

Photolithography II: Pattern Transfer

Kevin Huang, Alison Shull, Monica Plisch

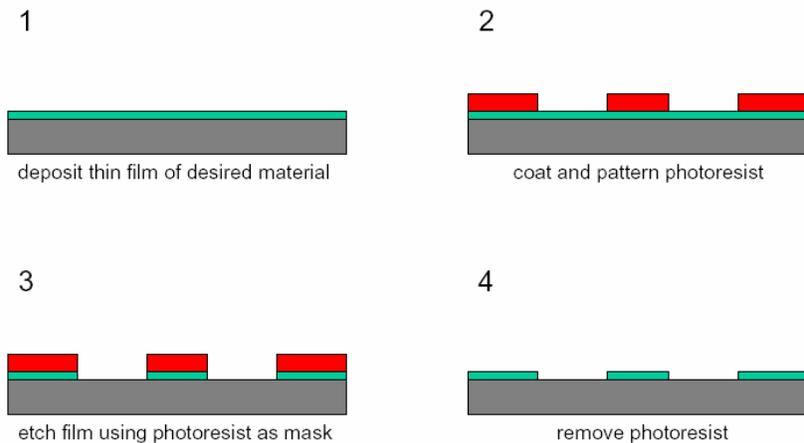
I. Introduction

In this lab you will fabricate and test four Al resistors using the mask you made in the previous lab. You will learn about and use basic photolithographic techniques for patterning thin metallic films. The rest of the Introduction section gives background information on these techniques. The section below on “Patterning metallic films” discusses two overall strategies for patterning films and the following sections discuss individual steps in the process in more detail.

Overview of Patterning Thin Films

In general, there are a few different ways to pattern thin films on surfaces, including “etch-back” and “lift-off” techniques. In the etch-back method, a thin film is deposited on the wafer. Then the thin film is coated with a layer of photoresist, which is subsequently patterned. Various acids or etchants are used to remove areas of the thin film that are not protected by photoresist. Finally, the remaining photoresist is stripped leaving behind the patterned thin film.

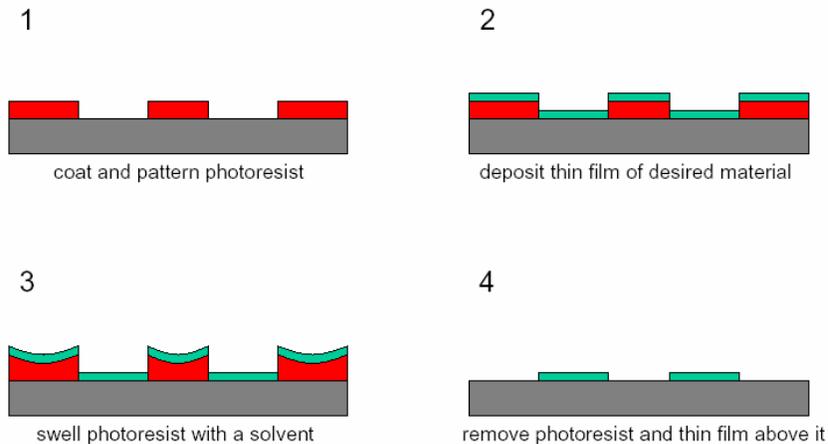
Etch-back



In the lift-off method of patterning thin films, the first step is to apply a layer of photoresist on the substrate. Then the photoresist is exposed and developed in the desired pattern. Next, a thin film is deposited uniformly over the entire sample, on top of photoresist where present and on top of the wafer where photoresist has been removed. Finally, a photoresist stripper is used to lift off the remaining photoresist along with the thin film on top of it leaving behind only the thin film attached directly to the wafer.

A challenge with the lift-off process is ensuring a clean break between the thin film on the wafer and the thin film on the photoresist. In some cases, a solvent is applied to swell the photoresist and break any connections. In other cases, the photoresist patterning process is designed to create an undercut at the edges, preventing connections from forming during thin film deposition.

Lift-off



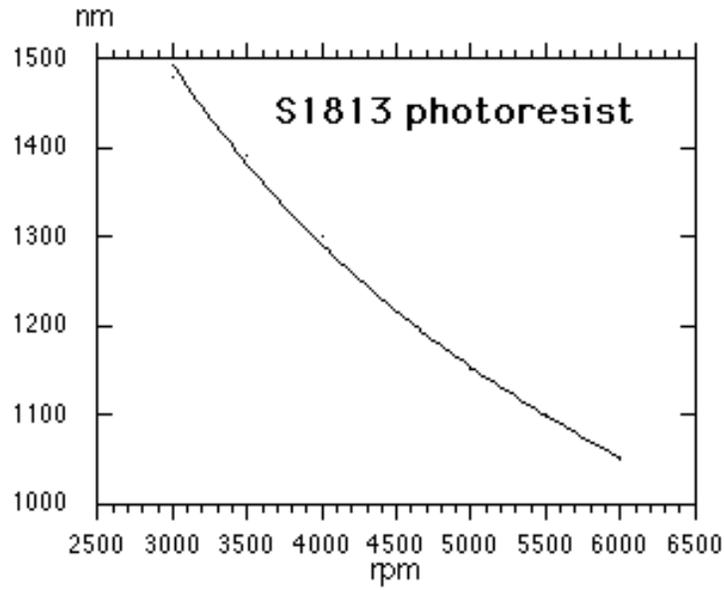
Prime Surface

The sample is prepared for the photoresist with a primer, which promotes adhesion of the photoresist to the surface. The primer forms bonds with the substrate and produces a polar (electrostatic) surface to which the photoresist can adhere more easily. You will use P20 primer in the lab.

Spin Photoresist

The photoresist is applied to a surface through a process known as spin coating. This is done in a high-speed centrifuge and produces a very thin (1—2 μm), uniform layer of the photoresist on the wafer. Artifacts such as a thick ring of resist at the edge of the wafer or streaks across the resist result from large, solid particles and contaminants remaining on the wafer's surface.

Below is a spin curve for the Shipley 1813 photoresist you will use in the lab. Thickness of the photoresist in nanometers is plotted as a function of the spin speed in rotations per minute. In general, the thickness of the photoresist is not dependent on the length of time the wafer is spun beyond some initial time period.



Bake

The pre-exposure bake or “soft bake” is a critical step in which nearly all solvents are removed from the layer of resist and it is made photosensitive in anticipation of the light exposure. Photoresist is composed of three parts, a polymer matrix or resin, a solvent that controls viscosity, and a photoactive compound. Baking drives off the solvent and establishes the exposure characteristics of the photoresist. Over-baking degrades the photosensitivity of the resist by reducing the developer solubility or destroying the parts of the sensitizer. Under-baked positive resists will be attacked by the developer in both the exposed and non-exposed areas of the resist, decreasing the precision of the photolithographic process. Typically, the resist thickness is decreased by 25% during the soft bake.

After exposure and development, and before processing the exposed thin film, the photoresist is sometimes baked a second time in what is called a “hard bake.” The purpose of the hard bake is to further harden the photoresist and improve its adhesion to the surface. This step will not be needed in our process.

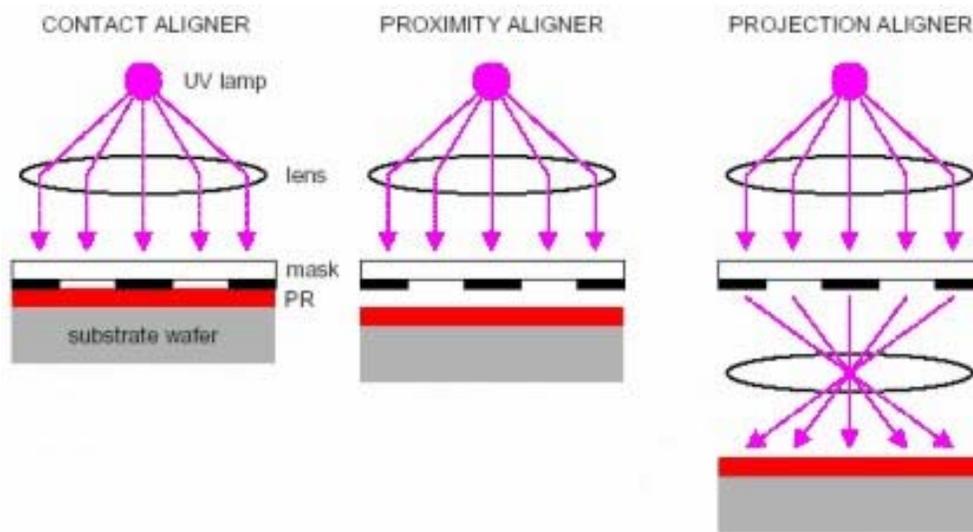
Expose

During exposure, a controlled dose of parallel light is shone on the wafer, typically by a mask aligner. The aligner also holds the mask and allows the user to position it relative to the wafer (important for processes involving more than one layer). Typically, photoresist is only sensitive to the total energy it receives, not the time over which the exposure occurs. For the Shipley 1813 photoresist you will use, the optimum dose for exposure is 150mJ/cm².

During exposure, in the case of a positive photoresist, the UV light breaks chemical bonds causing the long-chain polymers to become shorter and thus more soluble. In the case of a negative resist, UV light cross-links polymer chains causing the exposed resist

to become less soluble. The change in solubility allows the resist to be selectively removed, as described in the following development step.

Three different methods exist for exposing a wafer through a mask: contact, proximity, and projection (see diagram below). In contact printing, the mask is brought in direct contact with the resist-covered wafer. The wafer is positioned on a vacuum chuck that is slowly raised until it contacts the mask. Then UV light is applied on the assembly. While high resolution is possible with contact exposure, there exists the possibility of debris being caught between the mask and the wafer, causing serious defects in the pattern and damage to the mask.



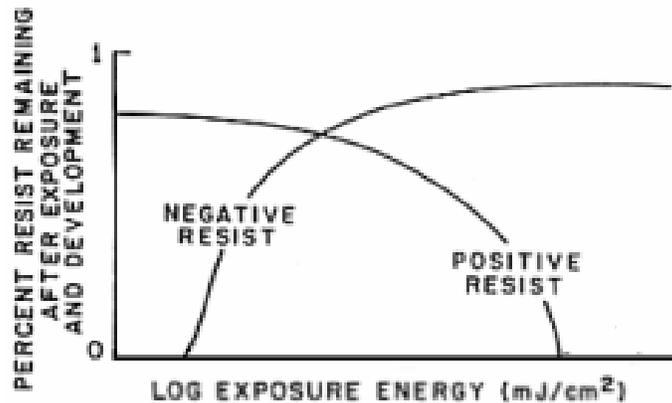
Proximity printing is very similar to contact; in proximity, however, there is a small 10-25 micron gap between the mask and the resist. This minimizes, but does not completely eliminate, the occurrences of defects. A resolution of about 2—4 μm is possible, limited by diffraction.

To entirely avoid damage caused by the mask and foreign contaminants, projection printing can be used. In projection printing, the mask image is projected onto the wafer which can be many centimeters away. Projection printing also has the advantage that the size of the image projected onto the wafer can be reduced using lenses; an image 5 or 10 times smaller than the mask can be achieved. Systems that can scan or step the mask image over the surface of a wafer can achieve resolutions well below 1 μm .

Develop

In the development stage, the soluble photoresist is chemically washed away. The schematic below shows the amount of photoresist remaining after development as a function of exposure energy. At low exposure energies, the negative resist will still be relatively soluble in the developer. As energy increases, more and more will remain as the negative resist becomes more insoluble in the developer. Alternatively, for positive

resists, solubility in developer is finite even without exposure. As exposure energy increases, a point is reached in which all of the resist becomes very soluble and none of the resist remains after using the developer. For properly exposed photoresist, the “soluble” areas will be ~100 times more soluble than the “insoluble” areas. You will use AZ developer to develop your pattern.



Etch

You will use a wet chemical etch to remove the metal film in all areas that are not protected by photoresist. This type of etching involves submerging the wafer in an acidic solution (in the case of this lab “Al Etchant Type A”). Wet chemical etches are generally isotropic, meaning that they remove material at the same rate in all directions.

Strip Photoresist

To remove the remaining unexposed photoresist, a variety of solvents may be applied to the photoresist. For positive resists, such solvents include trichloroethylene and acetone. If the photoresist has received a hard bake after development, the remaining resist will be more difficult to remove and the solvents listed above will not be effective. After photoresist is stripped from the wafer, the photolithography step is completed.

References

Some of the figures and text in the Introduction were accessed at the following sites:

<http://www.ece.gatech.edu/research/labs/vc/theory/photolith.html>

<http://www.ee.washington.edu/research/microtech/cam/PROCESSES/PDF%20FILES/Photolithography.pdf>

<http://fy.chalmers.se/assp/sn1/public/resists/s1813.html>

II. Procedure

General Notes

To protect yourself from chemical exposure, take the following precautions:

- Wear long pants and shoes that entirely cover your feet.
- Always work at a hood when using chemicals.
- Wear chemical splash goggles, an apron, and gloves whenever handling chemicals.
- Notify TA of spills immediately.

To protect your chip from getting contaminated by the environment (mainly from you):

- Always handle your chip with wafer tweezers, not your hands.
- Always wear nitrile gloves when handling your chip.
- Whenever possible, place your chip inside a wafer carrier with patterned side down.

A. Steps for Pattern Transfer

1. Clean wafer (chemical hood)
 - a. If needed, switch on power to spinner and mechanical pump.
 - b. Center silicon chip on spinner chuck and press “Vacuum” button.
 - c. Set “Timer I” to 0 s and “Timer II” to 30 s. Place acetone and isopropyl alcohol bottles near the spinner. Press “Start.”
 - d. While chip is spinning, spray it first with acetone for a few seconds, then isopropyl alcohol (IPA) for a few seconds, beginning IPA before ending acetone.
 - e. Adjust spin speed to 3000 r.p.m. using “Speed II” dial if necessary.
2. Spin primer (chemical hood)
 - a. Set “Timer II” to 10 s.
 - b. Using the pipette, draw primer from the bottle marked “P20 primer.”
 - c. Dispense a few drops of primer in the center of the chip. Let rest for 10 seconds.
 - d. Press “Start” and wait until spinner is done. Put remaining primer back in bottle.
3. Spin photoresist (chemical hood)
 - a. Set “Timer II” to 30 s.
 - b. Using the plastic pipette for photoresist, draw it from the “Shipley 1813” bottle.
 - c. Drop photoresist in the center of the chip forming a nickel-sized spot.
 - d. Press “Start” and wait until spinner is done.
 - e. Press “Vacuum” to turn vacuum off, remove chip and place in carrier.
4. Bake in oven
 - a. Check that temperature of oven is 110—115°C.
 - b. Place chip on Al block in oven. Start timer.
 - c. After 120 seconds, remove chip from oven.
5. UV exposure through mask
 - a. With scissors cut out mask and discard rest of transparency.
 - b. Place chip onto stack of three clear plastic plates.
 - c. Place mask in desired orientation on the chip with ink side down.

- d. Place quartz plate on top of chip and mask.
 - e. Place UV lamp onto the stack making sure light source is centered above the chip.
 - f. Turn on UV lamp (power button) and expose for 60 seconds.
6. Develop (chemical hood)
 - a. Remove cover plate from developer dish.
 - b. Put chip in small Pyrex dish marked "AZ developer."
 - c. Let develop for approximately 1 minute. Developer should be clear at the end, with no more red photoresist coming off of the chip.
 - d. Remove chip and place in Pyrex dish of deionized (DI) water.
 - e. When removing chip from DI water, spray with DI water and compressed air dry.
 - f. Replace cover plate on developer dish
 7. Al etch-back (chemical hood)
 - a. Put chip in small Pyrex dish and cover with "Al etchant Type A."
 - b. When darker Si wafer is visible and etched surfaces appear uniform, etching is complete.
 - c. Remove chip, rinse in Pyrex dish of DI water for at least 10 s.
 - d. When removing chip from DI water, spray with DI water and compressed air dry.
 8. Strip remaining photoresist (chemical hood)
 - a. Center silicon chip on spinner chuck and press "Vacuum" button.
 - b. Set "Timer I" to 0 s and "Timer II" to 30 s. Place acetone and isopropyl alcohol bottles near the spinner. Press "Start."
 - c. While chip is spinning, spray it first with acetone for several seconds, then isopropyl alcohol (IPA) for a few seconds, beginning IPA before ending acetone.
 - d. Press "Vacuum" to turn vacuum off, remove chip and place in carrier.

B. Resistor Characterization

1. Electrical characterization
 - a. Place one probe of a handheld multimeter on each contact pad of a resistor. Be careful not to scratch your resistor!
 - b. Measure and record the resistance for each of your resistors.
2. Optical inspection
 - a. Use 10X scaled loupes and optical microscope as needed to inspect your resistors.
 - b. Measure and record the lengths and widths of all your resistors as accurately as possible. Be sure to use an appropriate number of significant digits.
 - c. Record any defects (holes, ragged edges, breaks, etc.).

III. Analysis

1. Did you use an etch-back or a lift-off process in fabricating your resistors? Justify your answer.
2. Given a spin speed of 3000 r.p.m., what should be the thickness of the Shipley 1813 photoresist? How thick would the photoresist be if you spun it twice as fast (6000 r.p.m.)? What is the percentage change in thickness between the two speeds?
3. What type of exposure did you use (contact, proximity, projection)? Is it possible to reduce your mask pattern with this type of exposure? Which type(s) of exposure allow you to reduce a pattern?
4. Draw a cross-section diagram of your chip showing what would happen if you left it in the Al etchant for too long (i.e. “overetch” the Al film)? Do you expect overetching to significantly affect your results in this case? Why or why not?
5. Make a chart with the following columns for all four resistors: target resistance, measured resistance, target width, measured width, target length, measured length, target thickness and measured thickness (from crystal monitor reading in previous lab). Be sure to use an appropriate number of significant figures.
6. For each resistor, calculate the expected resistance based on its measured width, length and thickness. Can the observed deviations in length, width and thickness from their target values account for the deviation of resistance you observed? Explain.
7. Given $R = \rho l/A$, is there an additional quantity besides thickness, width and length that may be responsible for the deviation of resistance values from their targets? Explain.
8. Calculate the resistivity of each resistor, given its measured dimensions and resistance. Average your results to come up with a value for the resistivity of the evaporated Al film. Use the standard deviation to derive an uncertainty value.
9. How does your calculated resistivity from question 8 compare to the bulk resistivity of Al, $2.65 \times 10^{-8} \Omega\text{m}$? If it is significantly different (i.e. the bulk resistivity does not lie within the uncertainty range of your measured value), can you explain what might have happened to change the resistivity of the Al?
10. What factor (width, thickness, length or resistivity) caused the largest deviation of resistance from target values? If you were to fabricate another set of resistors, describe what you would do differently to make the resistance values more accurate.