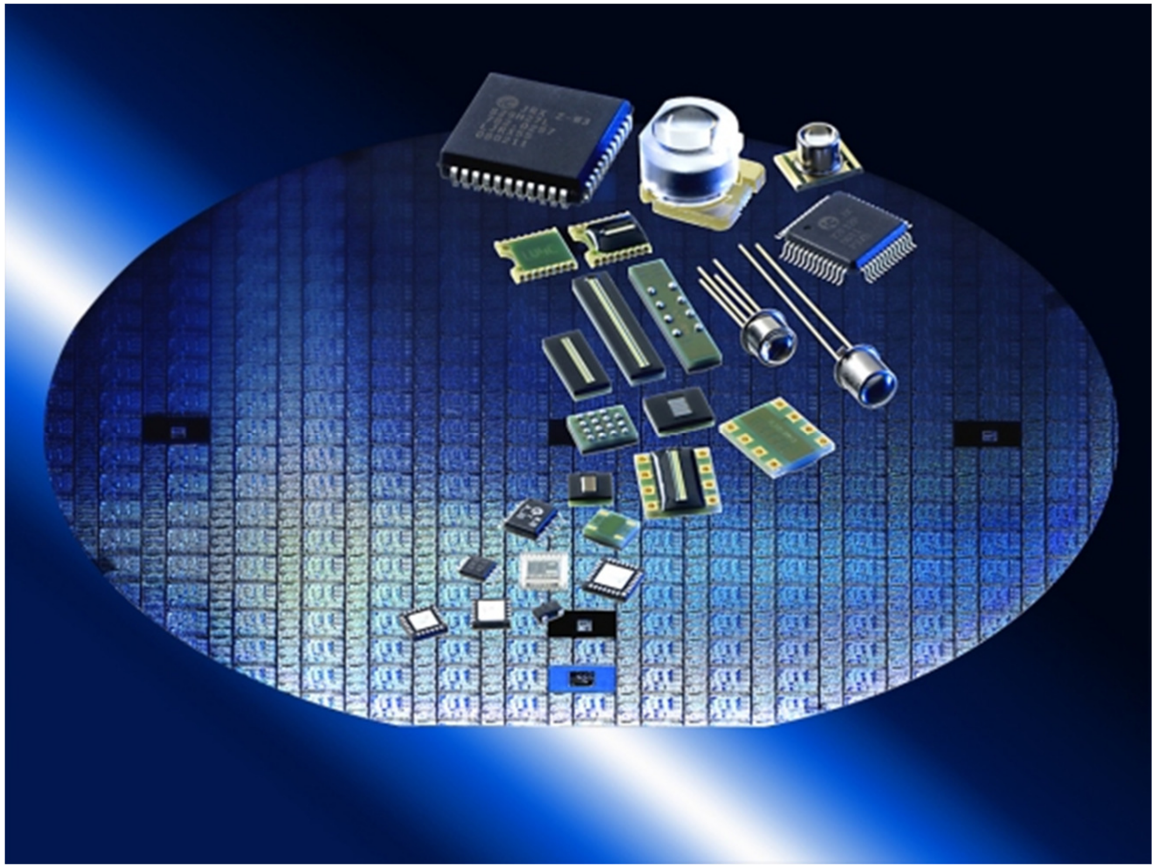
Introduction to Photolithography



http://www.ichaus.de/news/72

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Photolithography

The following slides present an outline of the process by which integrated circuits are made, of which photolithography is a crucial part. They may be presented as part of a lecture introducing the lithography activity.

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Photolithography is the central technology in fabricating integrated circuits (ICs)

Here is a photo tour of an IC fabrication plant

http://www.extremetech.com/computing/85304-intelmicron-fabrication-plant-tour?print

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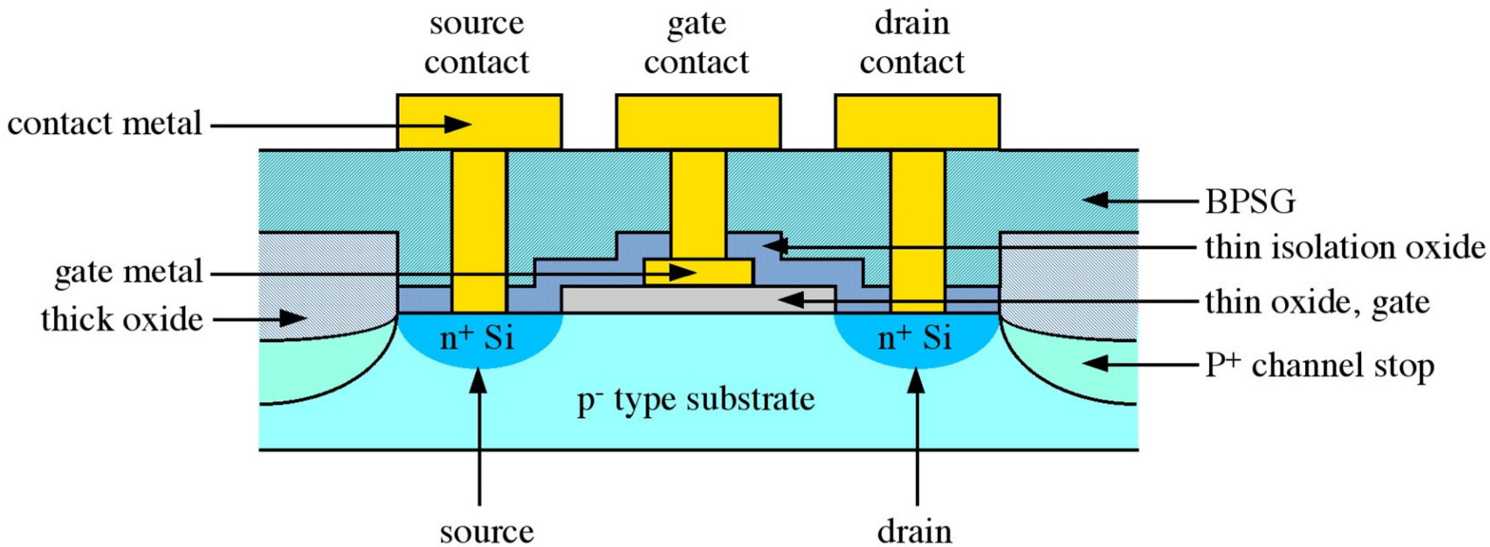
Typical Integrated Circuit Element:

A MOSFET Transistor

Idealized transistor design



With permission from: Andrew Barron *Applications for Silica Thin Films* http://cnx.org/content/m24883/1.5/

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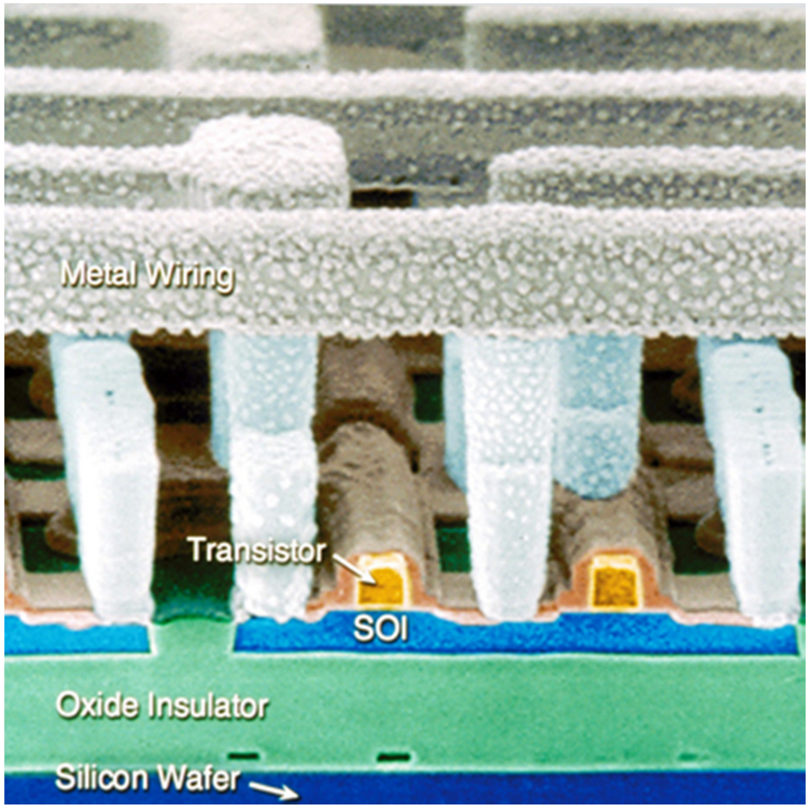
Actual CMOS transistors as made on a wafer

Transistor dimensions are less than 100 nanometers



http://www.computerhistory.org/

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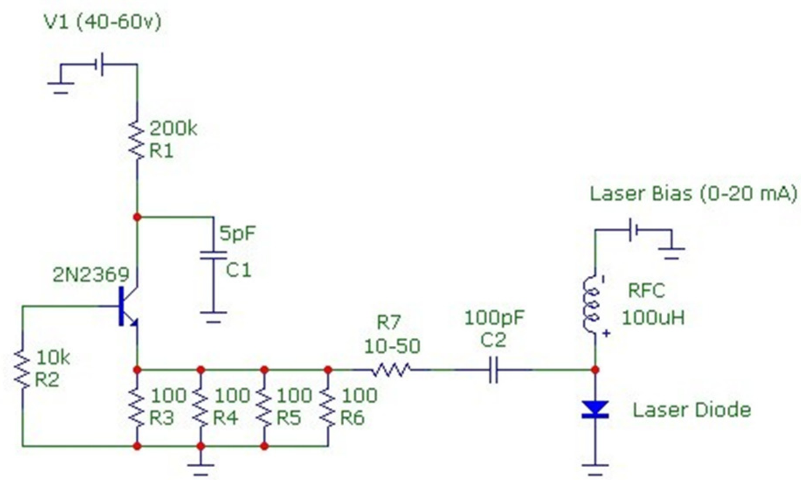
Microfabrication Step 1: Circuit Design

Design the 3D circuit structure.
Turn this: Schematic diagram

Into this: 3-D layout of components



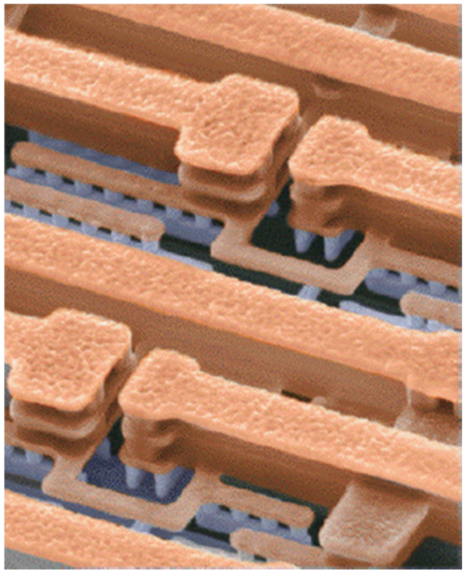
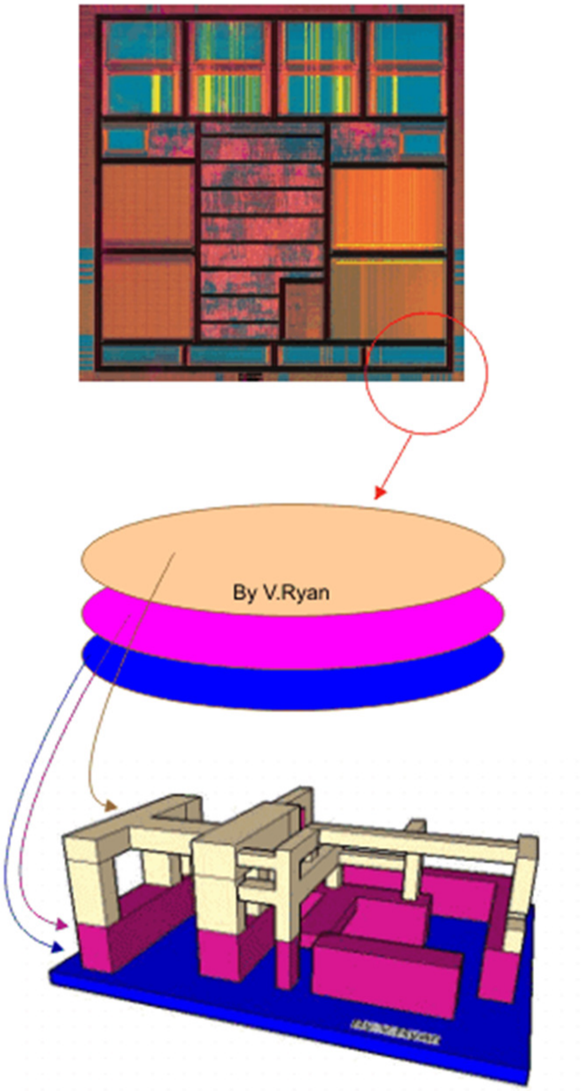


Photo – courtesy IBM
http://www.kasap.usask.ca/photos/

Microfabrication
Step 2: Mask Design

Divide the structure into horizontal layers

Capture the design of each 2-D layer in a *photomask*



Figures from www.technologystudent.com/elec1/ic2.htm, © 2006, V. Ryan

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The Circuit Photomask

The photomask is the “master” pattern for all the circuit elements across the whole wafer for one layer

Used repeatedly to make many, many copies

http://www.electrooptics.com/features/feature.php?feature_id=126

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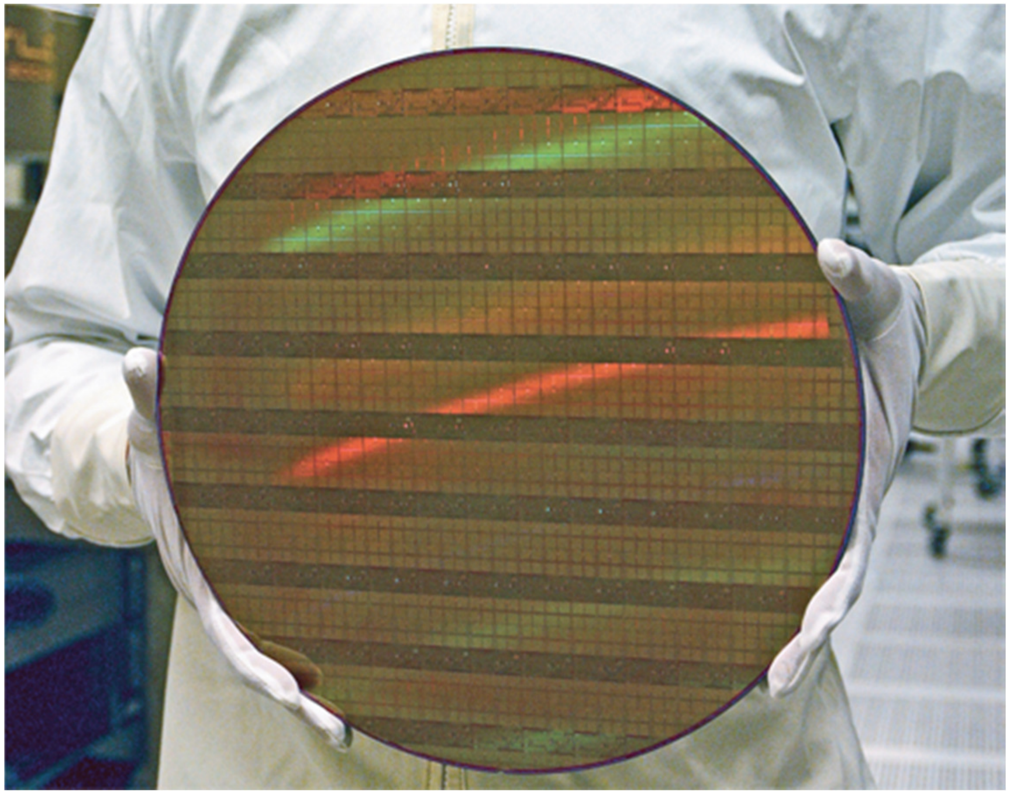
Microfabrication

Using a mask and photolithography, we can replicate complicated circuits with millions of components in a very small space.

→ Hundreds of circuits made on each wafer; cut up, packaged, and tested

→ Basis for relatively inexpensive, powerful electronics



http://amath.colorado.edu/cmsms/index.php?page=an-immersed-interface-method-for-modeling-semiconductor-devices

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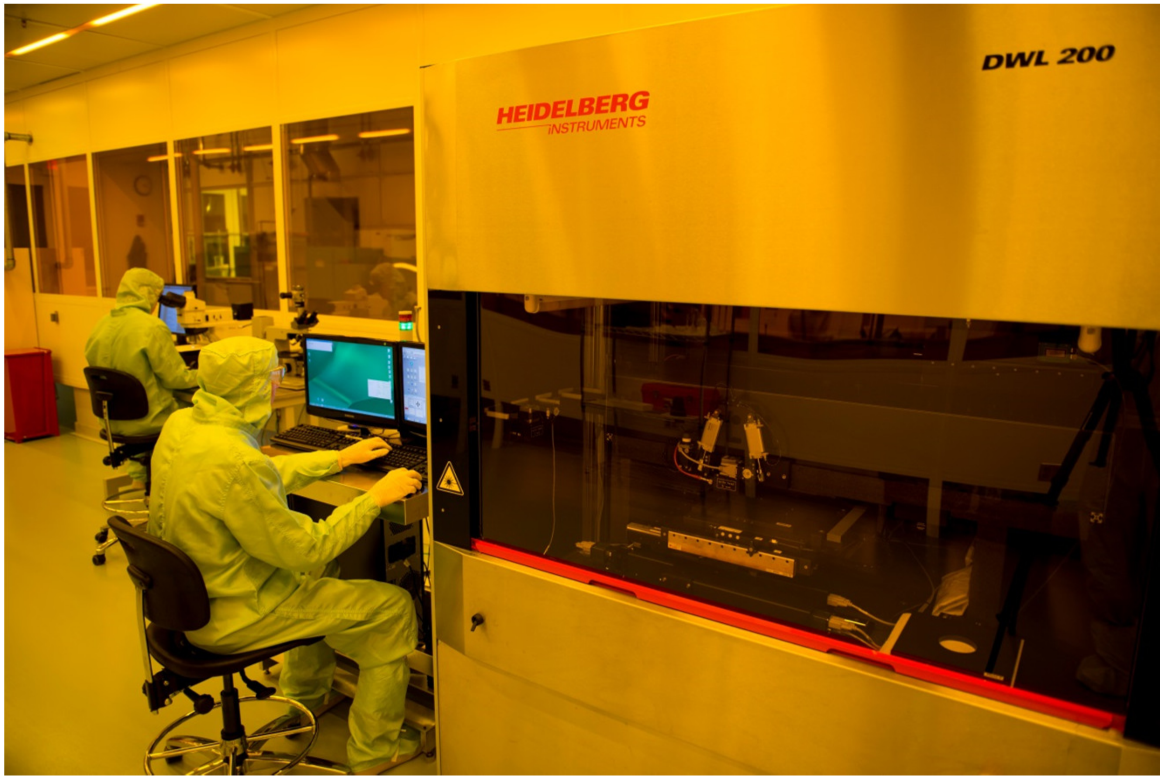
Making the Photomask



Photomask generator, University of Minnesota Nano Center

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Photo: James Marti, University of Minnesota

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Microfabrication Step 3: Set up Process Steps

Determine how to form each layer

- **add material** (*deposition*): build up a thin film of metal, insulator, or semiconductor material
- **remove material** (*etching*): take away previously deposited material from selected areas. This is similar to *sculpting* a block of stone or *machining* a block of metal to produce a structure to match the design.
- **modify a layer**:
  - *Doping:* intentionally adding ionized impurities to tailor the layer's electrical properties
  - *Oxidation:* exposing a previously deposited layer (e.g., silicon, a semiconductor) to oxygen to make an *oxide* (e.g., silicon dioxide, a good insulator).

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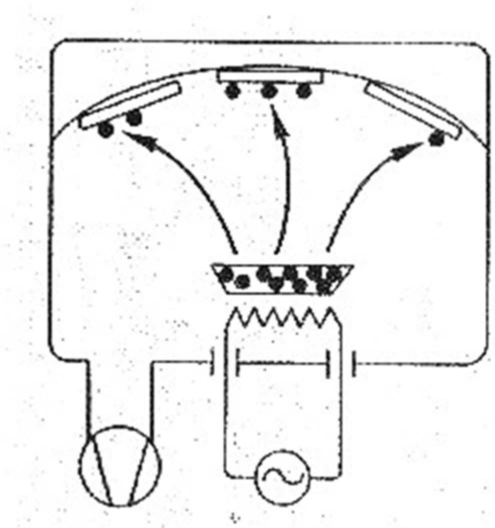
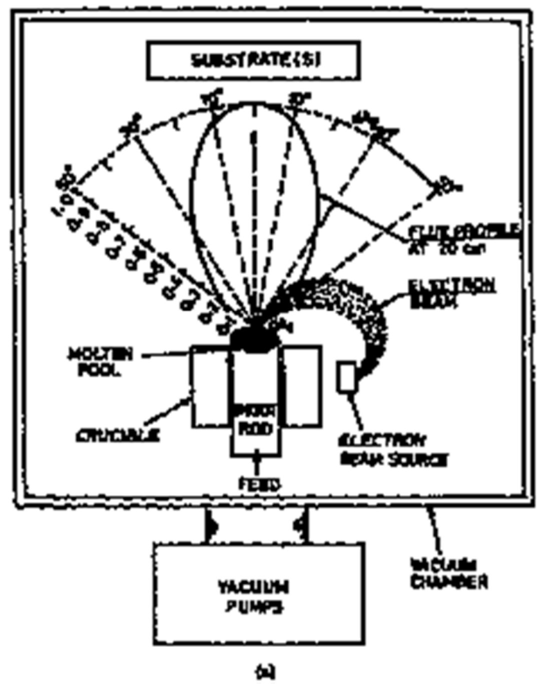
Deposition Processes

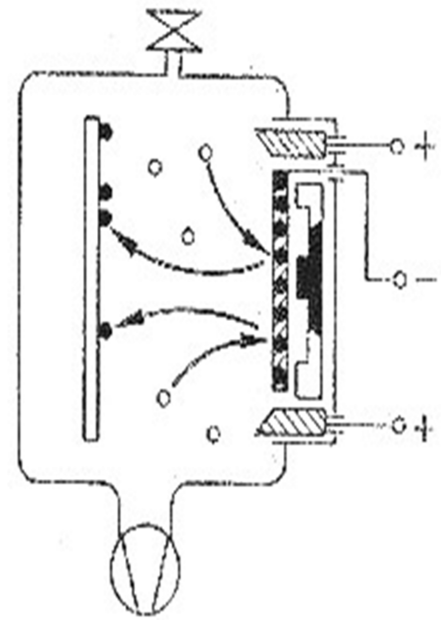
Depositing metal films



Thermal Evaporation



e-Beam Evaporation



Sputtering

Figures from: http://www.vacuum-guide.com/english/equipment/ae_thin_film_deposition.htm

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Deposition Processes

Items to be coated (*substrates)* are placed in a vacuum chamber. A vapor of metal atoms is created in the chamber, which will coat all exposed surfaces in the chamber including the substrates.

In *thermal* evaporation, a block or wire of metal is heated with a resistive heating element to form the metal vapor.

In *electron-beam* evaporation, a block of metal is heated when a beam of energetic electrons is caused to impact the metal.

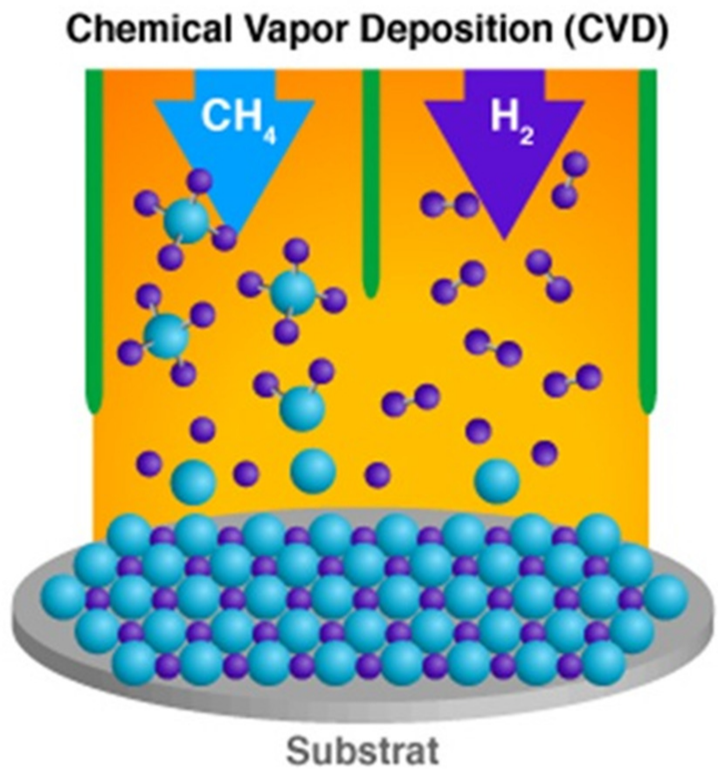
In *sputtering,* an ionized gas (*a plasma*) is formed and electrically attracted to a solid sheet of metal. This causes metal atoms to enter the vapor phase and move to the substrate, coating it.

Deposition Processes

Depositing semiconductors and insulators.

Sputtering can be used

Also used is **Chemical Vapor Deposition.** Reactive chemicals (*precursors)* are introduced into the vacuum chamber where they react in the vapor phase. The reaction products form a condensing compound that coats the substrate with a thin, regular film.



http://www.mechanicalengineeringblog.com/tag/graphene-properties/

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Layer Modification

- **Doping**
  - To make a useful component like a transistor or diode, a semiconductor like silicon must have certain impurities added. These are called ***dopants**.*
  - Common dopants include boron, aluminum, gallium, nitrogen, phosphorus, and arsenic.

- **Oxidation**
  - A pure layer of silicon can have its surface turned into silicon dioxide (a very good insulator) by placing it into a hot oven with a pure oxygen atmosphere.

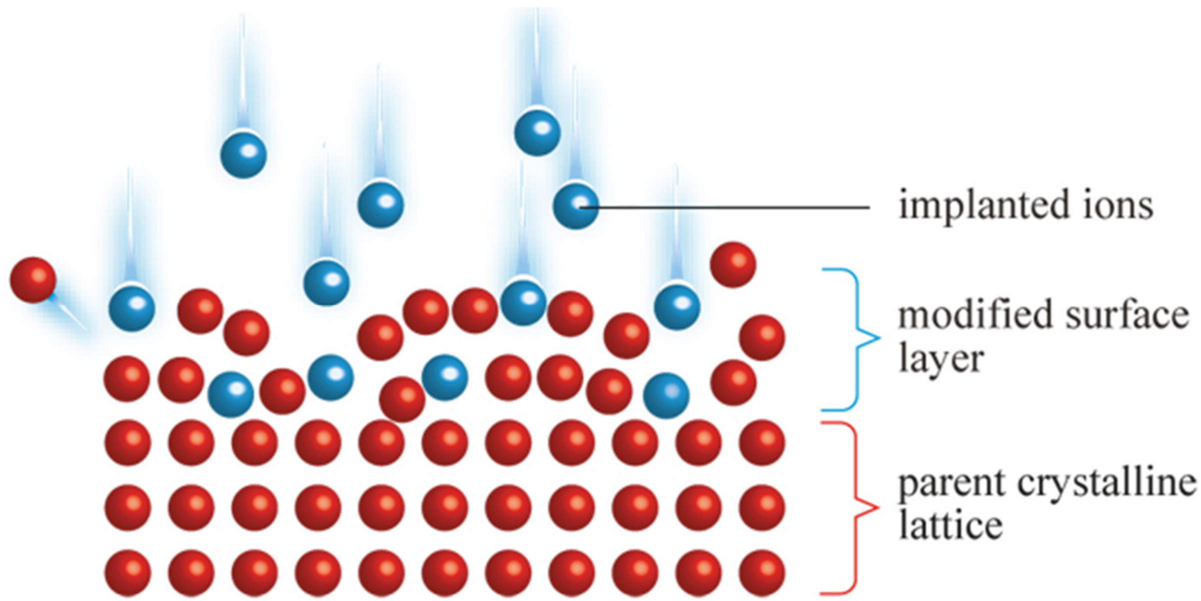
Dopant introduction

Dopant atoms are introduced into a silicon substrate by either

- **Vapor deposition**
  Diffusion of gas-phase atoms
- **Ion Implantation**
  Accelerating a beam of dopant ions at the surface

Dopants by ion implantation

A beam of energetic dopant ions is impacted into the silicon surface, implanting the ion in the solid. These impacts introduce undesirable flaws in the silicon crystal, which must be repaired by annealing the materials at high temperature.



http://eng.thesaurus.rusnano.com/upload/iblock/1ba/ion%20implantation1.jpg with permission

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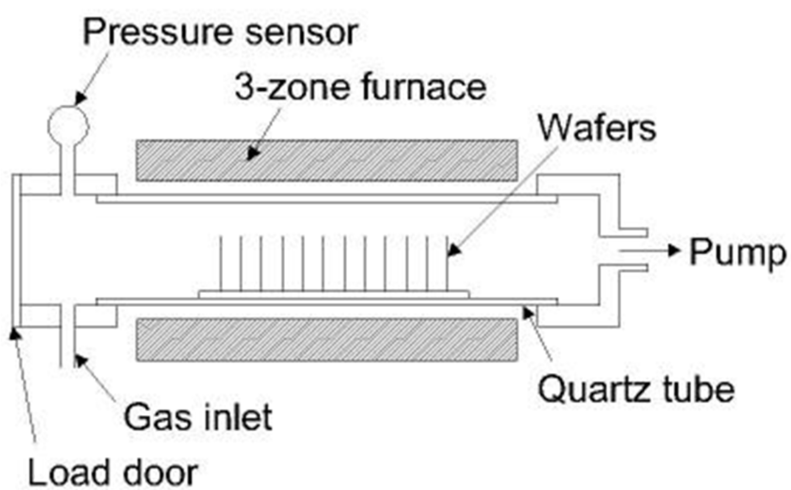
Dopants by vapor diffusion

Gas-phase atoms are introduced into a vacuum chamber where they can diffuse into the solid silicon. Elevated temperatures must be used to speed up the diffusion.



http://www.memsnet.org/mems/processes/deposition.html

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Microfabrication Step 4: Pattern Transfer

The pattern is contained in the photomask.
To replicate this pattern on a wafer substrate:

•Deposit liquid *photoresist* on wafer by spin coating

•Pattern the resist via exposure to light through the photomask

•*Develop* the photoresist

•Expose wafer to etchant. This attacks any exposed areas and "sculpts' the wafer according to the pattern.

•Wash the wafer

•Repeat for next layer

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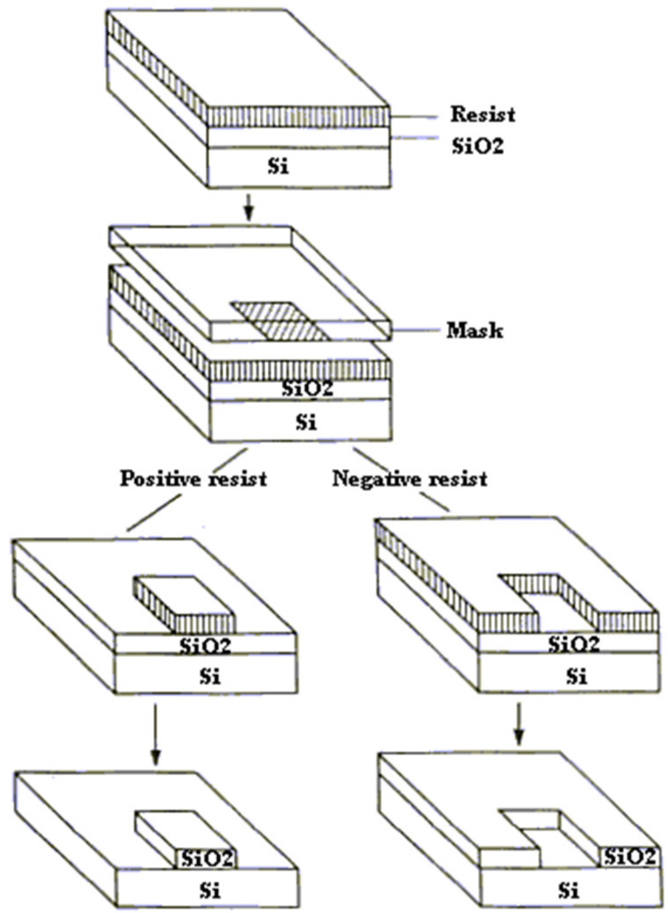
Photolithography process schematic



http://ahshonorschemistry.wikispaces.com/A-Silicon+Wafer+Patterned with permission

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Applying the Photoresist to a Substrate

Photoresist is a liquid chemical. It may be applied to the silicon wafer in many ways, but is most commonly *spin coated.*

A spin coater is a small, enclosed turntable that can spin at around 3000 rpm. It holds the wafer on its platter with a vacuum.

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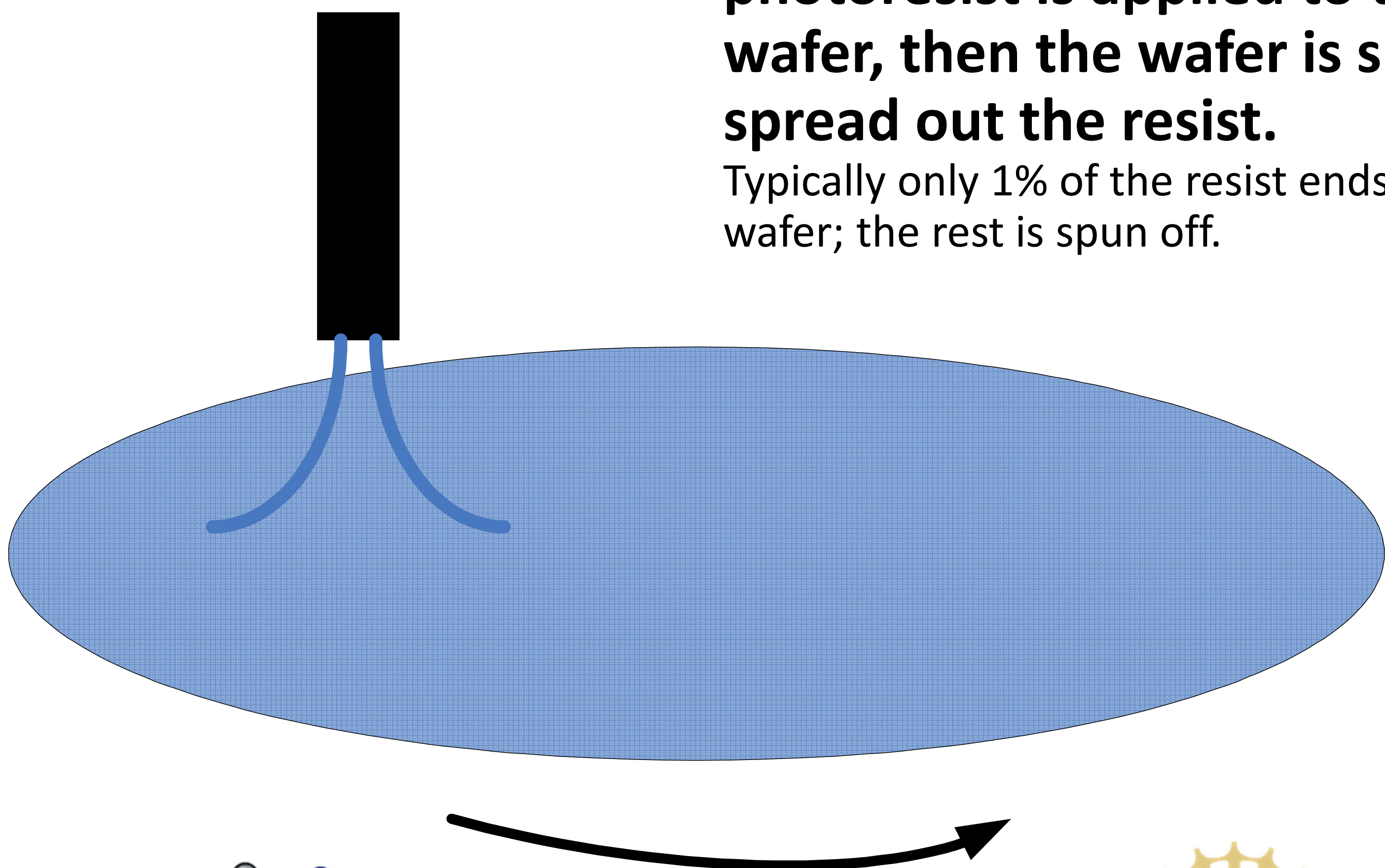
Applying the Photoresist to a Substrate



First, a small amount of photoresist is applied to the wafer, then the wafer is spun to spread out the resist.

Typically only 1% of the resist ends up on the wafer; the rest is spun off.

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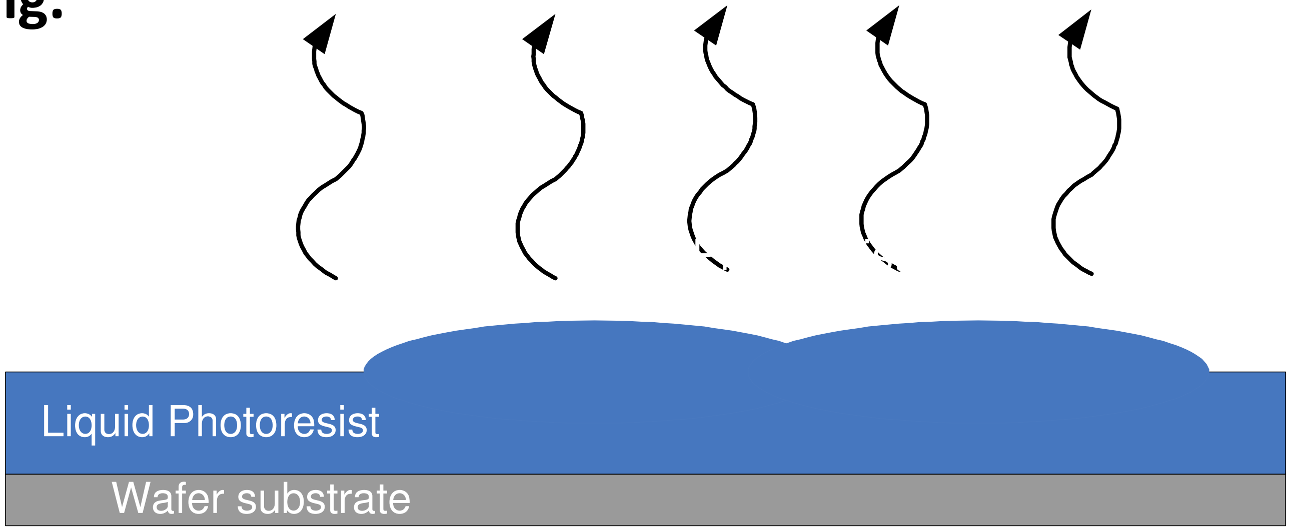
Applying the Photoresist to a Substrate

The photoresist dries by solvent loss as it thins out via spinning.



The result is a thin, uniform layer.

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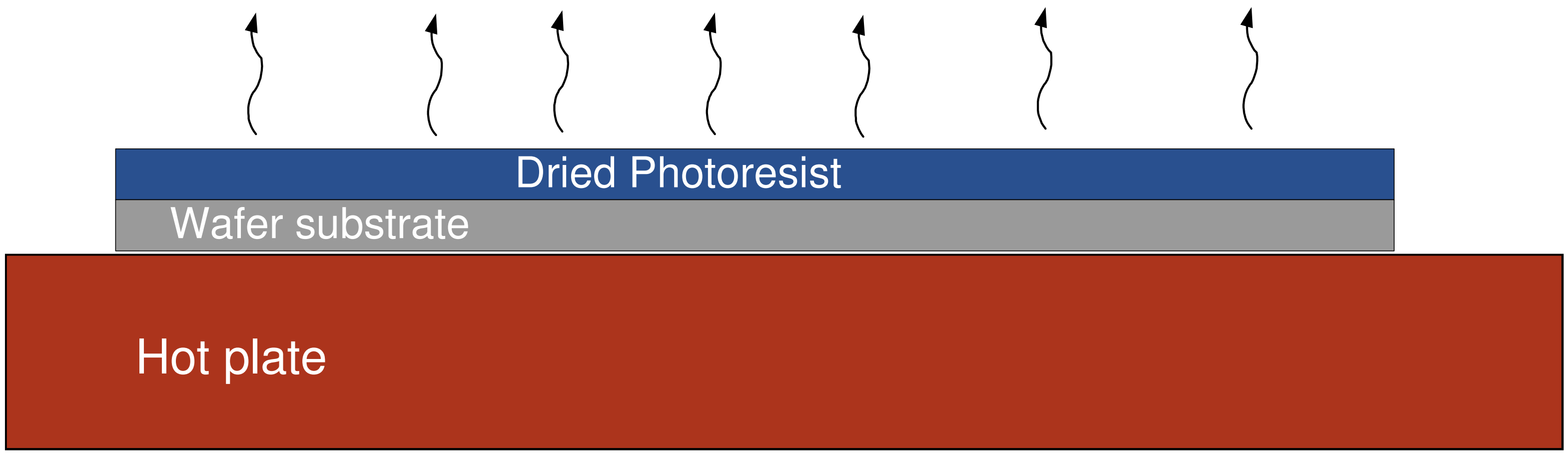
Baking the Photoresist

The photoresist will still have some solvent left in it after spinning. It is heated slightly (the "soft bake") to drive off any remaining solvent.



The wafer is now ready for exposure.

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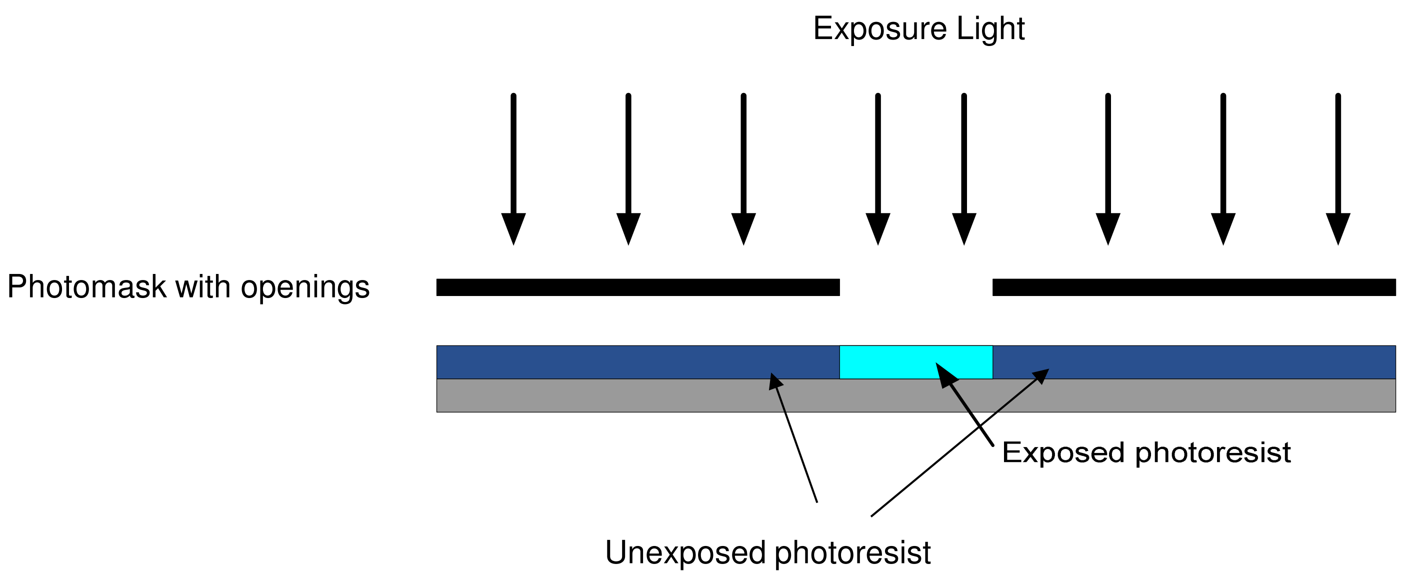
Photoresist Exposure

In the simplest form of lithography, called contact lithography, the photomask is placed on the photoresist-coated wafer, and intense light is applied. Wherever the mask has openings, the resist is exposed and undergoes a chemical change.



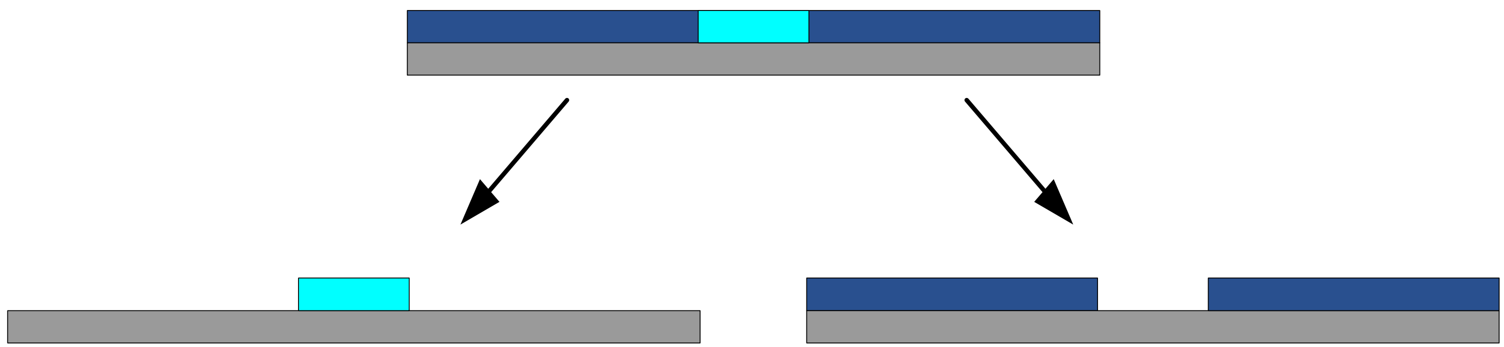
Photochemistry

When light strikes the photoresist, its molecules under go a chemical reaction. The type of reaction depends on the type of resist used, either a *negative* or *positive* resist.

- In a negative resist, the areas exposed to light become *less* soluble in a water-based solution called *developer.* The exposed areas remain while the rest of the resist is dissolved away.
- In a positive resist, the areas exposed to light become *more* soluble in the developer. These areas are dissolved away in the developer, leaving everything else untouched.

Negative and Positive Photoresists

Exposed photoresist on wafer

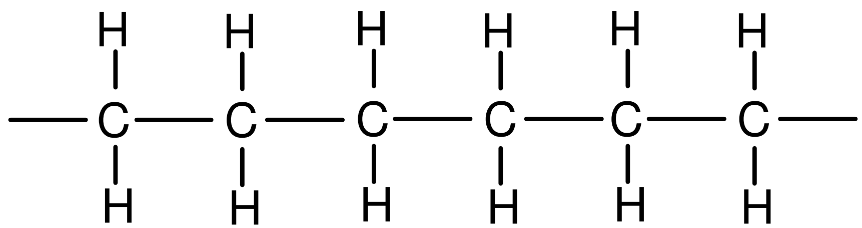


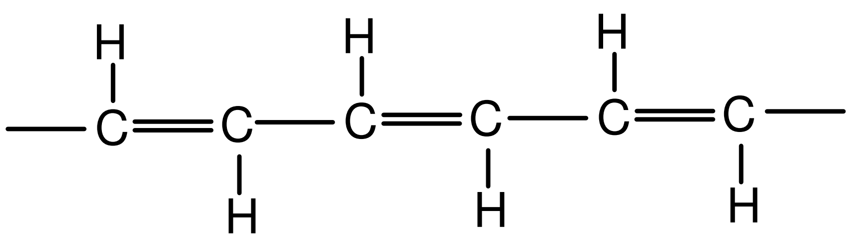
Negative resist: open space in mask becomes an opaque feature on the wafer.

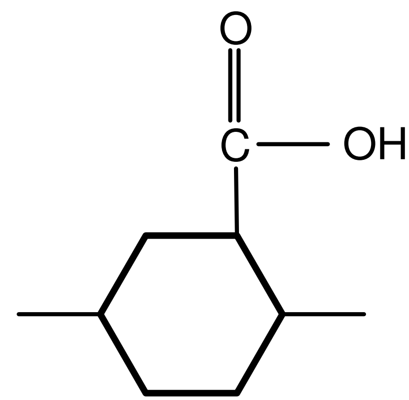
Positive resist: open space in mask remains an open feature on the wafer.

Photoresist Chemistry

Photoresists consist of *polymer* molecules dissolved in a solvent. Three very simple polymer molecules are shown here.







The C's represent carbon atoms, the H's are hydrogen atoms, and the hexagon is a 6-carbon ring. The pattern can repeat many thousands of times in a polymer.

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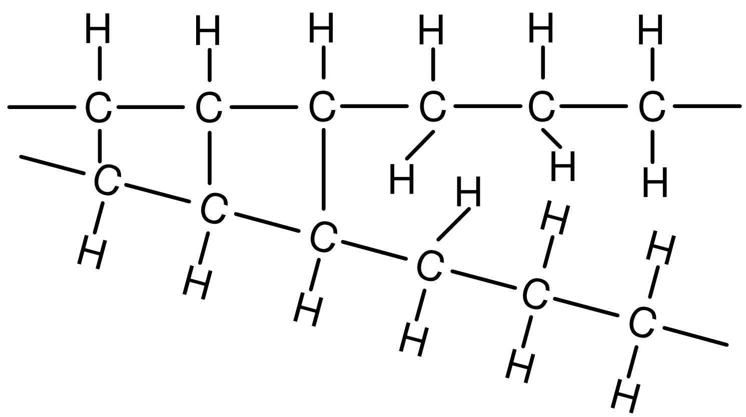
Photoresist Chemistry

When light strikes these polymer molecules, they undergo a chemical reaction. The type of reaction depends on the type of resist used.

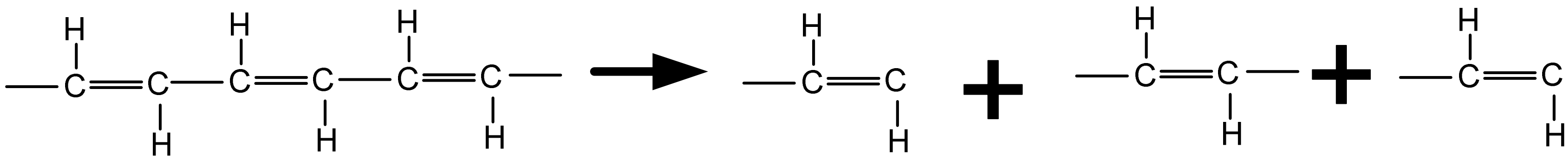
In a negative resist, light exposure may make the polymers *crosslink,* which means they bond to neighboring molecules to form a strong network, like this:



These larger polymer molecules are much less soluble in a solvent (like the developer). So any spot on the resist-coated wafer that was exposed to light will not dissolve when the wafer is immersed in the developer solution. The unexposed (and thus un-reacted) molecules, on the other hand, will dissolve away in the developer.

Photoresist Chemistry

When a positive resist is exposed to light, the polymer molecules tend to break into smaller fragments.



These smaller, lighter molecules are more likely to dissolve (or will dissolve more quickly) in the developer. The reaction with light may also create *polar* regions on the molecule, making it more likely to dissolve in water or water –based solutions.

So any spot on the resist-coated wafer that was exposed to light will readily dissolve when the wafer is immersed in the developer solution. The unexposed resist molecules will remain on the wafer.

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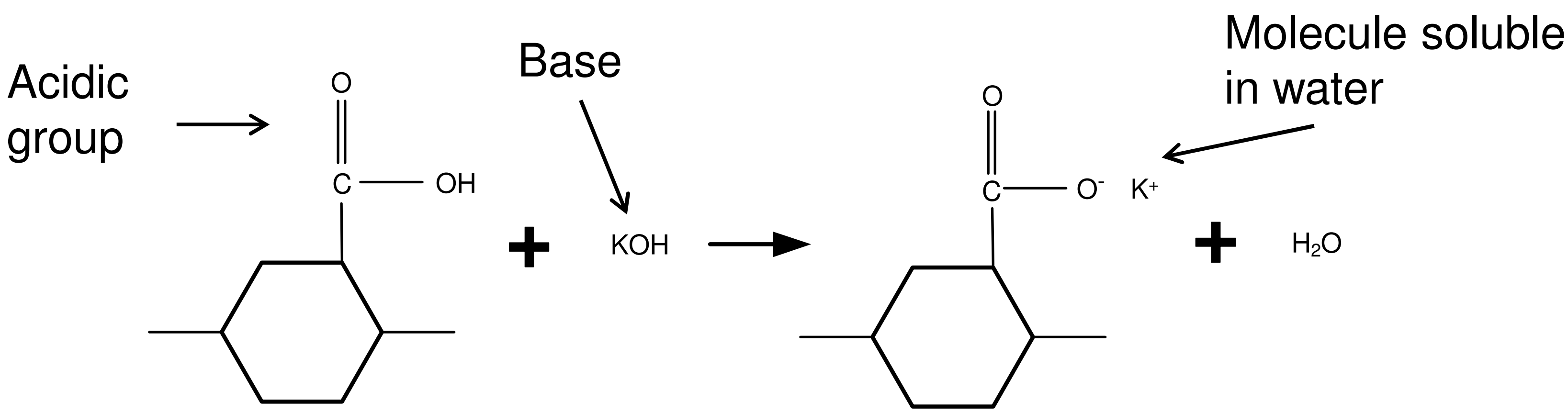
Developer Chemistry

After the photoresist-coated wafer has been exposed to light, it is immersed in a water-based solution called *developer.*

Photoresists are formulated so that the areas to be removed are acidic. If these acidic areas are exposed to a basic (or alkaline) solution, they will react and dissolve in the developer**.**



Developers are often basic solutions, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) in water.

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Optical Systems for Exposing the Photoresist

Exposure systems must have intense light sources and precision optics to focus the light

This mercury arc lamp produces intense light in the blue, violet, and ultraviolet wavelengths

Photo: Osram Sylvania

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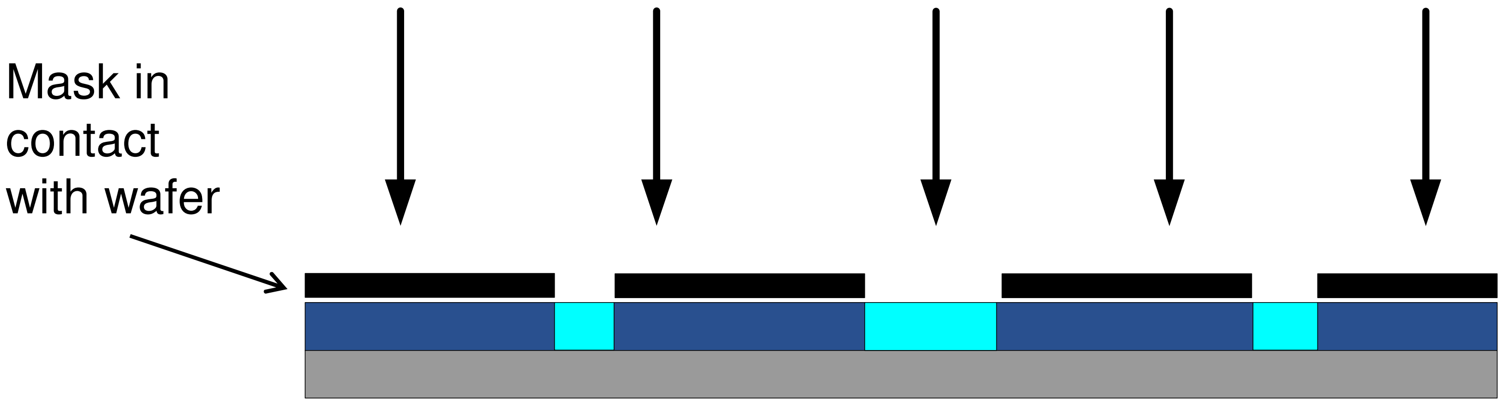
Contact and Projection Systems

In *contact* lithography, the mask is laid on the photoresist-covered wafer.

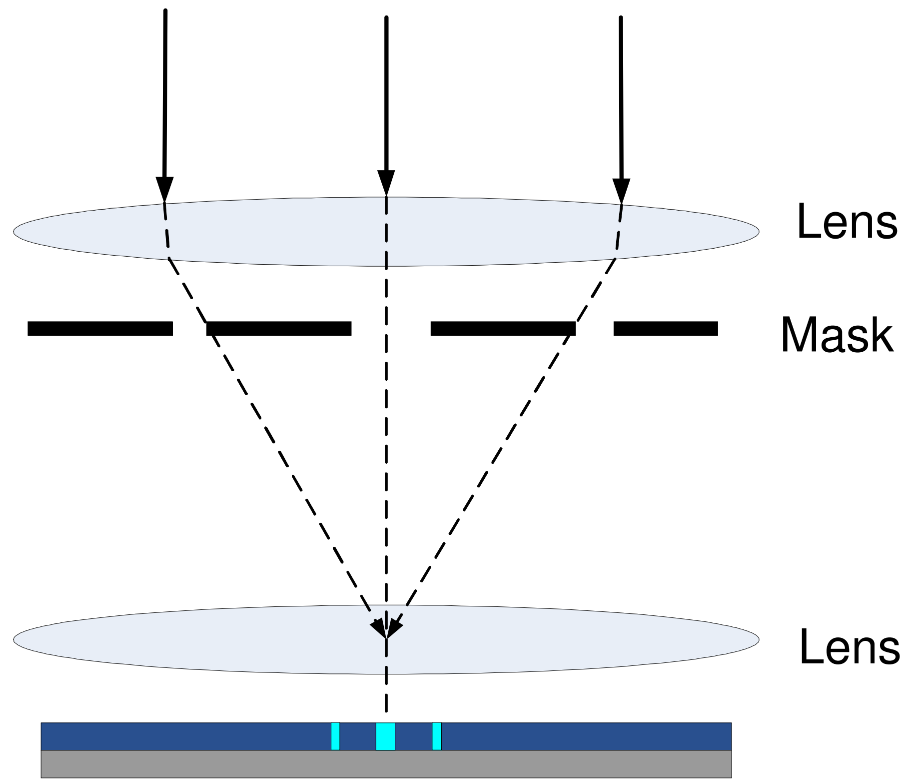


The mask pattern is directly reproduced in the resist—no change in size.

Contact and Projection Systems

In *projection* lithography, the mask patern is reduced in size using lenses.

The mask pattern is reduced by 5-10x in the resist, which allows much smaller features to be made.



Exposed pattern in resist is much smaller than in the mask

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Step 5: Etching Processes

- **Wet (chemical) etching**
  - Use a chemical that will dissolve the material that needs to be removed, while not interacting (as much) with the masking layer
  - For Si, SiO_2, hydrofluoric acid is used

- **Dry Etching**
  - Uses reactive ions/plasma to attack material
  - Material is forced into vapor phase and pumped away

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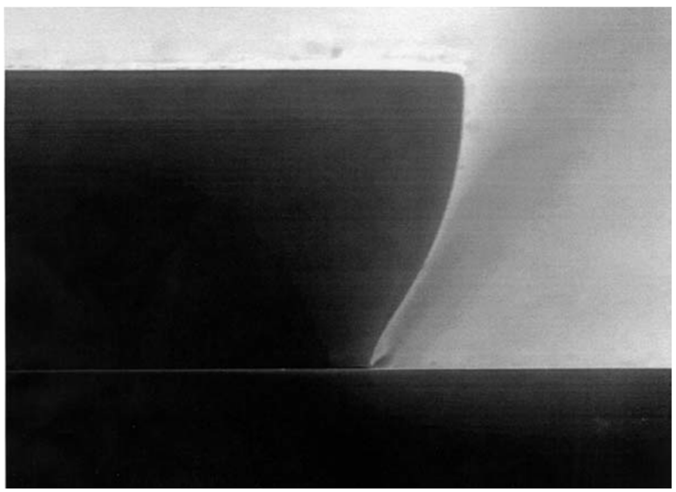
Results of Etching

Wet (chemical) etching

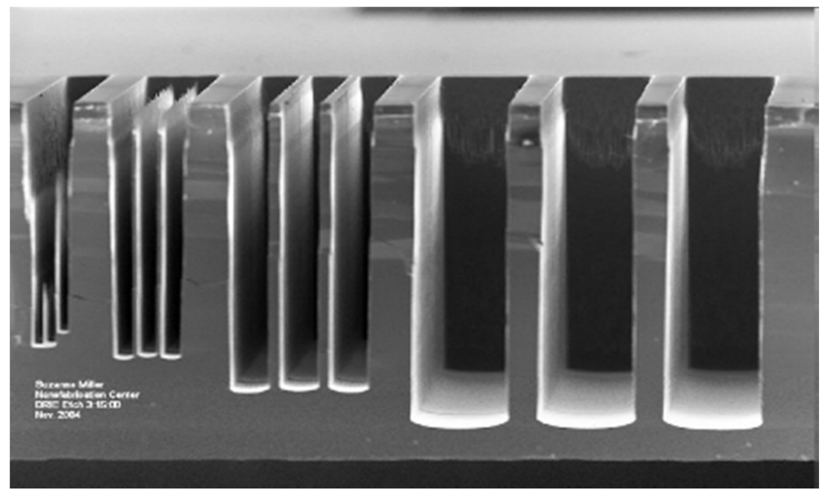
– Rapid, isotropic (etches out as fast as down, may under-etch a feature)

Dry Etching

– Slower, anisotropic (can etch straight walls with a high *aspect ratio*)



Wet etching.



Dry reactive ion (DRIE) etching.

Photo:
Futurrex Inc.

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Photo:
University of Minnesota
Nanofabrication Center

Step 6: Repeat

- **Wafer is washed, and the next layer is built using same series of steps:**
  - Deposit film layer
  - Modify if desired
  - Transfer pattern using photomask and resist
  - Etch
- **A typical IC can have over 15 layers**

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An animated summary of the making of an integrated circuit can be found here:

The making of a chip - Youtube video
www.youtube.com/watch?v=d9SWNLZvA8g

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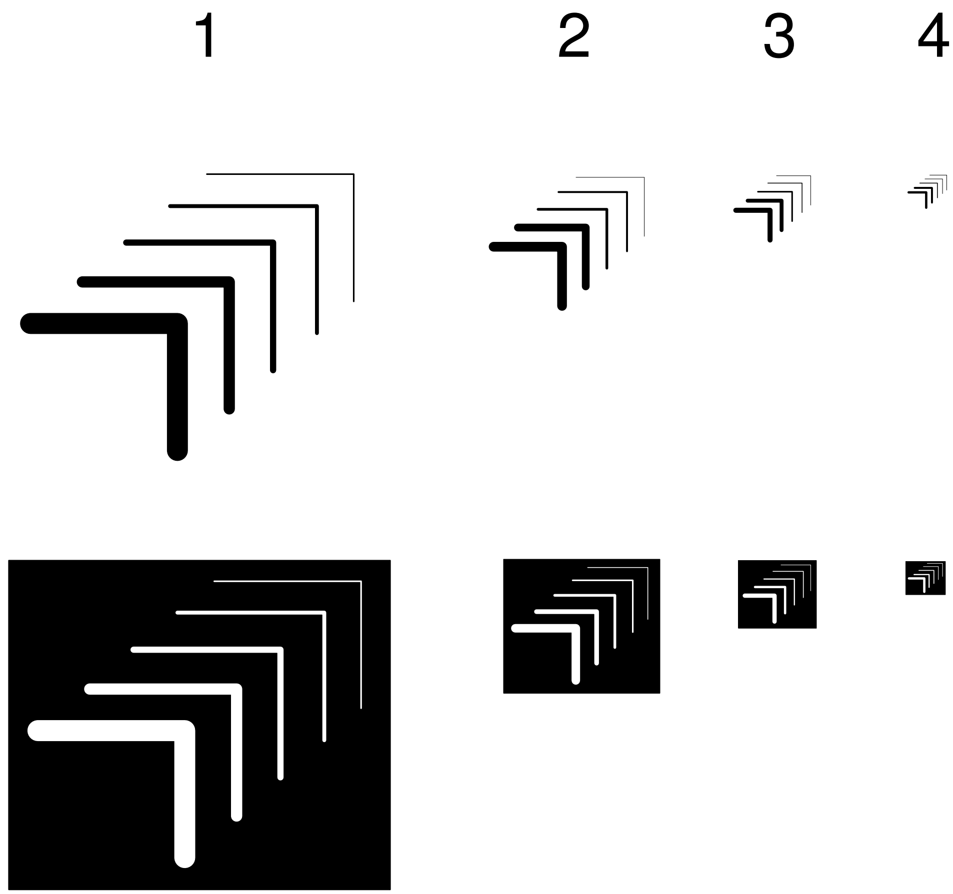
Mask Patterns



Module Title: Photolithography
Module section title: Graphical Content
Version Number: 3
Date modified: 08/29/12
Author: James Marti, Ph.D., University of Minnesota

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