Photolithography

Option B (Water-based)

Center for Nanotechnology Education

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Abstract

This module presents an introduction and demonstration of a key step in photolithography, the process of patterning a substrate used in the manufacture of integrated circuit chips. Students replicate some of the 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 water-based chemicals and processes, allowing it to be used with younger students and/or in classrooms and labs without a fume hood.

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].

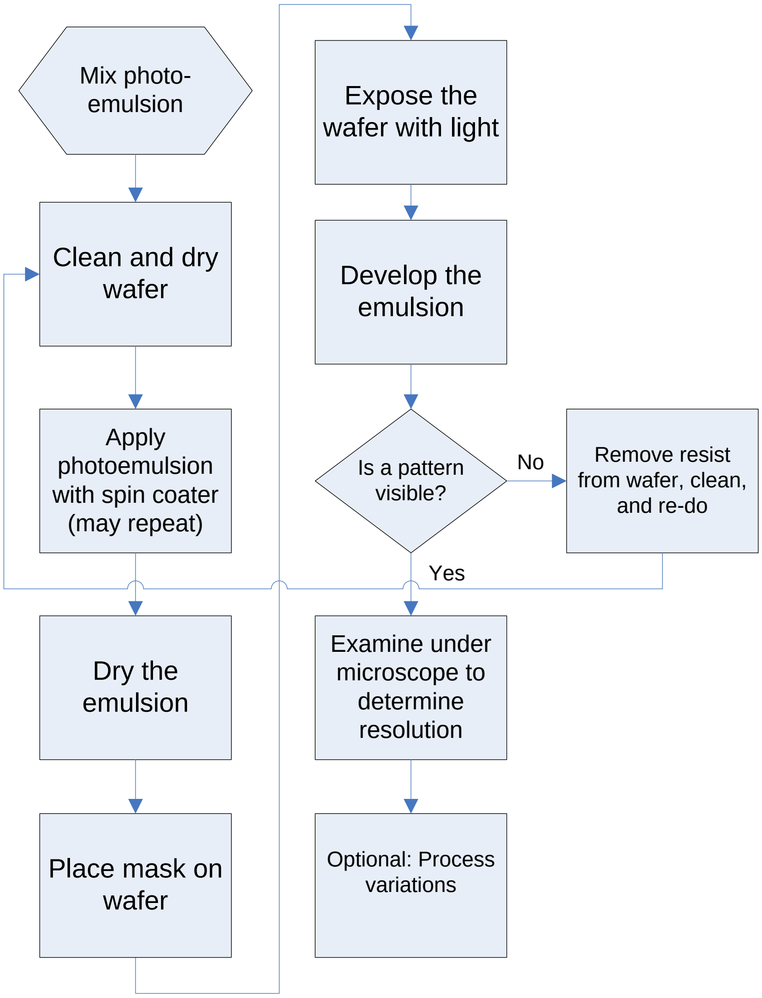
Current and Future Applications

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



About This Version

The photolithography activity may be done using two different chemistries, solvent-based and water based. The solvent-based approach (titled Option A on the Nano-Link website) yields excellent pattern transfer with high resolution, but requires highly volatile solvent photoresist, a set of solvents for cleanup, and a fume hood to remove solvent vapors.

This method, Option B, uses a water-based photosensitive material which removes the need for air exhaust and allows water cleanup. However, the resolution of the transferred pattern may be somewhat lower (fine details will not be faithfully transferred).

Materials and Equipment

Consumable materials

- 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
- Liquid photoemulsion. Store the emulsion in its opaque bottle until ready to use.
- Distilled or filtered tap water
- Solvents: acetone, isopropanol (rubbing alcohol with 70% isopropanol can also be used)

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
- One or two desk lamps with a 45W compact fluorescent lightbulb
- 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.

Preparation (Prior to Activity)

1. Line the containment box with paper towels.
2. 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.
3. Set up the desk lamps with bulb facing downwards, about 25 cm above the table top.
4. Set up and pre-warm the hot plates. If the hot plate has a temperature readout, set it at 60 degrees C. If not, set the hot plate control so that the plate is warm, not hot, to the touch.

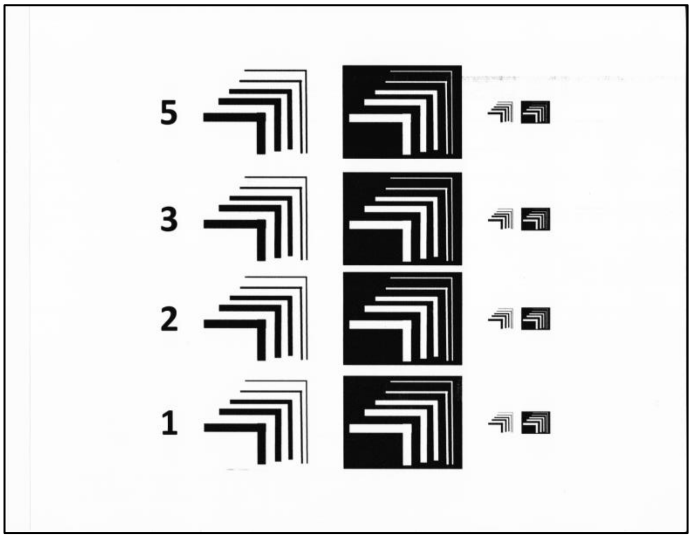


Figure 1. Scanned image of 5x overprinting using an ink jet printer to produce a highly opaque mask (original size 8 x 11 in)

(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.

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 the photoemulsion; use soap and water to remove any material that touches skin.
- Wear gloves when handling photoemulsion and wafers – this models good industry practice
- Use care when handling silicon wafers; they are fragile and may shatter into sharp fragments if dropped.

Photolithography—Option B

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. In a semiconductor fabrication facility (fab), wafers are cleaned by immersing them in a series of solvents. In this lab, you will use pre-cleaned wafers, which need only light finish cleaning and drying of the wafer surface.

   1.1. Place a pre-cleaned wafer on a dry, clean laboratory wipe.
   1.2. Squirt a small quantity of isopropanol on the wafer and gently wipe with a laboratory wipe. Allow the alcohol to dry from the wafer.
   1.3. Blow-dry the front of the wafer with particle-free compressed air.

2. **Preparing the Photoemulsion.** The emulsion kit consists of the photoemulsion (large bottle) and the sensitizer (small bottle). The two components must be mixed fresh before each use.

   2.1. The diazo sensitizer is shipped as a dry powder that must be mixed with water before use. If not already done, prepare the sensitizer by filling the bottle half full with DI water. Mix thoroughly. Store unused sensitizer in the refrigerator.
   2.2. Measure out 15ml of photoemulsion in a beaker. The emulsion is very viscous, so pour carefully.
   2.3. Add 2 ml of sensitizer and stir. The initial blue color of the emulsion should turn greenish.
   2.4. Add 10ml of water to the emulsion to reduce the viscosity and prepare it for spin coating.

3. **Applying the Emulsion.** The photoemulsion must be applied in a thin, uniform layer to ensure success in subsequent processing steps. Here we use a simple spin coater to spread the emulsion in a layer approximately 0.2 mm thick.

   3.1. Line the containment box with paper towels to catch excess emulsion. Place the spinner inside the containment box.
   3.2. Place a wafer on the spinning device so that the flat edge of the wafer is next to one of the small nylon screws on the spinner disk. Rotate the wafer about 20 degrees so that the outer edge is under all three pegs.
   3.3. Position the spinner 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.
   3.4. With the lid on, turn the spinner on and allow it to run about 30 seconds to reach full speed.
   3.5. While the spinner is spinning up to speed, withdraw enough diazo photoemulsion to fill a disposable dropper (about 3 ml).
   3.6. When the spinner 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.
   3.7. Squirt all the emulsion 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. Repeat this

process two more times to build up a thick layer of the photoemulsion. After the last application of emulsion, allow the spinner to run 30 seconds, then shut it off and let it spin to a stop.

3.8. Dry the coated wafer by placing it on a warm (~60C, not hot!) hotplate for about 10-15 seconds to drive off the water.

4. **Exposure.** In this step, the pattern on the mask is transferred to the wafer by interaction of light with the photosensitive emulsion. At the end of this step, 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 surface.

4.3. Expose the wafer per emulsion kit instructions. Use the lamp with a 45W compact fluorescent bulb. Place the bulb ~20cm above the wafer, and expose for 7 to 8 minutes.

5. **Development of the Emulsion.** This reveals the pattern you have made.

5.1. Wash the wafer under running warm (~38^o C) tap water for 1-2 minutes to remove unreacted emulsion and reveal the pattern.

5.2. Blow dry the wafer using clean air if available, or just allow to air dry.

6. Inspection

6.1. Visually inspect the pattern(s) on the wafer. Check to see how faithfully the pattern on the mask was transferred to the wafer.

6.2. Look for signs of
  - 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.

6.3. Using an optical microscope, 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 the pattern on the wafer. Check with your instructor for what measures of resolution to use.

6.4. Remove photoemulsion by immersion in warm tap water and wiping with a paper towel, or use emulsion remover from kit. The cleaned wafer can then be reused.

7. **Variation of process conditions.** Can you improve pattern transfer by changing the process?

7.1. Using the same emulsion and light source, adjust one of the following parameters as follows:
  - Light exposure: decrease light exposure to 5 minutes and increase to 10 minutes.
  - Photoemulsion concentration: Further dilute the photoemulsion 1:1 with water and observe the effects on quality of the image.

7.2. Repeat steps 2-5, (application, drying, exposure, development and QA) above. Inspect the new pattern on your wafer and determine the smallest feature size transferred.
7.3. Clean and dry your wafer and return to your instructor.

Discussion Questions

- What step in the photolithography process was the most difficult for you? Why?
- Did you find that changing the processing conditions changed the resulting pattern? In what way?
- Sometimes no image at all is transferred to 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) http://litografia.pl/en/lito_senefelder.html
2) http://www.robinsonlibrary.com/finearts/print/lithography/senefelder.htm
3) http://www.nndb.com/people/948/000205333/
4) J. Madou,"Fundamentals of Microfabrication: the science of miniaturization," CRC Press, 2002.
5) S. Franssila, "Introduction to Microfabrication," John Wiley & Sons, LTD, 2004
6) D. J. Elliot, "Integrated Circuit Fabrication Technology," McGraw-Hill Book Company, 1982.
7) S. A. Campbell," Fabrication Engineering at the Micro and Nanoscale," Oxford, 2008.
8) http://www.ee.washington.edu/research/microtech/

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*