Photolithography

Organization: Lawrence Hall of Science, University of California, Berkeley
Contact person: Rashmi Nanjundaswamy
Contact information: rashmin@berkeley.edu, 510-642-7441

General Description

Type of program:

Facilitated activity, classroom activity

This activity is designed for high school students. In this experiment students use light to transfer a pattern onto a surface, either a network of very small metal wires or self-drawn patterns on a plastic board. The pattern is transferred by placing a mask (transparency sheet with the pattern) on a plastic board. The board is coated with a copper film that is covered with a light-reactive polymer (photo-resist). The polymer is exposed to UV light through the mask to make a pattern in the polymer. The metal under the exposed polymer is then chemically etched, leaving only the pattern on the surface of the board as determined by the mask. This top-down approach to nanotechnology is commonly used in manufacturing circuit boards for computers and other electronics.

Program Objectives

Big idea:

Demonstrate the top-down approach to fabrication of nanometer sized electronic components commonly used in manufacturing circuit boards for computers and other electronics and teach the basic chemistry and physics necessary for photolithography.

Learning goals:

As a result of participating in this program, students will be able to:

1. Understand what lithography is and become familiar with different types of lithography.
2. Get a conceptual understanding of photolithography, and understand the Physics and Chemistry behind it.
3. Draw a simple pattern for a mask, and transfer it onto a plastic board covered with copper and a thin film of photo resist.
4. Etch the unwanted copper away to result in the pattern in copper.

NISE Network content map main ideas:

[x] 1. Nanometer-sized things are very small, and often behave differently than larger things do.

[ ] 2. Scientists and engineers have formed the interdisciplinary field of nanotechnology by investigating properties and manipulating matter at the nanoscale.

[x] 3. Nanoscience, nanotechnology, and nanoengineering lead to new knowledge and innovations that weren't possible before.

[ ] 4. Nanotechnologies have costs, risks, and benefits that affect our lives in ways we cannot always predict.

National Science Education Standards:

[ ] 1. Science as Inquiry
- [ ] K-4: Abilities necessary to do scientific inquiry
- [ ] K-4: Understanding about scientific inquiry
- [ ] 5-8: Abilities necessary to do scientific inquiry
- [ ] 5-8: Understanding about scientific inquiry
- [x] 9-12: Abilities necessary to do scientific inquiry
- [ ] 9-12: Understanding about scientific inquiry

[ ] 2. Physical Science
- [ ] K-4: Properties of objects and materials
- [ ] K-4: Position and motion of objects
- [ ] K-4: Light, heat, electricity, and magnetism
- [ ] 5-8: Properties and changes of properties in matter
- [ ] 5-8: Motions and forces
- [ ] 5-8: Transfer of energy
- [ ] 9-12: Structure of atoms
- [ ] 9-12: Structure and properties of matter
- [x] 9-12: Chemical reactions
- [ ] 9-12: Motions and force
- [ ] 9-12: Conservation of energy and increase in disorder
- [x] 9-12: Interactions of energy and matter

[ ] 3. Life Science
- [ ] K-4: Characteristics of organisms
- [ ] K-4: Life cycles of organisms
- [ ] K-4: Organisms and environments
- [ ] 5-8: Structure and function in living systems
- [ ] 5-8: Reproduction and heredity
- [ ] 5-8: Regulation and behavior
- [ ] 5-8: Populations and ecosystems
- [ ] 5-8: Diversity and adaptations of organisms

- [ ] 9-12: The cell
- [ ] 9-12: Molecular basis of heredity
- [ ] 9-12: Biological evolution
- [ ] 9-12: Interdependence of organisms
- [ ] 9-12: Matter, energy, and organization in living systems
- [ ] 9-12: Behavior of organisms

[ ] 4. Earth and Space Science

- [ ] K-4: Properties of earth materials
- [ ] K-4: Objects in the sky
- [ ] K-4: Changes in earth and sky
- [ ] 5-8: Structure of the earth system
- [ ] 5-8: Earth's history
- [ ] 5-8: Earth in the solar system
- [ ] 9-12: Energy in the earth system
- [ ] 9-12: Geochemical cycles
- [ ] 9-12: Origin and evolution of the earth system
- [ ] 9-12: Origin and evolution of the universe

[ ] 5. Science and Technology

- [ ] K-4: Abilities to distinguish between natural objects and objects made by humans
- [ ] K-4: Abilities of technological design
- [ ] K-4: Understanding about science and technology
- [ ] 5-8: Abilities of technological design
- [ ] 5-8: Understanding about science and technology
- [x] 9-12: Abilities of technological design
- [x] 9-12: Understanding about science and technology

[ ] 6. Personal and Social Perspectives

- [ ] K-4: Personal health
- [ ] K-4: Characteristics and changes in populations
- [ ] K-4: Types of resources
- [ ] K-4: Changes in environments
- [ ] K-4: Science and technology in local challenges
- [ ] 5-8: Personal health
- [ ] 5-8: Populations, resources, and environments
- [ ] 5-8: Natural hazards
- [ ] 5-8: Risks and benefits
- [ ] 5-8: Science and technology in society
- [ ] 9-12: Personal and community health
- [ ] 9-12: Population growth
- [ ] 9-12: Natural resources
- [ ] 9-12: Environmental quality
- [ ] 9-12: Natural and human-induced hazards
- [ ] 9-12: Science and technology in local, national, and global challenges

[ ] 7. History and Nature of Science

[ ] K-4: Science as a human endeavor
[ ] 5-8: Science as a human endeavor
[ ] 5-8: Nature of science
[ ] 5-8: History of science
[ ] 9-12: Science as a human endeavor
[ ] 9-12: Nature of scientific knowledge
[ ] 9-12: Historical perspective

Table of Contents

Time Required

Set-up	Program	Clean Up
2 hours (Can be done previous day)	2 hours	1 Hour

Background Information

Definition of terms

Nano is the scientific term meaning one-billionth (1/1,000,000,000). It comes from a Greek word meaning "dwarf."

A nanometer is one one-billionth of a meter. One inch equals 25.4 million nanometers. A sheet of paper is about 100,000 nanometers thick. A human hair measures roughly 50,000 to 100,000 nanometers across. Your fingernails grow one nanometer every second.

(Other units can also be divided by one billion. A single blink of an eye is about one-billionth of a year. An eyeblink is to a year what a nanometer is to a yardstick.)

Nanoscale refers to measurements of 1-100 nanometers. A virus is about 70 nm long. A cell membrane is about 9 nm thick. Ten hydrogen atoms are about 1 nm.

At the nanoscale, many common materials exhibit unusual properties, such as remarkably lower resistance to electricity, or faster chemical reactions.

Nanotechnology is the manipulation of material at the nanoscale to take advantage of these properties. This often means working with individual molecules.

Nanoscience, nanoengineering and other such terms refer to those activities applied to the nanoscale. "Nano," by itself, is often used as short-hand to refer to any or all of these activities.

Materials

Reusable:
UV exposure station, consisting of 2 UV lamps (black lights)
Black cloth or big basket to cover the UV lamps.
Applicator sticks of Photoresist Stripper
Large Beakers (plastic and glass, 500 to 750 ml)
Small Beakers (150-250ml)

Glass Slides
Tweezers
Photomasks (electrode pattern on transparency)
Permanent Marker
250 mL Glass Beakers
Watch Glass (Beaker Cover)
Heat resistant gloves
Stopwatch timer
Digital Multimeter

Consumables:
Photoresist Developer (Solid or solution can be bought, solution available at http://www.mgchemicals.com/products/4170.html and solid from Mega in UK http://www.megauk.com/pcb_chemicals.php)
1 - Box of gloves (size Small)
1 - Box of gloves (size Medium)
1 - Box of gloves (size Large)
Etching Powder (Ferric Chloride) [Etchant stations with hotplates and etching liquid]: Premade solution http://www.mgchemicals.com/products/415.html or Ferric Chloride in solid form: Iron(III) chloride hexahydrate, 97%, 236489 -ACS reagent, Sigma Aldrich)
Neutralizing Powder (Baking Soda, $NaHCO_3$)
Bag of Concrete (for disposal)
Photoresist-coated boards (http://www.mgchemicals.com/products/600.html; they have large photo resist covered boards that you can get cut to size, 1.5" square is a good size)
Boiling Chips

Each student should have:
1 Circuit board
1 photomask
1 pair of gloves
1 pair of tweezers

Set Up

Time:
You will need 2 hrs the day of or the day before the activity.

Masks: Please make sure that all the materials have been ordered ahead of time (in some cases it takes about 3-4 weeks for the chemicals to be delivered). The Masks need to be printed ahead of time too. Mylar or transparency masks are a very inexpensive, quick-turnaround alternative to conventional Cr masks, for defining non-critical features.
Using a 3600 or better, photo-reproduction quality laser printer, you can generate a transparency with geometries defined down to the tens of microns in resolution.
<u>Here are a couple of print shops which can provide this service</u>.

1. ArtnetPro, San Jose, CA. Phone: 408-954-8383

EPS and Illustrator files are accepted. Output printer is up to 3800 dpi, depending on the data received. Quality Kodak film is used. A typical single mask printout will be $15-$20.

2. CAD/ART Services, Bandon, OR. Phone: 541-347-5315. Output is up to 20,000 dpi and you can FTP data to their server.
3. Infinite Graphics, Minneapolis, MN, offers film plotting to 50,000 dpi.

Sometimes the company might ask for files in the *.gbr format instead of *.eps (Artnet Pro requires in the *.gbr or you can pay them to convert eps to gbr which costs $95.00 per sheet). Some of our mask patterns in the gbr as well as pdf versions are attached in supplemental documents.

Setting Up: Before the students arrive, have the various stations: UV station, developing station, etching station and photo resist stripping station ready. The UV station is the same for all students. For the developer, etchant and photo-resist strip, about 3-4 students can be accommodated at each station without too much time being spent in taking turns.

Arrange the following at each station: Students will be using these stations in the order described.

1. UV station: This is for exposing the photo-resist covered plastic board to the pattern on the mask using UV (black light). (See photo for setup guidelines)
    - 2 UV lamps
    - Alignment sheet
    - Glass slides (cleaned and having no finger prints or dirt on them)
    - Black cloth or a big container that can cover the lamps
    - 4 large plastic beakers to serve as stands for the lamp
    - Stop watch timer
2. Developer station: You can have this set up in corner of the room or alternatively bring it to the students at their stations.
    - Developer solution in small beakers (if using solid, make solution ahead of time using instructions on bottle)
    - Tweezers to hold the pcb's.
    - Plastic beakers filled with water for rinsing
    - Stop watch timer
3. Etchant station: This station will have to be in a fume hood, the etchant beakers will be on the hot plates boiling at 80C-90C .
    - Add 125 g of etching powder to 4 Oz of water (118.5 ml) in a 250 mL glass beaker. Distilled water is better, but you can add bottled water too. Add some of the boiling chips, place the beaker on the hot plate, and turn the hot plate up to the highest setting. Cover the beaker with a watch glass to prevent rapid evaporation. At the time of etching the liquid should be bubbling gently and be over 80^{o}C.

- Heat resistant tweezers
- Plastic beakers with water
- Heat resistant gloves (in case you need to handle the beaker)
- Stop watch timer

4. Photo-resist strip station: This can be set up anywhere; you can do it at the independent student stations too.
    - Applicator sticks of Photo-resist Stripper
    - Gloves
    - Plastic beakers with water for rinsing

Program Delivery

Time:

2 Hours

Safety

Even though the chemicals used in this experiment contain very low hazardous content, the nature of all chemicals can be hazardous to some extent (i.e. corrosive, irritant, etc.). It is advised to use protective clothing, gloves and goggles. For the utmost safety, any chemicals that come into contact with skin should be immediately and thoroughly rinsed with water.

- Wear gloves, clothing protection, and eye protection throughout the experiment.
- The etchant will stain clothes and temporarily turn skin yellow. Take proper precautions.
- Make sure to add boiling chips to the etchant solution before heating.
- Cleaning up the etchant solution: If you will be doing this experiment again, the etchant can be stored in a leak-proof container.
  If you are ready to dispose of the etchant: see clean up section.

Talking points and procedure: Before nanotechnology, microtechnology (1 micron = 10^{-6}m), dominated the electronics industry (thus the term 'micro chip'). One of the main goals in the silicon chip industry has always been to increase the speed and performance of their chips. The path to smaller (and thus faster) chips has been evolving at an extraordinary rate.

Today Nanotechnology is used in the chip industry on a daily basis. Two different approaches are used in the nano manufacturing industry. The first "bottom up" method builds a structure atom by atom or molecule by molecule, much like building a wall by stacking bricks. The second "top down" method involves cutting down a bulk material to the appropriate size, much as a sculptor would carve a statue out of a large block of marble. This top-down approach to nanotechnology is commonly used in manufacturing circuit boards for computers and other electronics.
Though because of the small feature size in the chip industry (a few nanometers), light cannot be used and they rely on electron-beam lithography, in this experiment, the students will be exposed to its bigger counterpart: photo-lithography. The reason is photo-lithography cannot be used to make features smaller than the wavelength of light (with the smallest being UV around 350nm). For smaller features, x-rays (or e- beams) have to be used. In this experiment

students use light to transfer a pattern onto a surface (either resulting in a network of very small metal wires on a plastic board or any self- drawn pattern) using a top down process. The pattern is transferred by placing a mask with the wanted design on a plastic board. The board is coated with a copper film that is covered with a light-reactive polymer (photo-resist). The circuit boards used here come with a ready-made layer of hardened photoresist under the black tape. The polymer is exposed to UV light through the mask to make a pattern in the polymer. The metal under the exposed polymer is then chemically etched, leaving only the pattern on the surface of the board as determined by the mask.
UV light changes the structure of the photoresist, in this case weakening the internal bonds so that the exposed photoresist is removed by the developer. By covering part of the photoresist with a mask that blocks UV light, portions of the photoresist will not be exposed. This is like using a stencil (mask) with spray paint (UV light) to transfer a pattern onto a substrate. The photoresist can then be developed, much like a photograph, so that only the exposed portions are removed, leaving behind a photoresist film in the form of the desired pattern. Once we have the desired pattern in photoresist, we etch away the remaining exposed copper. The last step is to strip the photo resist on the desired pattern.
This experiment uses one exposure and one etching step to create a copper pattern. To create a more complicated structure, such as a computer chip, more sequences of exposure and etch would be involved.

<u>Procedure:</u> Keep room lights to a minimum until after developing is done.

Exposure: Take a piece of prepared circuit board that has black tape covering the top side. The tape protects the underlying photoresist layer from light. Have each student write its name or initials on the back of the circuit board with the supplied marker. Give each one a preprinted mask and/or a marker for drawing their pattern.
Have your UV exposure station (UV light off) completely ready (see Figure 1 and 2 for setup guidelines). Cover the setup with black cloth covering most of the lamp with enough space to slide in all the boards.
Let each student bring their circuit board+mask to you, just before place it under the UV light, peel off the black tape to reveal the photoresist. Be careful not to get fingerprints on the photoresist. This should be done at the last minute to avoid exposing the photo-resist to the ambient light. Make sure the black pattern of the mask is completely on the substrate. Be careful not to put fingerprints on the mask and that all the circuit boards are positioned directly under one of the bulbs of the UV lamps.

Figure 1 UV exposure setup with one lamp

Figure 2 Exposure setup, both lamps top view

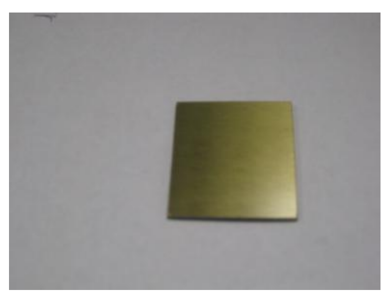

Figure 3 Resist on copper film (on plastic board)

a. Place a clean glass slide on top of the mask, to keep the mask flat against the photoresist. Again, be careful to avoid getting any fingerprints or dust on the glass slide. Photomasks being placed unevenly will result in blurry patterns and inconsistent developing and etching.
b. Cover the black cloth over the entire setup. Take care not to knock over the UV lights. Ensure that the covering is such that the room lights are not interfering with the exposure.
c. Use a timer to expose the boards for 12 min. Do not over expose.

2. Develop the Photoresist:
    a. Pour the developer solution into the small glass/plastic beaker and fill large plastic beakers with water. Label the two beakers, developer solution and rising water.
    b. Two substrates can be developed in each developer beaker simultaneously. Place them back to back such that the exposed surfaces both face outwards (use a pair of locking tweezers to do so). Try not to touch the pattern left by the photomask
    c. Gently shake/stir with the tweezers for 40 seconds. Use the included stopwatch for accurate timing.
    d. Immediately rinse the substrates in the large beaker filled with water to reveal the copper layer with the photomask pattern clearly visible in green and the surrounding copper metal is exposed (see figure 4). Thus, developing removes the photoresist that was exposed to UV light. Development is not complete until you see the pattern from the photomask as a green pattern on top of the copper metal (you can always develop more but cannot go back!). Clean with water after developing is done.
    e. Now room lights can be turned on fully.

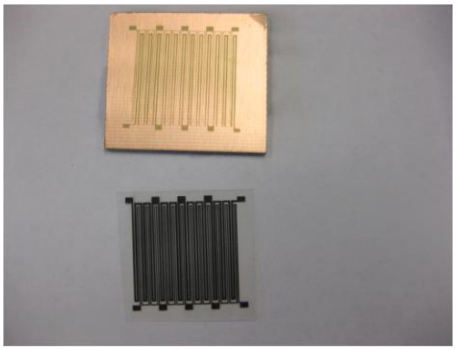

Figure 4 Pattern (green) on Copper after developing

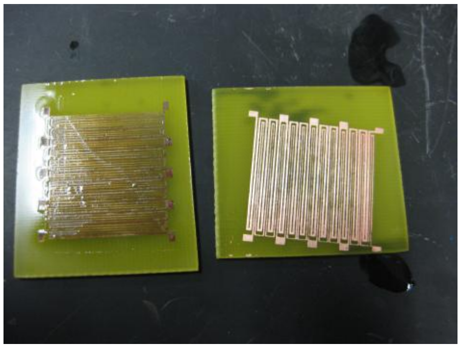

Figure 5 After Etch (left-before strip, right-after strip)

3. Etch the Copper:
    a. Once the boards have been developed (i.e. the photoresist has been removed from the unwanted copper), it is time to etch away the unwanted copper so that only the pattern is left.

b. Before starting the etching, check to make sure that the etchant solution is boiling on the hotplate, has a few boiling stones in it and is maintained at or above 80^{o}C. (If are planning on leaving it on the hotplate for sometime, cover with a watch glass so that the etchant does not boil away)
c. Use a pair of heat resistant locking tweezers to hold the board. Make sure that the tweezers are not on the pattern needed.
d. Completely immerse the substrates in the boiling etchant solution and gently shake/stir with the tweezers for 40 seconds. Use the included stopwatch for accurate timing. You may wish to wear the heat-resistant gloves during this step. Students can take turns in doing this if you have enough stations.
e. Immediately rinse the substrates in water. Inspect the copper pattern. If the copper around the pattern is still visible, put the substrates in the etchant for an additional 10 seconds, followed by an immediate rinse in water. Continue etching in 10 second intervals until the copper around the circuit pattern is gone, revealing the plastic underneath. Be careful not to over etch, the copper underneath the photoresist covered pattern should not get etched away (see figure 5, left image).
f. After everyone is done etching, turn off the hotplate and let the etchant cool before disposing off or transferring into bottles for reuse.

4. Strip the photoresist on the pattern:

a. Check the stripper applicator sponge. If it looks dirty, clean it with a damp paper towel. Gently dab the applicator on a paper towel to moisten the sponge with stripper fluid. It may help to squeeze the applicator stick while dabbing.

b. Using the stripper applicator stick, cover the entire photoresist surface, including the edges with stripper solution. The developer will dissolve the photoresist that is covering the copper pattern.

c. Rinse in a beaker with clean water.

d. The copper pattern should appear shiny and metallic (figure 5, right image). If not, repeat the photoresist stripping until all of the photoresist is removed. Dry the board.

Your Printed board with the circuit or the pattern is now ready!

Discussion:
It will take about 2 hours for the students to finish this activity; you can have a discussion during/after with the following topics:

1. Limitations of Photo-lithography (in terms of size): The biggest limitation to Photolithography is the wavelength of light. In order to make features smaller than the wavelength of UV (350nm), either a series of lenses or electron beam (e-beam) lithography is used.
2. Sources of error during the experiment: All steps have to be performed very carefully; each step from exposure to etching can cause errors if over/under done.
3. Necessity of clean room facilities, equipment and gear: dust particles are larger than the features being made.
4. Advantages and disadvantages of scaling down size: Speed and space occupied are the biggest advantages to miniaturization; however when the size is scaled down the resistance and heat loss in device also change. If you have the time, you can go into a discussion of Ohm's law and how resistance varies with size.

Tips and troubleshooting

All of the steps have to be performed very carefully: Exposure, developing, etching can all cause problems if they are either under-done or over-done. Timing is critical, always use a stop watch and time carefully.

Common visitor questions

Check discussion section

Going further…

1. History and types of lithography: http://en.wikipedia.org/wiki/Lithography
2. Making Silicon and Computer Chips: http://www.youtube.com/watch?v=aWVywhzuHnQ&feature=related
3. Intel: http://www.youtube.com/watch?v=VI5GCsZCgeo&feature=related

Clean Up

Time: 1-2 hours

Disposing of the etchant:
Pour the etchant solution into the plastic-ware container. If two beakers were used, both will fit into the container. Make sure the etchant has cooled down sufficiently before pouring into the plastic-ware. Add the neutralizing powder to the solution while mixing. The solution will bubble and begin to rise. Be careful not to let it overflow. Stirring with the supplied spoon will help. Add the quick cement to the solution while stirring. Over time the solution will harden after which it can be thrown into trash. Alternatively you can give it to a local Chemistry lab who disposes chemicals regularly.

Universal Design

NA

This project was supported by the National Science Foundation under Award No. 0940143. Any opinions, findings, and conclusions or recommendations expressed in this program are those of the author and do not necessarily reflect the views of the Foundation.