images on the substrate. The general sequence of processing steps for a typical optical lithography process is: substrate preparation, photoresist spin coating, pre-bake, exposure, post-exposure bake, development and post-bake. Metrology and inspection followed by resist strip are the final operations in the lithographic process, after the resist pattern is transferred to the underlying layer via etching or ion implantation.

In general, the ideal photoresist image has the exact shape of intended pattern in the plane of the substrate, with vertical walls through the thickness of the resist. Thus, in the final resist pattern, parts of the substrate are covered with resist while other parts are completely uncovered. This pattern is needed for pattern transfer since the parts of the substrate covered with resist will be protected from etching, ion implantation, or other pattern transfer mechanisms. The key components that should be considered are the glass mask and the exposure system to perform the lithography. Despite the high cost of the optical mask and the lithographic system, lithography popular since it allows parallel production. That means we can lithograph a lot of systems using only one step of light exposure.

3 THEORY

Types of Optical Lithography

There are three methods of exposure of UV light during optical lithography.

1. Contact Exposure
2. Proximity Exposure
3. Projection Exposure

The three types of exposures are shown in figure 1 and explained further in table 1.

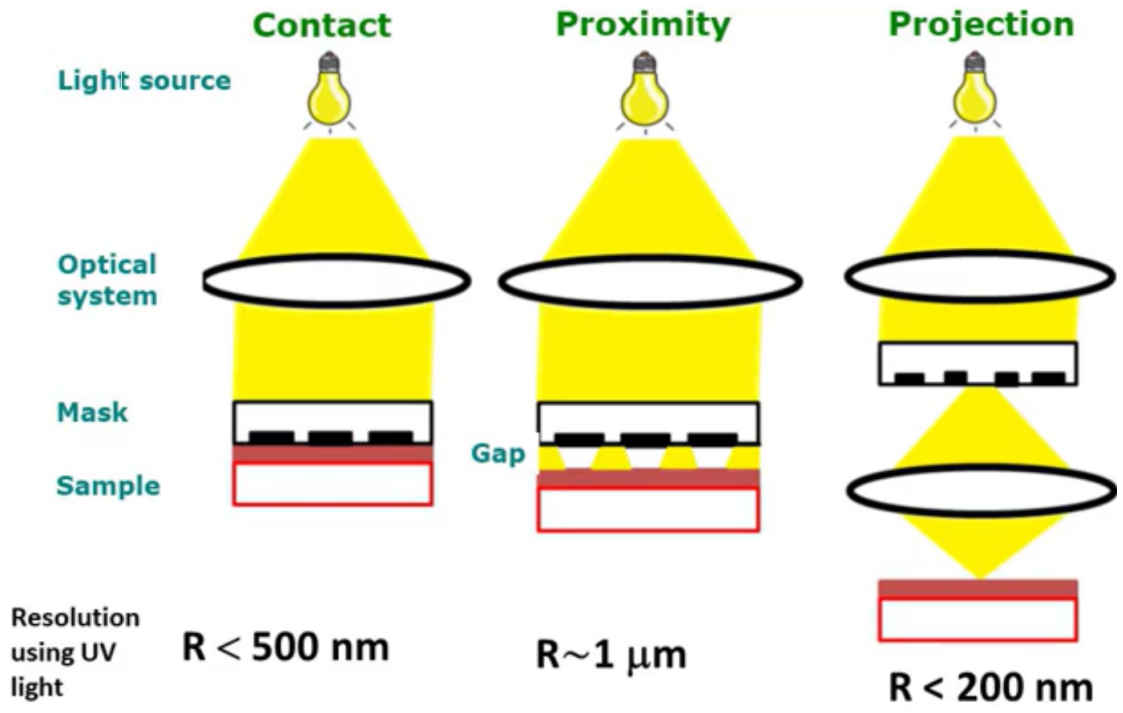


Figure 1: Schematic showing contact, proximity and projection printing techniques.

Table 1: Types of exposures in optical lithography

Types of Lithography Printing			
Criteria	Contact Exposure	Proximity Exposure	Projection Exposure
Description	The photomask is pressed against the resist-covered wafer with a certain degree of pressure,contaminating the mask with the resist.	The photomask and wafer have no contact, usually with a minimum distance of 10 μ m between them. Light diffracts (by Fresnel diffraction) upon reaching the wafer, lowering the quality.	The photomask and wafer have a large gap between them and uses a lens to collect diffracted light and project this onto the wafer.
Minimum Feature Size	$MFS \propto \sqrt{d\lambda}$ where d is the photoresist thickness and λ is the light wavelength.	$MFS = \sqrt{\frac{d}{2+g}\lambda}$ where g is the distance between mask and substrate.	$MFS = 0.61\frac{\lambda}{NA}$ where NA is the numerical aperture of the lens system.
Mask Size	1:1	1:1	1:1 or 5-10:1
Advantages	Good resolution quality.	No damage to mask or sample.	No damage to mask or sample. Reduction imaging may be used along with stepper (step and repeat) systems, so mask size may be increased, making its manufacturing easier.
Disadvantages	Mask and sample may be damaged due to contact (friction).	Resolution quality decreases due to diffraction loss.	More complex design and more expensive.

PHOTORESIST

In the field of lithography, photoresists play a central role. A photoresist is a light-sensitive material, which consists of polymers which react under the impact of light, to form a patterned coating on a surface. There are two different types of resists, they are also illustrated in figure 2.

1. Positive Photoresists: Exposed areas are removed in the development. Upon exposure, the photoresist becomes more soluble in the developer solution, forming positive images of the mask patterns on the wafer.

2. Negative Photoresists: Exposed areas remain after the development. Upon exposure, the photoresist becomes less soluble in the developer solution, forming negative images of the mask patterns on the wafer.

   A disadvantage of negative resists is that their exposed portions swell as their unexposed areas are dissolved by the developer. This swelling results in distortions in the pattern features and limits the resolution of negative resist processes.

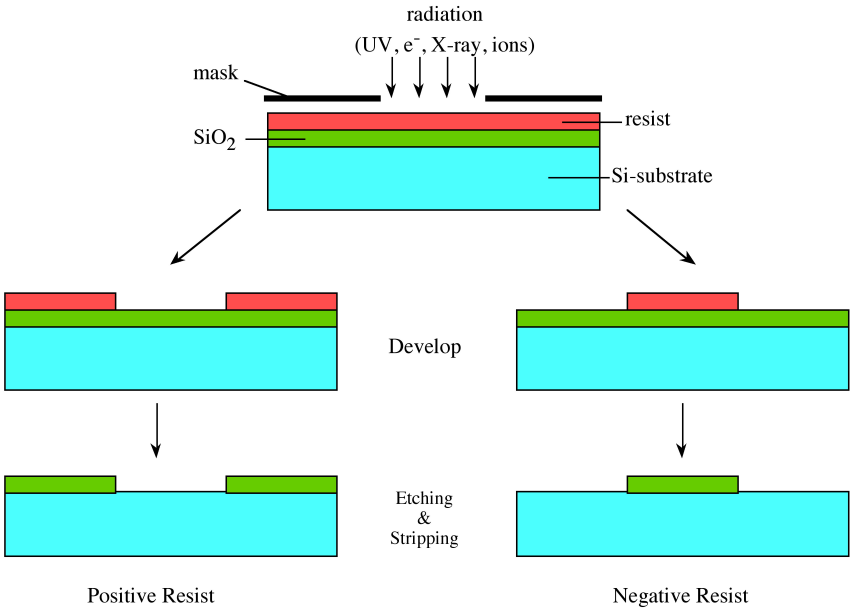


Figure 2: Schematic showing positive and negative photoresists.

Photoresists consist of three main components:

1. Synthetic resin: It determines the mechanical characteristics of the resist as a binding material.
2. Photo-active component (PAC): It reacts with the photons. This reaction depends on the energy of the photons, which explains the different sensitivity of the resist in relation to the wavelength. In a positive photoresist, the PAC initially stops the removal of the resist in the developer. After exposure, it reacts to produce chemicals that improve the solubility of the resist. In a negative photoresist, the PAC reacts upon exposure, such that the polymers in the binding material react making them insoluble in the developer.
3. Solvent: It keeps the resist in a fluid state.

EXPOSURE

In a lithographic exposure tool, there is a glass mask which is partially covered with chromium to partially expose areas of the resist.

Depending on the type of the resist, exposed areas become soluble or insoluble. With a wet-chemical developer, the soluble parts are removed (for a positive photoresist), so that a patterned resist layer remains. The exposure time is a very important value to achieve the correct dimensions of the structures. The longer the wafers are exposed to the radiation, the larger the radiated area is. Due to fluctuating ambient temperatures a precise determination of the correct exposure time has to be investigated with one or more dummy wafers, because the characteristics of the resist can change with temperature.

For a positive photoresist, an overexposure causes smaller resist patterns, and therefore smaller structures beneath, in contrast vias will be enlarged. With a too short exposure time, larger resist patterns will be formed and the vias may not be not opened correctly, conductors may be in contact to each other (short circuit).

For a negative photoresist, an overexposure means more area is hardened by the incoming radiation. This causes larger structures beneath, in contrast vias will be smaller than desired. With a too short exposure time, smaller resist patterns and enlarged vias will be formed.

The effects of over and under exposure for a positive photoresist are shown in figure 3.

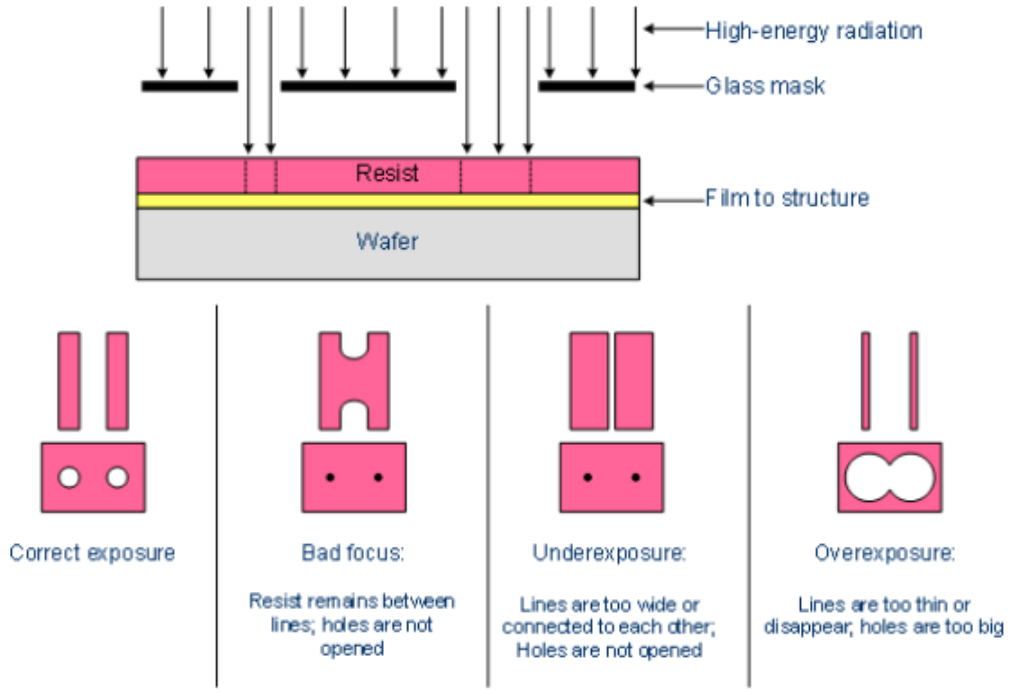


Figure 3: Effects of exposure time on resist patterns.

For a positive photoresist, the film thickness of the resist after the development depends on the exposure dose, as shown in figure 4. Below a threshold, the exposure has no effect on the resulting film thickness; above it, the film thickness falls linear according to the logarithm of the exposure dose. As soon as the resist is exposed to the maximum dose E_o it is completely exposed, any further increase of the dose has no effect. The variation in thickness $T(E)$ with exposure dose E is given by equation 1.

$$T(E) = T_o \gamma ln(\frac{E_o}{E})$$

The negative gradient γ is called contrast. The contrast depends on the used photo resist and its processing (duration and temperature of the pre-bake) as well as on the developer. It affects the exposed edges of the lithographically produced structures. Because of bending effects, the exposure dose does not fall abruptly at the edge of a structure. By using a resist with high contrast, one can produce vertical flanks. However, high contrast causes the whole process to become very sensitive to over-exposure and fluctuating process parameters.

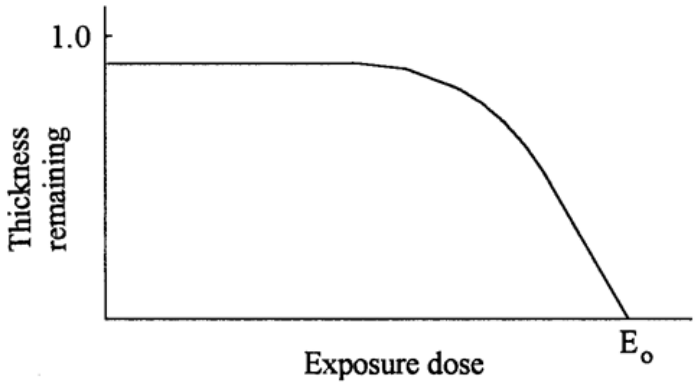


Figure 4: Effect of exposure dose on resist thickness.

4 EXPERIMENTAL WORK

1- Cutting

Using the diamond cutter, we cut microscopic glass slides into six pieces of glass of around 2.5cm x 2.5cm. The vernier caliper scale was set a few points smaller than 2.5 cm, to account for the uncertainty in cutting.

The glass slides were labelled using a diamond scribe pen, from number 1 to 6.

2- Substrate Cleaning

Next, we needed to clean the glass substrates from any particles or other impurities. First, the glass substrates were placed in a plastic sample holder. Then, they were placed in acetone for 10 minutes and dried thoroughly with nitrogen gas. Next, they are placed in isopropanol with 10 minutes and dried again with nitrogen gas.

To get rid of the last organic remnants and humidity on the surface, the samples are treated with an O2-Plasma for 2 minutes. This is done inside a plasma oven.

3- HMDS Deposition

The cleaned samples are placed again in the sample holder and then inside a desiccator. 60 μl of HMDS(hexamethyldisilazane) are put into a small beaker, which is also placed inside the desiccator. The desiccator is evacuated by a vacuum pump for 10 minutes. Then, the valves of the desiccator were closed, and the vacuum was kept for another 10 minutes so that the HMDS vapour is able to settle down on the sample surface, forming a mono-layer of molecules.

This HMDS layer increase the adhesion of photoresist to the sample. This is because the sample becomes hydrophobic, which helps the spin-coating process, so the photoresist can stick with the substrate.

Beyond this step, it is important to note that only one side of the samples should be used and the slides should not be flipped. Also HMDS is a toxic chemical and should treated with care.

4- Spin-coating

Spin-coating is a common method of applying the photoresist, which allows applying consistent coats between 0.1 μ m and 100 μ m. For this procedure, the photoresist used was AR-P 3120. The spin-coating curve given in the photoresist datasheet are given in figure 5.

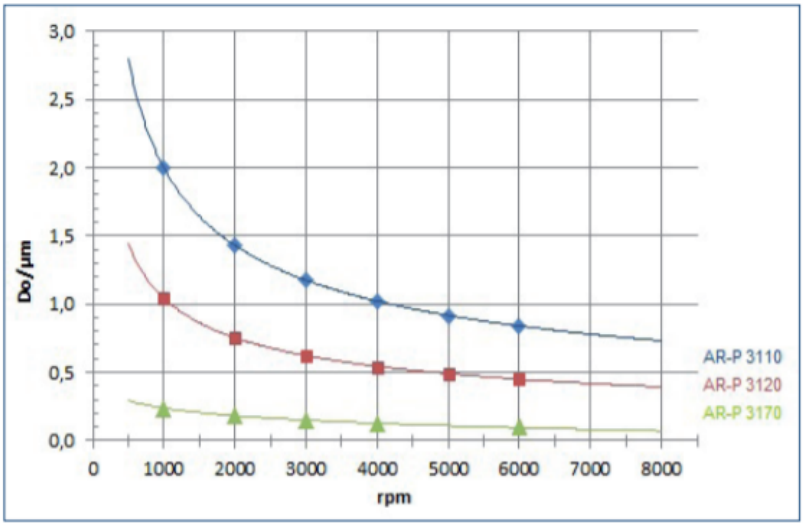


Figure 5: Spin-coating characteristics for the photoresist, AR-P 3120.

To coat our 2.5cm x 2.5cm samples homogeneously, we needed 180 μl of photoresist for each sample. The sample was placed on the metal chuck in the spin-coater. The photoresist amount was set on the pipette scale and the pipette was used to drop the photoresist onto the glass sample.

During this step, we had some difficulty using the pipette and dropping the photoresist onto the samples homogeneously. It is important that the photoresist is homogeneously dropped onto the sample, as the photoresist is viscous and does not spread well onto the sample otherwise.

Next, the spin-coater is started. According to the datasheet, 4000 rpm is needed for 60 seconds to obtain 550 nm thickness of photoresist. However, using a one step spin-coating process does not produce sufficient homogeneity, as the thickness of photoresist at the sample edges will be larger than the sample center. Thus, for this procedure, we used a two-step process for spin-coating; 800 rpm for 30 seconds and 2500 rpm for 30 seconds. The low speed distributes the photoresist onto the whole surface and the higher speed produces a more homogeneous photoresist surface.

5- Photoresist Pre-baking

In order to remove the remaining solvent of the photoresist and harden the photoresist, it is necessary to heat up the photoresist on a hot plate. According to the datasheet of the AR-P 3120, the pre-baking should be done at a temperature of 100C for 1 minute. It is important to lift all the samples quickly onto the hotplate so that they all experience the same time on the hotplate.

6- Sample Exposure

The exposure of the samples is conducted on the mask-adjusting and exposure device MJB3. This device uses a mercury lamp is used with wavelengths 350-500 nm and a power of 6.4 mW/cm^2. According to the datasheet of the photoresist, the exposure dose should be 65 mJ/cm^2, which means that the required time for exposure should be 10.1 seconds.

However, due to some modification in our lab device, the lamp power is higher than the aforementioned value (higher than 6.4 mW/cm^2) and thus, the correct exposure time is expected to be lower than the calculated time.

The MJB3 device provides contact exposure of the sample. First, the mask is placed

in the mask holder. The sample is then placed on the plate such that it is aligned to the mask, by observing it with the available microscope objective and moving the micrometer knob. It is important that the sample is not flipped, so that the correct side is facing the UV radiation. When the sample is in the correct orientation, the lever is pulled counterclockwise, till the "contact" sign lights up. It was also advised to manually check that contact is made between the sample and mask. Then, the timer is set to the desired exposure time and the device is started.

For our samples, we tested an exposure time of 1, 2, 3, 10, 11 and 20 seconds on the 6 glass samples, in order to see the effect of over- and underexposure.

7- Developing

For the development of the ARP-3120 photoresist layer, the developer AR-300-35 is used. It is an aqueous-alkaline solution which is mixed 5:1 with de-ionized water (5 parts developer with 1 part DI-Water). The samples are immersed for 60 seconds into the developer, then dried thoroughly using the nitrogen gas.

8- Observation

The developed samples are observed and their images recorded under a light microscope to check the success of the process.

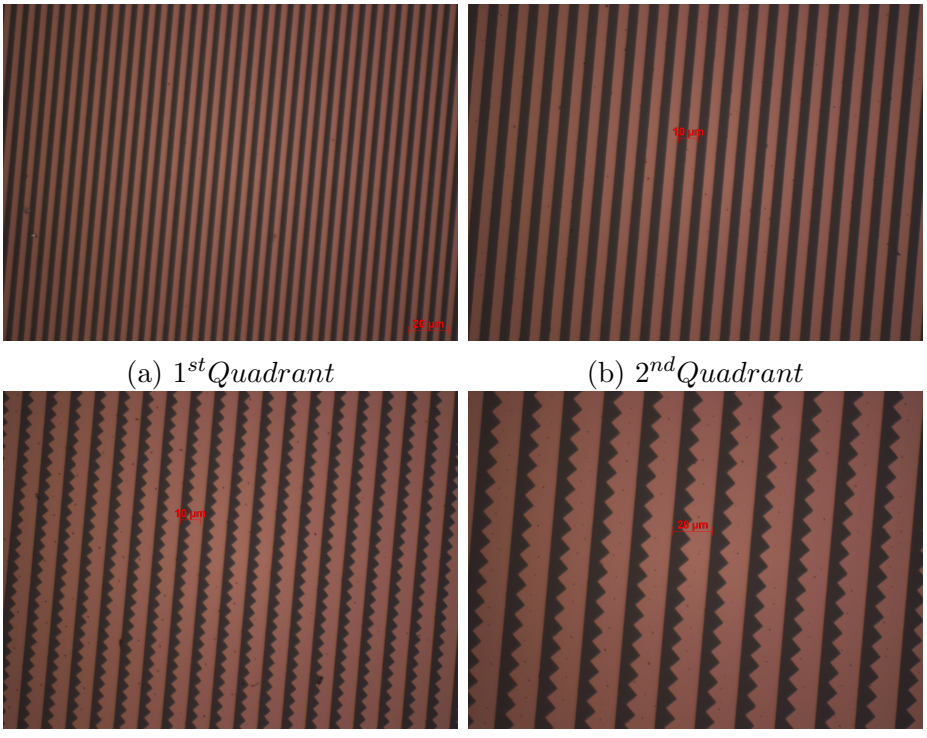
5 OBSERVATION AND ANALYSIS

The observation is divided into observation of mask patterns and dimensions, observation of the underexposed sample, observation of the correctly exposed sample and observation of the overexposed sample.

1. Observation of Mask Pattern

The mask pattern is divided into four patterns that were observed using a light microscope, as shown in figure 6.

The mask patterns were measured using the scale bar of the microscope image,



(a) $1^{st}Quadrant$ (b) $2^{nd}Quadrant$

(c) $3^{rd}Quadrant$ (d) $4^{th}Quadrant$

Figure 6: Mask patterns under the light microscope.

with a scale of: 20 μm = 181 pixels, and using MATLAB image processing toolbox. For the first and second quadrants, the width of the line (black) was measured. For the third and fourth quadrants, five measurements were taken to characterize the saw-tooth structure. M1 represents the width of the line at the saw-tooth maxima,

while M2 is the line width at the saw-tooth minima. M3 represents the width of the gap between the maxima of one line and boundary of the adjacent one, while M4 is the width of the gap measured from the minima of one line to the boundary of the adjacent one. M5 is the period of the saw-tooth structure, from one peak to the adjacent peak. These five measurements are labelled and shown in the annotated and magnified version of the third quadrant, shown in figure 7.

The dimensions of the mask structures will be compared with the dimensions of

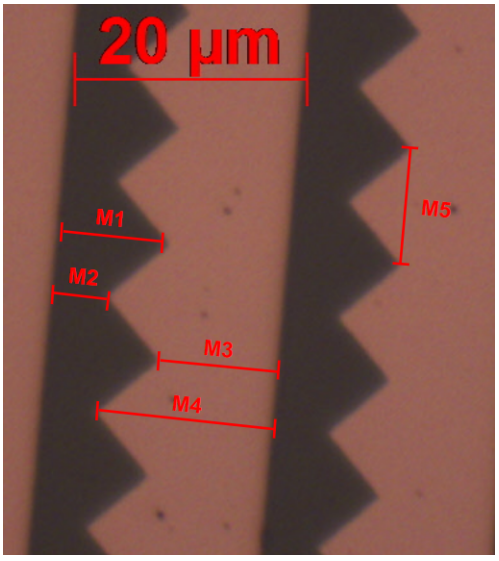


Figure 7: Third quadrant of the mask pattern, annotated to show five measurements taken.

the samples after exposure, to determine if the samples are under- or over-exposed. The dimensions of the mask structures are given below in table 2.

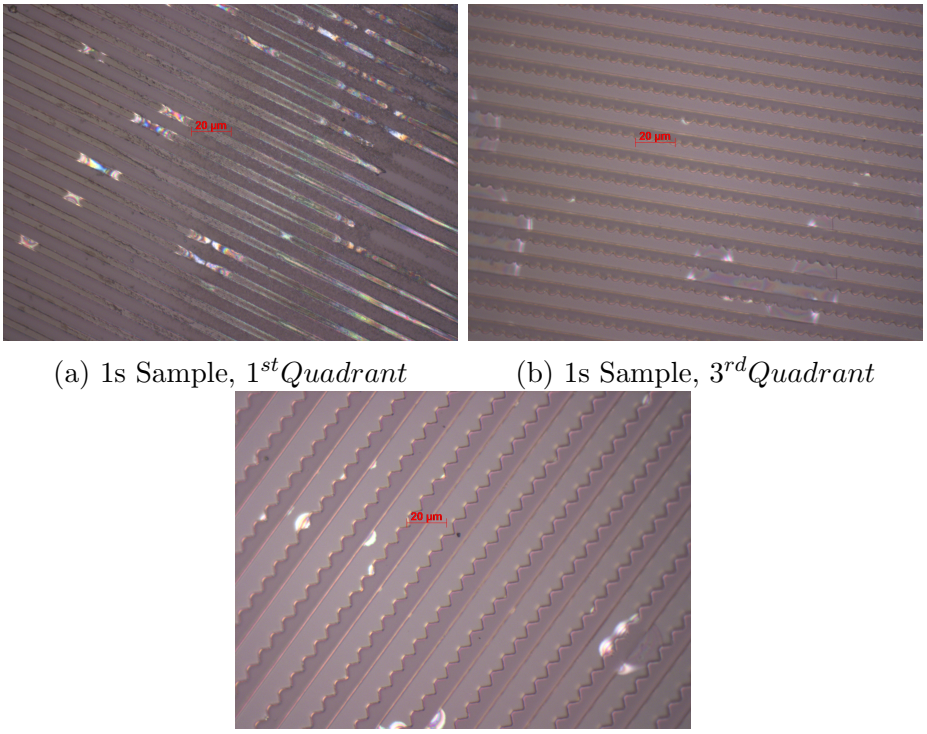
Table 2: Measured dimensions of mask structures

Mask Structures		
Measurement	$1^{st}Quadrant$	$2^{nd}Quadrant$
Line Width	2.5 μm	4.5 μm
Measurement	$3^{rd}Quadrant$	$4^{th}Quadrant$
M1	5.6 μm	9.5 μm
M2	2.8 μm	5.4 μm
M3	6.4 μm	10.5 μm
M4	9.3 μm	15.1 μm
M5	6.1 μm	10.0 μm

2. Observation of Sample 1

The first sample that was attempted was exposed to UV light for 1 second. The results are shown in figure 8.

As can be seen from figure 8, the patterns show some light diffraction and the



(a) 1s Sample, $1^{st}Quadrant$ (b) 1s Sample, $3^{rd}Quadrant$

(c) 1s Sample, $4^{th}Quadrant$

Figure 8: Patterns of sample exposed for 1 second under the light microscope.

2nd quadrant of the sample was lost due to improper spin-coating and insufficient photoresist. However, for the remaining three quadrants, we can compare the dimensions of the mask structures with the dimensions of the samples after exposure, to determine if the samples are under- or over-exposed. This comparison is given below in table 3.

As can be seen from table 3, from the first quadrant there is an increase in the line thickness of the sample exposed for 1 second. The measured thickness is 3.3 μm while the mask linewidth is 2.5 μm, showing a 32% increase.

For the third and fourth quadrant, there is an increase in the widths of the lines when measured from the peak or trough of the pattern, as shown in the measurements M1

Table 3: Comparing mask and sample (1) dimensions

Mask vs 1s Sample				
Measurement	$1^{st}Quadrant$		$2^{nd}Quadrant$	
Measurement	Mask	Sample 1	Mask	Sample 1
Line Width	2.5 μm	3.3 μm	4.5 μm	–
Measurement	$3^{rd}Quadrant$		$4^{th}Quadrant$	
Measurement	Mask	Sample 1	Mask	Sample 1
M1	5.6 μm	7.3 μm	9.5 μm	10.3 μm
M2	2.8 μm	5.6 μm	5.4 μm	6.8 μm
M3	6.4 μm	4.8 μm	10.5 μm	9.8 μm
M4	9.3 μm	11.9 μm	15.1 μm	13.5 μm
M5	6.1 μm	6.0 μm	10.0 μm	10.4 μm

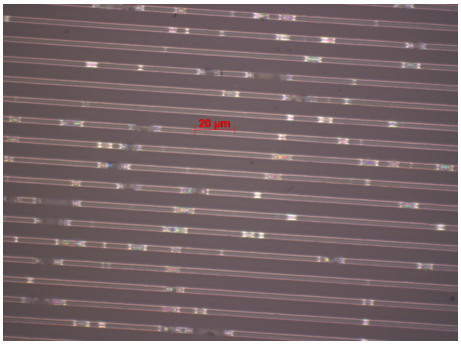
and M2. As for the gaps M3 and M4, as expected, these gaps become wider than the original value of the mask. Meanwhile, the periodicity of the structure is not much affected as the peak position is still well-defined.

From these measurements, we can conclude that Sample 1 was underexposed to the light. This means that the exposed regions, especially the regions at the edges, did not have sufficient time, thus the exposure dose was insufficient for the photoresist to react and become soluble in the developer. This means that the gaps, or areas where the photoresist should have been removed, are narrower than expected, as shown by measurements M3 and M4 in table 1. This also means that the resist patterns, which are the line widths of our structures are wider than the desired value of the mask. This is shown by the increase in dimensions in the first quadrant line width as well as measurements M1 and M2 in the third and fourth quadrants in table 3. Thus, the exposure time of 1 second was insufficient to produce this pattern correctly.

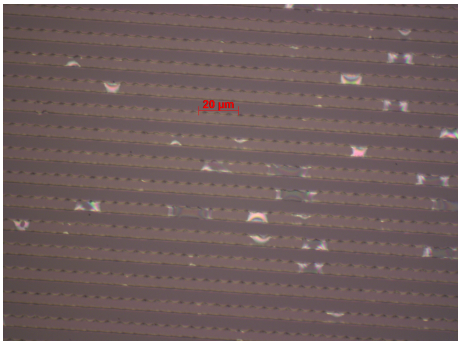
3. Observation of sample 2

The second sample was exposed to UV light for 3 seconds. The results are shown in figure 9.

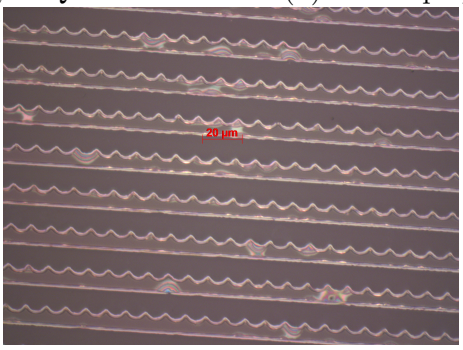
As can be seen from figure 9, the patterns show some light diffraction and once again, the 2nd quadrant of the sample was lost due to improper spin-coating and insufficient photoresist. However, for the remaining three quadrants, we can compare the dimensions of the mask structures with the dimensions of the samples after exposure, to determine if the samples are under- or over-exposed. This comparison



(a) 3s Sample, $1^{st}Quadrant$



(b) 3s Sample, $3^{rd}Quadrant$



(c) 3s Sample, $4^{th}Quadrant$

Figure 9: Patterns of 3 second sample under the light microscope.

is given below in table 4. As can be seen from table 4, in the first quadrant, there

Table 4: Comparing mask and sample (2) dimensions

Mask vs Sample 2				
Measurement	$1^{st}Quadrant$		$2^{nd}Quadrant$	
Measurement	Mask	Sample 2	Mask	Sample 2
Line Width	2.5 μm	2.6 μm	4.5 μm	–
Measurement	$3^{rd}Quadrant$		$4^{th}Quadrant$	
Measurement	Mask	Sample 2	Mask	Sample 2
M1	5.6 μm	5.7 μm	9.5 μm	9.4 μm
M2	2.8 μm	3.3 μm	5.4 μm	5.7 μm
M3	6.4 μm	6.3 μm	10.5 μm	10.5 μm
M4	9.3 μm	8.5 μm	15.1 μm	15.0 μm
M5	6.1 μm	5.9 μm	10.0 μm	10.1 μm

is a close match in the linewidth of the sample exposed for 3 seconds with the mask dimension. The measured thickness is 2.6μm while the mask linewidth is 2.5μm.

For the third and fourth quadrant, there is also a close match in measurements of line thicknesses and line gaps of the sample exposed for 3 seconds with the mask thickness, measured through M1, M2, M3, M4 and M5. There is a slight mismatch in values of M2 and M4 for the third quadrant, however, this might be due to insufficient photoresist during the spincoating process, causing worsened resolution later during development and making it harder to identify the position of the troughs, while the peaks are reasonably well-defined.

From these measurements, we can conclude that Sample 2 received almost the correct exposure dose of light, and thus was able to achieve a good match with the mask dimensions. This means that the exposed regions, especially the regions at the edges, had sufficient time, thus the exposure dose was sufficient for the photoresist to react and become soluble in the developer. This means that the gaps, or areas where the photoresist should have been removed, were also developed correctly. Thus, this sample was very close to the correct exposure time.

4. Observation of sample 3

The next sample that was attempted was exposed to UV light for 10 seconds. The results are shown in figure 10.

As can be seen from figure 10, the patterns show again some light diffraction due to

(a) 10s Sample, $2^{nd}Quadrant$ (b) 10s Sample, $4^{th}Quadrant$

Figure 10: Patterns of 10 second sample under the light microscope.

improper spin-coating and uneven photoresist coating. The two recognizable quadrants are the second and fourth quadrant, which have larger dimensions. Meanwhile, the first and third quadrants may have been too overexposed and thus fully removed and not visible properly.

Table 5: Comparing mask and sample (3) dimensions

Mask vs Sample 3				
Measurement	$1^{st}Quadrant$		$2^{nd}Quadrant$	
Measurement	Mask	Sample 3	Mask	Sample 3
Line Width	2.5 μm	0 μm	4.5 μm	1.55 μm
Measurement	$3^{rd}Quadrant$		$4^{th}Quadrant$	
Measurement	Mask	Sample 2	Mask	Sample 2
M1	5.6 μm	0 μm	9.5 μm	2.8 μm
M2	2.8 μm	0 μm	5.4 μm	1.8 μm
M3	6.4 μm	0 μm	10.5 μm	17.4 μm
M4	9.3 μm	0 μm	15.1 μm	18.4 μm
M5	6.1 μm	0 μm	10.0 μm	10.1 μm

As can be seen from table 5, in the second quadrant, there is a decrease in the line thickness of the sample exposed for 10 seconds compared with the mask dimensions. This is a sharp decrease of about 70%, as the measured thickness is 2.8 μm while the mask line width is 9.5 μm. For the fourth quadrant, there is a decrease in the widths of the lines when measured from the peak or trough of the pattern, as shown in the measurements M1 and M2. As for the gaps M3 and M4, as expected, these gaps become wider than the original value of the mask. Moreover, some lines have gaps, or regions where the photoresist has completely disappeared. Meanwhile, the periodicity of the structure is not much affected as the peak position is still well-defined.

From these measurements, we can conclude that Sample 3 was overexposed to the light. This means that the exposed regions, especially the regions at the edges, were exposed for too long, giving them too much exposure dose. Thus, too much of the photoresist reacted under the UV light and became soluble and removable in the developer. This means that the gaps, or areas where the photoresist should have been removed, are wider than expected, as shown by measurements M3 and M4 in table 5. This also means that the resist patterns, which are the line widths of our structures are narrower than the desired value of the mask. This is shown by the decrease in dimensions in the second quadrant line width as well as measurements M1 and M2 in the fourth quadrants in table 5. Thus, the exposure time of 10 seconds was too much time and produced incorrect pattern dimensions.

6 CONCLUSION

In conclusion, during this lab, we were able to complete the optical lithography process in a clean room setting, to investigate the effects of exposure time on sample dimensions and to recognize overexposed and underexposed samples.

The lab steps involved cutting of the substrates, cleaning the substrates, improving their adhesion properties by HMDS coating, then applying the photoresist by a spin-coating process. The spin-coating process was a challenging part of the experiment, as we had some difficulty achieving a uniform photoresist coating. Following the spin coating, we performed the prebaking, exposure and development processes. We also learned how to use the mask aligner and exposure device and how to take microscope measurements.

Based on the exposure time, each sample was given a certain exposure dose. If the exposure time and exposure dose are less than the required value for the photoresist, the sample is underexposed. Thus, the line widths are narrower and gaps are wider than the mask dimensions. If the exposure time and exposure dose are higher than the required value for the photoresist, the sample is overexposed. Thus, the line widths are wider and gaps are narrower than the mask dimensions.