Photolithography

Option A (Solvent-based)

Center for Nanotechnology Education

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Abstract

This module presents an introduction and demonstration of photolithography, the process of copying a high-resolution pattern onto multiple substrates. Students replicate key steps in the process of photolithography, and learn how these processes fit into the fabrication of micro- and nanoscale devices such as integrated circuits. This activity uses solvents and chemicals similar to those used in the electronic industry to perform a key step in the process of manufacturing real integrated circuits. A modified version of this activity that uses water-based chemistry is also available.

Outcomes

After completing this module, the student will gain a basic understanding of the pattern-transfer step of the lithography process, and learn how it relates to producing micrometer- and nanometer-scale devices.

Prerequisites

- Some knowledge of basic chemistry and molecular structure.
- The photolithography module may be used in courses on chemistry, electronics, and nanotechnology at the middle school, high school, or college freshman level.

Alignments to Education Standards

See Appendix for alignments to the Next Generation Science Standards and the Common Core Educational Standards.

Science Concepts

- Interaction of light with matter

Nanoscience Concepts

- Lithography is a method of fabricating devices at the nanoscale

Background Information

Photolithography is the crucial process that makes possible the production of integrated circuit electronics and all devices based on them: computers, cell phones, digital cameras, calculators, compact sensors, displays, industrial controls, virtually anything that can be described with the word "electronics." Photolithography has progressed in its ability to produce smaller and more precise electronic structures, allowing the development of electronic and mechanical components that are presently approaching ten nanometers in size. Photolithography is thus a leading contributor to advances in nanotechnology.

Photolithography takes place after the circuit design of the electronic device has been completed. To set up the photolithography process, the three dimensional structure of the device design is "sliced" into thin two-dimensional layers, each of which will be fabricated in a separate step; the finished device will consist of features fabricated one layer at a time and carefully aligned to ensure proper device operation.

The main processes of photolithography are

1) preparing a pattern of the device layer to be fabricated, which identifies the position of each feature and the material from which it is to be made (metals for conductive wires, ceramic compounds for insulators, and semiconductors like silicon to form transistors);
2) miniaturizing the pattern to achieve the desired device scale, and reproducing numerous copies of the pattern on a print master, called a photomask;
3) depositing the base material (metal, semiconductor, or insulator) for the layer to be fabricated onto a convenient substrate, the latter usually being a thin, polished wafer of very pure silicon;
4) transferring the pattern photographically from the photomask to the base material through the use of a photosensitive polymer called photoresist;
5) etching by immersing the patterned wafer in an etching agent, where any material not protected by the patterned photoresist is etched away, leaving the desired features; and
6) removing the photoresist and cleaning of the wafer, revealing a set of exact copies of the original device layer pattern.

The process of depositing, transferring, etching and removing is repeated layer-by-layer, as many times as is necessary to build up the full device structure. Thousands of complex electronic devices consisting of billions of individual electronic components may be made simultaneously on a single wafer using this method, allowing very complex integrated circuit structures to be made at low cost.

History. Lithography (Greek for the word *stone* [*lithos*] and to write [*graphein*]) was invented by Aloys Senefelder [1]. Aloys explained lithography in "*A Complete Course of Lithography",* published in 1818 [2]. Aloys was an actor and playwright and wanted to sell his plays, but was unable to pay the high costs of printing using then-current methods. Aloys found that by properly treating Bavarian limestone with chemicals, it could transfer a carved image onto a paper [1]. Later, Nicéphore Niépce (1765-1833) became interested in Aloys's work, but lithographic stone was hard to find, and Niépce had no talent for draftsmanship, so he decided to try to find a way of using light to produce the picture for him [3]. He performed many experiments on chemical reactions caused by light to produce permanent images [4]. By 1816, Niépce was doing his first few experiments in a process he called *heliography*, or *sun-drawing*. By 1826 he developed the process to the point where he could produce a copy of an existing etching by mounting it on a sheet of glass and letting sunlight to pass through it onto a copper or pewter plate coated with an asphalt solution [3]. These experiments led to the invention of photography[4]. Decades later, photomasking, followed by chemical processing, formed the photolithography process that made fabrication of integrated circuits (ICs) and science of miniaturization possible [5].

How photolithography works. Photolithography and photography work in very similar ways [6]. Photolithography is a process in which a pattern is transferred to the surface of a wafer using a photosensitive polymer in solution (photoresist). Photoresists change their solubility properties upon exposure to light.

There are two types of photoresist: negative and positive. Exposing negative photoresists to radiation causes a chemical change that makes the resist insoluble in the developer solution, so when light passes through openings in the photomask, it leads to opaque areas in the developed resist. This creates a pattern on the wafer that is the opposite of that on the mask, i.e., a negative image.
A positive photoresist works the opposite way: the resist is insoluble in the developer unless light strikes it, so if light passes through an open area on the mask and exposes the resist, that region is dissolved away in the developer step, resulting in an open area in the resist as well (a positive image). Positive photoresists are generally used in IC fabrication because they exhibit better resolution [7]. The transferred pattern is used as an *etch mask*, that is, a protective layer that prevents chemical or physical etching wherever the resist is on the surface. The resist pattern may also be used for *ion implantation*, allowing energetic ions to penetrate the substrate only where desired [6, 8].

The steps that comprise the photolithographic process are:

- surface cleaning of the wafer substrate
- dehydration bake, to drive off water adsorbed on the wafer surface
- application of the photoresist
- soft bake, to set the properties of the photoresist
- alignment of the photomask on the wafer
- exposure of the photoresist
- development of the photoresist
- inspection
- removal of soluble resist and cleaning the wafer for subsequent steps
- repetition of the above steps for as many layers as are required

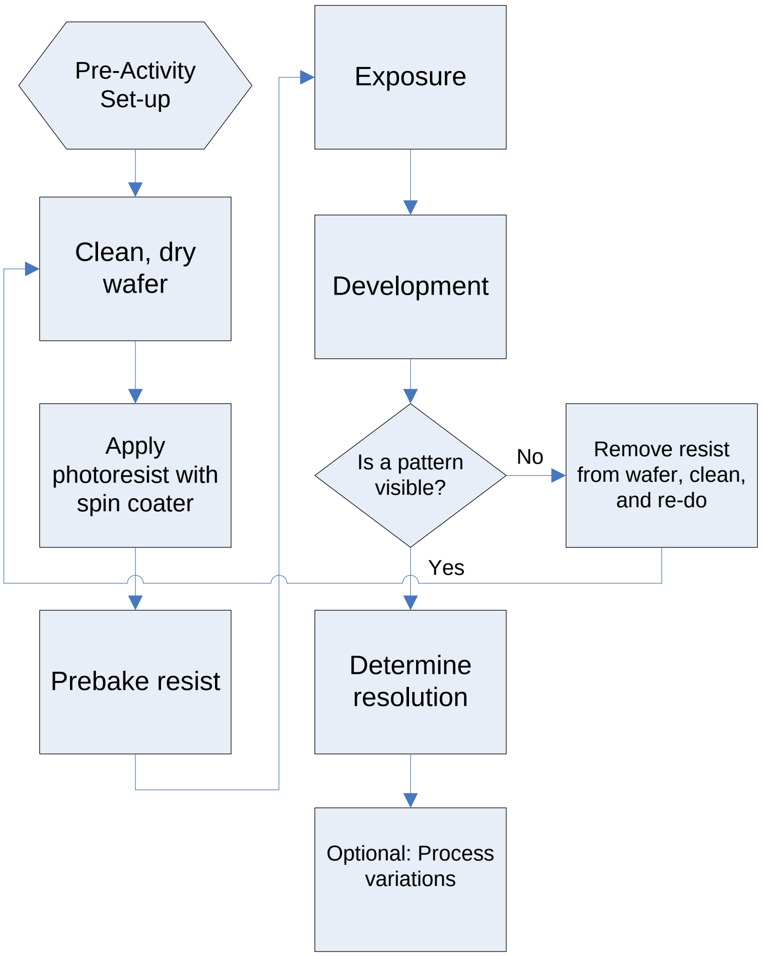
Current and Future Applications

Photolithography is one of the most broadly applied technologies in existence. It is used to make the circuits found in all modern electronics. The number of transistors made using photolithography each year exceeds the world's human population by several orders of magnitude. Photolithography techniques are also used to make microelectromechanical systems (called MEMS) which are found in a wide variety of devices, including gas sensors, solid state gyroscopes, and accelerometers used in automobiles and smart phones.

The future will continue to see the application of photolithography to making microelectronics, although the race to make smaller and smaller electronic components may force a shift to an alternative technology, such as electron beam lithography or imprint lithography.

Learning Activity: Photolithography

Activity Flow Chart



Materials and Equipment

Consumable materials supplied locally

- Light duty plastic gloves
- Clean compressed air (e.g., Dust-off particle-free compressed air in a can)
- Lint-free laboratory wipes
- Disposable plastic droppers
- Distilled or filtered tap water
- Solvents: acetone, isopropanol (rubbing alcohol with 70% isopropanol can also be used)
- Photoresist chemical, 100 ml (enough to coat 30 wafers). Safety Data Sheet provided.
- Developer chemical, 100 ml of concentrate. This must be diluted 5:1 with distilled water to make 600 ml of developer (enough to develop 30 wafers). Safety Data Sheet provided.

Equipment and supplies

- 10 polished silicon wafers (can be cleaned and re-used many times)
- Transparent photomask with pattern to be transferred
- Spin coater
- Clear plastic containment box
- Safety goggles
- Tweezers
- Stopwatch or digital timer
- One or two hotplates, preferably with temperature readouts
- Four shallow trays to hold liquids (developer solution, rinse water, acetone, isopropanol). Plastic sandwich storage boxes are good because they have tight fitting lids.
- One or two desk lamps with a 25W compact fluorescent bulb (do not use an incandescent or LED bulb)
- Optional: an optical microscope capable of using reflected (not transmitted) light

Sources for materials and specialty chemicals

- Acetone and pure isopropanol (IPA) may be obtained from local hardware or home supply stores. Rubbing alcohol with at least 70% isopropanol can be used in place of pure IPA; this is available from a drug or grocery store.
- Additional photoresist (Shipley 1813) and developer (Microposit 351) can be ordered from MicroChem Corp., Newton, MA; tel: 617-965-5511, e-mail: sales@microchem.com.
- Additional silicon wafers can be obtained from Polishing Corp of America (www.pcasilicon.com) and University Wafer (www.universitywafer.com). Wafers come in many grades; for this activity, test grade wafers will work fine.

Preparation (Prior to Activity)

1. Dilute the developer concentrate to make 600ml of developer. Place this in one of the shallow liquid trays and mark it “Developer”
2. Fill a second tray with distilled or filtered water. Mark it as “Water”.
3. Fill one tray with acetone and one with isopropanol. Place the covers on these trays and mark them appropriately.
4. Line each containment box with paper towels.
5. Set a spin coater in the center of each of the containment boxes. Align it so that the center of the spinning disk is right below the hole in the box lid. Plug in the spin coater.
6. Set up the desk lamps with bulb facing downwards, about 25 cm above the table top.
7. Set up and pre-warm the hot plates. If the hot plate has a temperature readout, set it at 105 degrees C. If not, set the hot plate control at about 40% of its maximum.

(Optional) Making your own photomask. As part of the activity kit, Nano-Link provides 1-2 photolithography masks with patterns containing very small features. At the teacher's option, a photomask may be made locally by producing a pattern with a computer drawing program, then printing that pattern to polyester transparency film using a xerographic copier or laser/inkjet printer. Potential mask patterns include students' names and the name of the school, written in a type face that is 1 mm tall or less. Your custom made mask can also use very fine lines, or a series of squares of decreasing size. These will be used at the end of the activity to quantitatively determine the resolution of the pattern transfer. See Figure 1 for an example of a pattern to try.

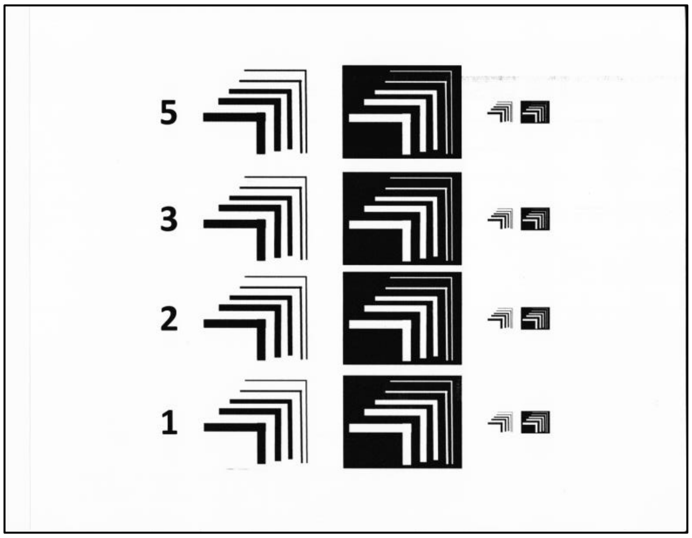


Figure 1. Scanned image of 5x overprinting using an ink jet printer to produce a highly opaque mask (original size 8 x 11 in).

When using some printers to produce these transparencies, the pattern may be insufficiently opaque to ensure a clean masking effect. To obtain a fully opaque pattern, the same sheet of transparency can be repeatedly printed with the pattern by passing it through the printer more than once. By carefully aligning the paper guides, the same transparency can be overprinted five times or more without serious degradation of the image. If using an inkjet printer, allow the ink to dry fully (at least 5 minutes) between passes. Clean images with feature sizes less than 0.1 mm can be reliably produced by this method. You may not need to do five overprintings; some experimentation will reveal how many passes are required with your equipment.

Safety

- Avoid contact with photoresist; use soap and water to remove any material that touches skin.
- Splash-proof safety goggles and light duty gloves are required when handling solvents, photoresist and wafers – this models good laboratory practice
- Solvents and solvent-based photoresist must be handled with adequate air circulation to avoid buildup of solvent vapor. Use of chemical fume hoods is recommended, but a well-ventilated laboratory may be acceptable; use your discretion.
- These chemicals must be stored, used, and disposed of safely following your organization's chemical hygiene and hazardous waste disposal procedures.
- Use care when handling silicon wafers; they are fragile and may shatter into sharp fragments if dropped.

Photolithography—Option A

Procedure

1. **Cleaning and Drying the Substrate.** To apply a good layer of photoresist, it is essential that the substrate be free of oils, dirt, or previous photoresist layers. (Note: if the wafers are being re-used and/or have traces of previous photoresist coating, follow the cleaning procedure under item 6 below.)

    1.1. Place the wafer on a dry, clean lab wipe.
    1.2. Squirt a small quantity of isopropanol on the wafer and gently wipe with a lint-free wipe. Allow the alcohol to dry from the wafer.
    1.3. Blow-dry the front of the wafer with particle-free compressed air.
    1.4. Place the wafer on the hotplate for 60 seconds to drive off any remaining water.
    1.5. Carefully remove the wafer from the hotplate using tweezers.
    1.6. Allow to cool for a minute or so.

2. **Applying Photoresist.** The photoresist should be applied in a thin, uniform layer to ensure success in subsequent processing steps. Here we use a simple spin to spread the photoresist in a layer approximately 25-50 microns thick.
    2.1. Place a wafer on the spin coater so that the flat edge of the wafer is next to one of the small nylon screws on the spinner disk. These screws act as clamps to firmly hold the edges of the wafer on the spin coater, preventing the wafer from flying off. Rotate the wafer about 20 degrees so that the outer edge is under all three screws.
    2.2. Position the spin coater so that its center is directly under the hole in the lid of the containment box. Place the lid on the box to check alignment, and adjust if needed.
    2.3. With the lid on, turn the spin coater on and allow it to run about 30 seconds to reach full speed.
    2.4. While the spin coater is spinning up to speed, withdraw enough photoresist into a disposable dropper to fill about 2-3 cm up from the bottom of the dropper tip.
    2.5. When the spin coater has reached full speed, insert the dropper into the hole in the box lid. Try to position the dropper directly over the center of the spinning wafer.
    2.6. Squirt all the photoresist in the dropper onto the wafer in one continuous motion (i.e., don’t stop and start but apply all the dropper contents at once) to ensure an even coating. Allow the spin coater to run 30 seconds, then shut it off and allow it to spin to a stop.

3. **Baking/Drying.** The photoresist needs to be dried in order to optimize its photoreactive properties.
    3.1. Place the wafer on the hotplate for 60 seconds.
    3.2. Remove the wafer from the hotplate using tweezers
    3.3. Allow the wafer to cool for 1-2 minutes. Since the wafer is now fully sensitized to light, keep it out of direct sunlight and strong room light during this step.

4. **Exposure and Development.** In this step, the pattern on the mask is transferred to the wafer by interaction of light with the photosensitive material. After exposure, the image is *virtual*, that is, not visible until developed.
    4.1. Place the wafer on a non-reflective surface.

4.2. Place the photomask directly on the wafer. ***Ensure that the correct side of the mask is down***. This means that the side on which the pattern is printed should be in the down position, closest to the wafer.
4.3. Position the light source about 10 cm above the wafer, and expose for 2 minutes
4.4. Submerge the wafer in the developer solution and agitate for 30 seconds. An image should gradually become visible.
4.5. Submerge the wafer in the water bath for two minutes to rinse off the developer. Agitate slightly.
4.6. Blow-dry the wafer using compressed air.

5. **Inspection.** Determine how well the pattern you made matches that on the mask.
5.1. Using an optical microscope, inspect the wafer for

- underexposure: the pattern is incompletely transferred
- overexposure: the pattern is "burned", i.e., features are wider than they should be
- overdevelopment: too much of the photoresist has been removed from the edges of features
- underdevelopment: photoresist remains in the areas where it should have been removed.

5.2. Examine the finest structures present on your wafer, and compare them to those on the photomask. Determine the smallest feature that was faithfully transferred to the wafer. If a scope-mounted camera is available, collect an image of pattern on the wafer. Check with your instructor for what measures of resolution to use.

6. **Wafer Cleaning (if needed)**
6.1. Place the wafer to be cleaned in a shallow tray filled with acetone. Allow to soak 60 seconds. This strips off the old photoresist. Keep acetone covered while not in use, as it evaporates quickly.
6.2. Retrieve the wafer with a pair of forceps and remove from the acetone bath, allowing the excess solvent to drip back into the container.
6.3. Transfer the wafer to a shallow tray filled with isopropyl alcohol. Allow to soak 30 seconds. This removes any traces acetone.
6.4. Retrieve the wafer and allow any excess liquid to drain back into the bath.
6.5. Transfer the wafer to the tray filled with water. Swirl the wafer in the bath, remove and inspect. Repeat the procedure as needed to remove any visible surface contaminants. Make sure to do a final water rinse on the wafer, and allow as much excess water as possible to drain off the wafer before moving to the next step.
6.6. Place the wafer on the hotplate for 60 seconds.
6.7. Remove the wafer from the hotplate using tweezers and allow the wafer to cool for 1-2 minutes before using.

7. **Variation of process conditions (optional)**
7.1. Using the same photoresist and light source, adjust one of the following parameters as follows:
   - Baking: decrease bake time to 45 seconds and increase to 90 seconds.
   - Light exposure: decrease light exposure to 90 seconds and increase to 150 seconds.
   - Development time: cut development time to 20 seconds and increase to 50 seconds.

7.2. Repeat steps 2-5 above using the chosen process conditions. Inspect the new pattern on your wafer and determine the smallest feature size transferred.
7.3. Clean and dry your wafer following the instructions under section 7, and return it to your instructor.

Discussion Questions

- What step in the photolithography process was the most difficult for you? Why?
- Did you find that changing the exposure time or development time changed the resulting pattern? In what way?
- Sometimes, students fail to get any image at all on the wafer. What might have gone wrong to prevent a pattern from being transferred to wafer?
- In addition to the processes we used in this activity, what other steps would be required to actually make a functioning device (electronic or mechanical)?

Contributors

- This module was written by Dr. James Marti at the University of Minnesota (Minneapolis MN), based on developmental work by Dr. Maryam Jalali, also at the University of Minnesota.
- Important contributions were made by Mr. Samuel Levenson of Harper College (Palatine IL).

Resources

Videos

- "How Do They Make Silicon Wafers and Computer Chips?": www.youtube.com/watch?v=aWVywhzuHnQ
- "The Fabrication of Integrated Circuits": www.youtube.com/watch?v=35jWSQXku74

Articles

1) www.robinsonlibrary.com/finearts/print/lithography/senefelder.htm
2) www.nndb.com/people/948/000205333/
3) J. Madou,"Fundamentals of Microfabrication: the science of miniaturization," CRC Press, 2002.
4) S. Franssila, "Introduction to Microfabrication," John Wiley & Sons, LTD, 2004
5) D. J. Elliot, "Integrated Circuit Fabrication Technology," McGraw-Hill Book Company, 1982.
6) S. A. Campbell," Fabrication Engineering at the Micro and Nanoscale," Oxford, 2008.

Appendix: Alignment to Standards

Alignments

to Next Generation Science Standards

TABLE 1. ALIGNED PRACTICES, DISCIPLINARY CORE IDEAS, AND CROSSCUTTING CONCEPTS

PRACTICE	***DCI***	***CROSSCUTTING CONCEPT***
HS. Obtaining, evaluating, and communicating information: Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats *Partial alignment in student materials*	*HS-PS2.B: Types of interactions:* Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects. *Strong in student materials*	*HS. Structure and function:* Investigating or designing new systems or structures requires a detailed examination of the properties of different materials, the structures of different components, and connections of components to reveal its function and/or solve a problem. *Partial alignment in student materials*

Alignment to Common Core State Standards: English Language Arts/Literacy & Mathematics

TABLE 2. ALIGNED COMMON CORE STANDARDS FOR ENGLISH LANGUAGE ARTS & LITERACY
CCR.L.6: Acquire and use accurately a range of general academic and domain-specific words and phrases sufficient for reading, writing, speaking, and listening at the college and career readiness level; demonstrate independence in gathering vocabulary knowledge when encountering an unknown term important to comprehension or expression. *Partial in teacher and student materials*
RST.11–12.3: Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks; analyze the specific results based on explanations in the text. *Partial in student materials*