



Nanolithography

The art of fabricating
nanoelectronic and
nanophotonic devices
and systems

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Outlines

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- Nanolithography
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- AFM nanolithography
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- Nanoimprint lithography
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- Electron spectroscopy
- Ionic Spectrometry

What is Lithography

- ❑ Lithography comes from the Greek word, *lithos*, means "stone" and *graphein*, means "to write".
- ❑ Lithography depend on the fact that water and grease repel.
- ❑ This method was invented in 1796 by German author and actor Alois Senefelder as a cheap method of publishing art work on paper or to print text.
- ❑ In this a pattern drawn onto a flat limestone and than paint the printing ink onto the stone. While the stone background absorbs water, the greasy substance holds wet ink on top.
- ❑ Press paper against the stone to transfer the pattern.
- ❑ In the 20th and 21st century, it becomes an important technique with unique dramatic capabilities in the Art field.
- ❑ Many techniques of lithography have been developed in the last half a century with various lens systems and exposure radiation sources including photons, X-rays, electrons, ions and neutral atoms.
- ❑ Photolithography is the most widely used technique in microelectronic fabrication, particularly for mass production of integrated circuits.



Fig 1 : Limestone rocks

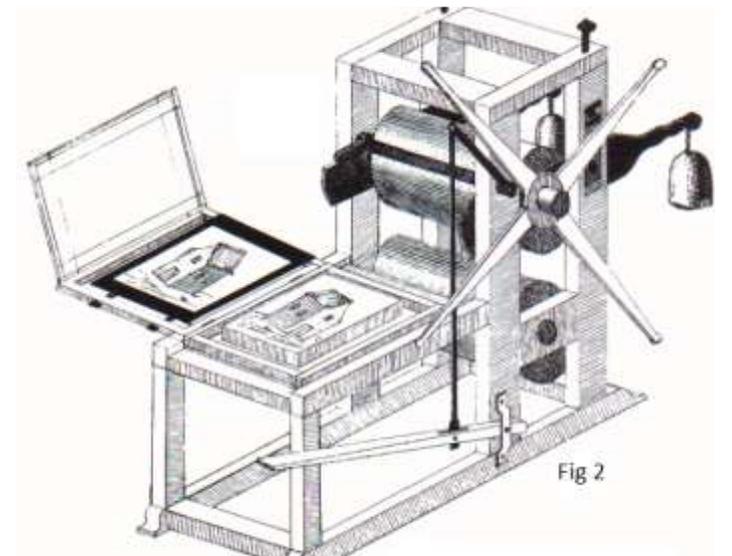


Fig 2

Photolithography

Photolithography is the process of transferring geometric shapes on a mask to the surface of a silicon wafer.

Photolithography Steps:

1) Wafer Cleaning:

In the first step, the wafers are chemically cleaned to remove organic, ionic, and metallic impurities.

2) Barrier Layer Formation:

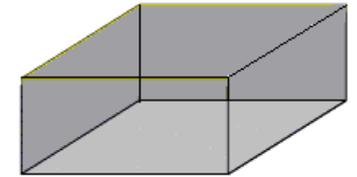
After cleaning, silicon dioxide, which serves as a barrier layer, is deposited on the surface of the wafer.

3) Photoresist Application:

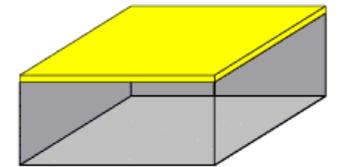
Photoresist is applied to the surface of the wafer by high-speed centrifugal spinning. This technique, known as "Spin Coating," produces a thin uniform layer of photoresist on the wafer surface. In this process a liquid solution of photoresist is give out from the wafer by rapid spin and produce uniform thin layer (0.5 μm to 2.5 μm). Spin coating/ spinner typically runs at 1200rpm to 4800rpm for 30sec to 60sec. Chemicals commonly use as photoresist are;

- Poly methyl methacrylate (PMMA)
- Poly methyl glutarimide (PMGI)
- Phenol formaldehyde resin (DNQ/Novolac)

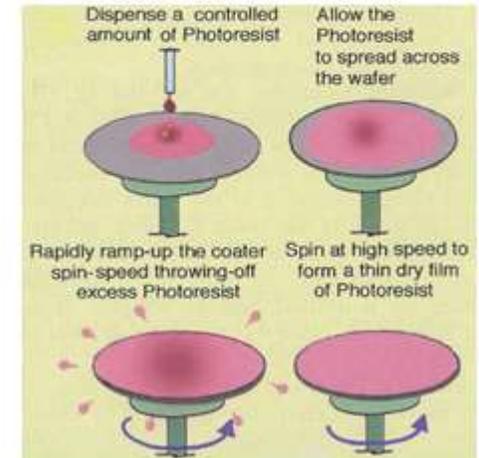
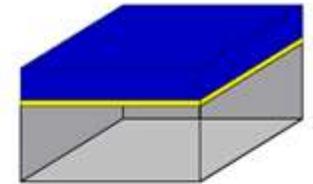
- Photoresist
- Silicon dioxide
- Silicon



1) Cleaning



2) Barrier formation



3) Spin-coating

a) Positive Photoresist:

Positive photoresists are exposed to UV light, the underlying material is to be removed. In these resists, exposure to the UV light changes the chemical structure of the resist so that it becomes more soluble in the developer. The exposed resist is then washed away by the developer solution. In other words, "whatever shows, goes."

b) Negative Photoresist:

Negative photoresists behave in just the opposite manner. Exposure to the UV light causes the negative resist to become polymerized, and more difficult to dissolve. Therefore, the negative resist remains on the surface wherever it is exposed, and the developer solution removes only the unexposed portions.

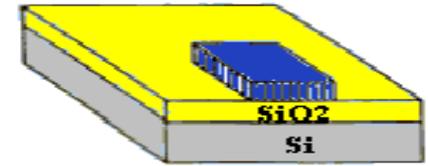
4) Prebaking:

Prebaking is the step during which almost all of the solvents are removed from the photoresist. The photoresist becomes photosensitive after prebaking. Photoresist is prebaked at 90°C to 100°C for 5 min to 30 min.

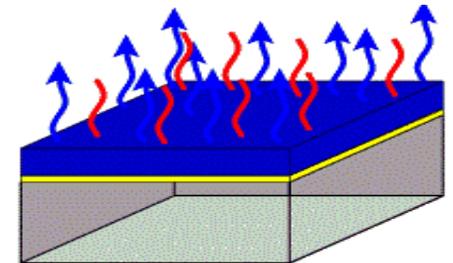
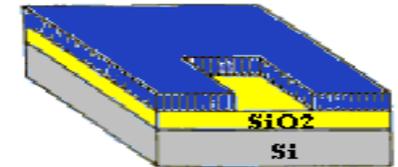
5) Mask Alignment and Exposure:

A mask or "photo mask" is a square glass plate with a patterned combination of metal film on one side, pattern transferred onto the wafer surface. There are three primary exposure methods: contact, proximity, and projection. They are shown in the figure below.

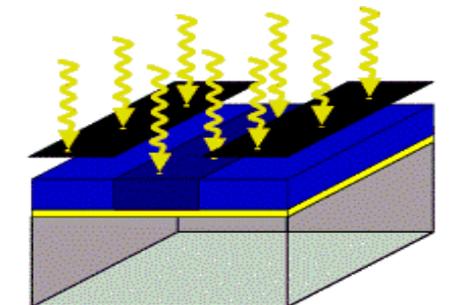
a) Positive Photoresist



b) Negative Photoresist



4) Prebake



5) Mask Alignment & Exposure

❑ Contact Printing:

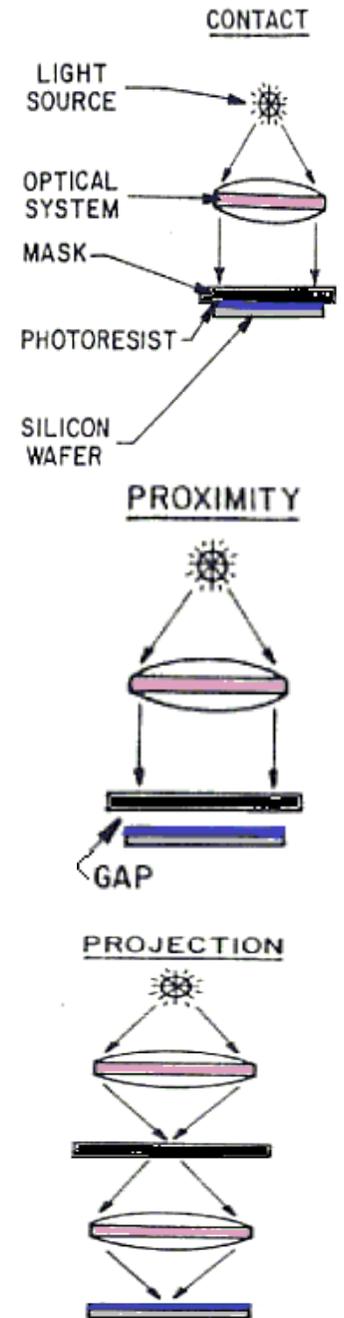
In contact printing wafer is brought into physical contact with photo mask. Because of the contact between the resist and mask, very high resolution is possible. The problem with contact printing is that fragments trapped between the resist and the mask, can damage the mask and cause defects in the pattern.

❑ Proximity Printing:

The proximity exposure method is similar to contact printing except that a small gap, 10 to 25 microns wide is maintained between the wafer and the mask. This gap minimizes (but may not eliminate) mask damage. Approximately 2 to 4 micron resolution is possible with proximity printing.

❑ Projection Printing:

Projection printing avoids mask damage entirely. An image of the patterns on the mask is projected onto the wafer, which is many centimetres away. To achieve high resolution, only a small portion of the mask is imaged it has about 1-micron resolution.



6) Development:

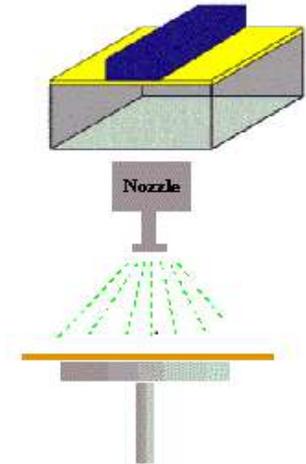
Development is a process in which exposed/non-exposed area is dissolved by developer. Most commonly used developer is tetra methyl ammonium hydroxide is used in concentrations of 0.2 - 0.26. Developer is important in controlling the development uniformity. Therefore two methods are mainly used i.e. spin development and spray development. During spin development wafers are spun and developer is poured onto the rotating wafer. In spray development, the developer is sprayed rather than poured, on the wafer by using a nozzle that produces a fine spray over the wafer.

7) Hard-Baking:

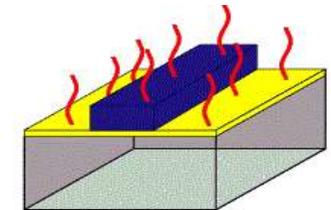
The hard bake is used to harden the final resist image at the temperature (120°C - 150°C), so that it will hold out the harsh environments of etching.

8) Etching:

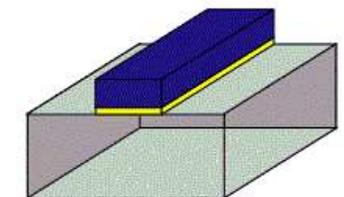
Etching is performed either using wet chemicals such as acids, or more commonly in a dry etching (*by exposing the material to a bombardment of ions*). The photoresist will “resists” the etching and protects the material covered by the resist. When the etching is complete, the resist is stripped leaving the desired pattern.



6) Development



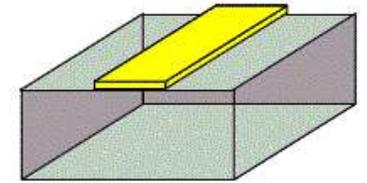
7) Hardbake



8) Etching

9. Stripping:

After the imaged wafer has been etched the remaining photoresist must be removed. There are two classes of stripping techniques; wet stripping and dry stripping. A simple example of stripper is acetone. Acetone tends to leave residues on the wafer. Most commercial organic strippers are phenol-based.



9) Stripping

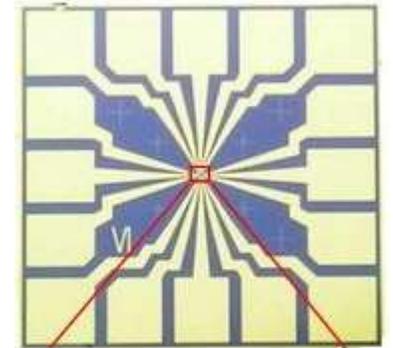
Applications of Photolithography

Main application:

IC designing process

Other applications:

Printed electronic board, nameplate and printer plate.



Sample fabricated
by photolithography

Electron Beam Lithography

- Electron Beam Lithography is a specialized technique for creating extremely fine patterns. It is derived from the scanning electron microscope. Electron beams can be focused to a few nanometres in diameter.
- The basic idea behind electron beam lithography is identical to optical lithography. The substrate is coated with a thin layer of resist, which is chemically changed under exposure to the electron beam, so that the exposed/non-exposed areas can be dissolved in a specific solvent.
- Electron beam lithography is the most powerful tool for the fabrication of features as small as 3nm to 5 nm.

The EBL system is normally referred to as the column. An EBL column (Fig. 4) typically consists of following components;

✓ **Electron source:**

Electrons may be emitted from a conducting material either by heating or by applying an electric field.

✓ **Stigmators:**

A stigmator is a special type of lens used for the alignment of e-beam. Stigmators may be either electrostatic or magnetic and consist of four or more poles.

✓ **Electron Lenses:**

Electron lenses can be made only to converge, not diverge. Electrons can be focused either by electrostatic forces or magnetic forces.

✓ **Apertures:**

Apertures are small holes through which the beam passes on its way down the column. There are several types of apertures. A blanking aperture is used to turn the beam on and off. A beam limiting aperture has two effects: it sets the beam convergence angle through which electrons can pass through the system, controlling the effect of lens aberrations and thus resolution.

✓ **Blanking Plates:**

Blanking plates are used to modify the e-beam, these are simple electrostatic deflector. One or both of the plates are connected to an amplifier with a fast response time.

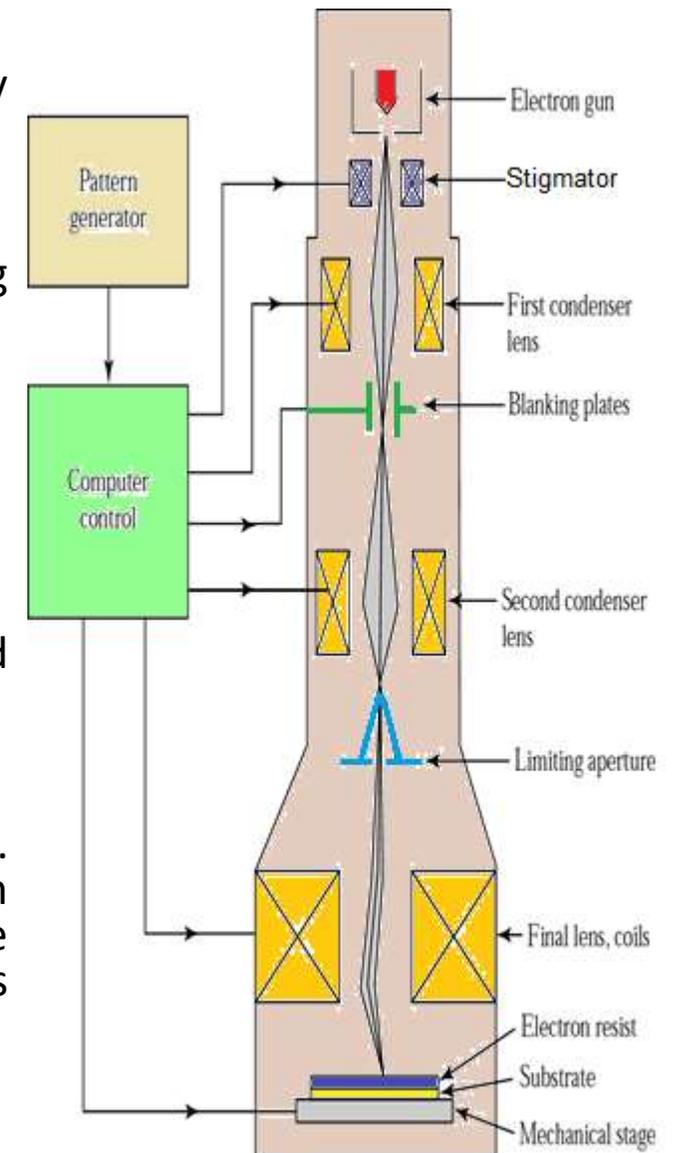


FIG 3

Advantages of EBL

- Print complex patterns directly on wafers
- Eliminates the diffraction problem
- High resolution up to 20 nm (photolithography ~50nm)
- Flexible technique

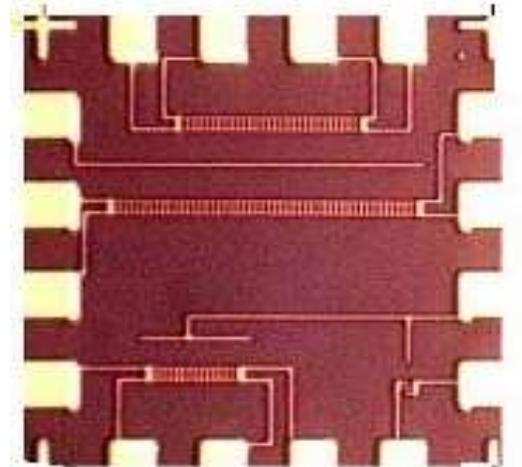
Disadvantages of EBL

- Slower than optical lithography (approximately 5 wafers / hour at less than 0.1 μ resolution).
- Expensive and complicated
- Forward scattering
- Backward scattering
- Secondary electrons

Applications of EBL

Electron beam Lithography (EBL) is used primarily for two purposes

- ❖ Very high resolution lithography.
- ❖ Fabrication of masks.



Sample fabricated
by E-beam lithography

Nanolithography

- » Nanolithography concerns with the study and application of nanometre-scale structures.
- » Nanolithography is derived from the Greek words “nanos”, meaning (*dwarf*) “lithos”, meaning (*rock or stone*) and “graphein” meaning (*to write*). Therefore the correct translation is “*tiny writing on stone*”.
- » Nanolithography is used e.g. during the nanofabrication of semiconductor integrated circuits (*nanocircuitry*), for nanoelectromechanical systems (NEMS) or for almost any other fundamental application across various scientific disciplines in nanoresearch. This method is different to various existing nanolithography techniques like;
 - ✓ X-ray lithography
 - ✓ Atomic Force Microscope (AFM) nanolithography.
 - Soft lithography
 - ✓ Nanoimprint lithography (NIL).
 - ✓ Dip-pen (DPN) nanolithography



FIG 4 *Nanocircuitry*

X-Ray Lithography

- X-rays having wavelengths of 0.04nm to 0.5 nm represent another radiation source for high-resolution design reproduction into polymeric resist materials.
- X-ray lithography was first demonstrated to obtain high-resolution designs using X-ray proximity printing by Spears and Smith.
- X-ray lithography can be extended optical resolution of 15 nm.
- ❖ **Essential elements in X-ray lithography**
 - ✓ A mask consisting of a pattern made with an X-ray absorbing material on a thin X-ray transparent membrane.
 - ✓ An X-ray source of sufficient brightness.
 - ✓ An X-ray sensitive resist material.

X-Ray Lithography Cont.

- The X-rays illuminate a mask placed in proximity of a resist-coated wafer.
- The X-rays are typically from synchrotron radiation source, allowing rapid exposure.
- X-ray lithography is expensive, because of the expense of operating a synchrotron. The actual operating expenses without considering the initial investment of tens-of-millions of dollars. Therefore, the LIGA process was developed to reduce the dependency on a synchrotron.
- LIGA is the abbreviation from the German words, “Lithographie” (*Lithography*), “Galvanik” (*Electroplating*), & “Abformung” (*Molding*).

X-Ray Lithography Steps

1. Irradiation:

The first step in x-ray lithography is irradiation which involves exposing a thick layer of resist to high-energy beam of x-rays from a synchrotron. The mask membrane is normally a low atomic number material such as diamond, beryllium, or a thin membrane of a higher atomic number material such as silicon or silicon carbide.

2. Development:

In this step the pattern is etched into the resist substrate by the use of x-rays.

3. Electroforming:

Electroforming is the same as electroplating. Electroforming suggests that the plating is used to create an actual metal component.

4. Mould insert:

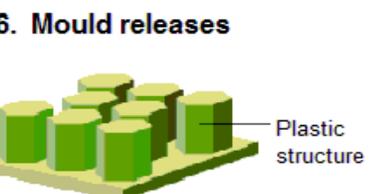
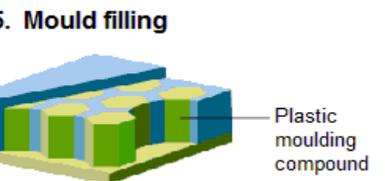
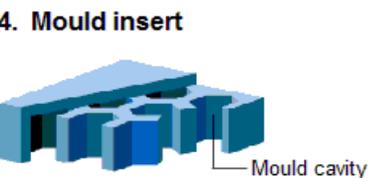
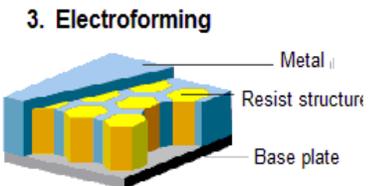
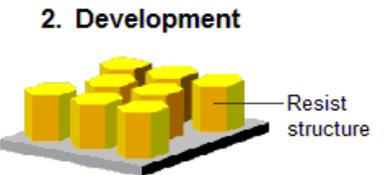
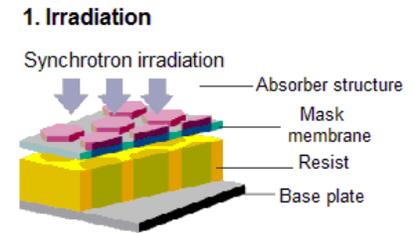
A chemical solvent PMMA (*poly methyl methacrylate*) $C_5O_2H_8$ is used to dissolve material, resulting model of the mask pattern. After removal of the resist, a freestanding metal structure is produced.

5. Mould filling:

The metal structure may be a final product, or serve as a mold insert for precision plastic moulding.

6. Mould releases:

The plastic mold retains the same shape, size, and form as the original resist structure but is produced quickly. Moulded plastic parts may then be final product.



Advantages of X-Ray Lithography

- Short wavelength from X-rays 0.4-4 nm
- No diffraction effect
- Simple to use
- No lens
- Faster than EBL
- Uniform refraction pattern
- High resolution for small feature size

Disadvantages of X-Ray Lithography

- Thin lens
- Distortion in absorber
- Cannot be focused through lens
- Masks are expensive to produce

Application of X-Ray Lithography

- X-ray lithography is primarily used in nanolithography
- 15 nm optical resolution
- Utilizes short wavelength of 1 nm
- Requires no lenses
- Allows for small feature size



Sample fabricated by
X-ray lithography

Atomic Force Microscope Lithography

- » AFM nanolithography is a tool for materials structuring and designing with nanometre precision, AFM was invented in 1986.
- » AFM can be used to study both insulating and conducting materials, and can be operated in liquid, air or vacuum
- » AFM nanolithography design a wide range of materials including metals, semiconductors, polymers and biological molecules in different media.



FIG 5; Multi-Mode AFM

Working Principle of AFM

- ❖ The working principle of AFM nanolithography is based on the interaction between the probe and substrate. In AFM a tiny cantilever with a sharp tip is scanned across a surface. The interaction between the surface and the tip cause the cantilever to bend and the bending is monitored using a laser beam. In this way, nanometre changes in height can be measured and used to generate a three dimensional image of the surface.
- ❖ The typical radius of curvature of the probe is 20–60 nm, and the probe–substrate separation in close contact condition is <math><1\text{ nm}</math>. AFM exactly feels the surface. *AFM is a nanoscale game of blind man's buff!*

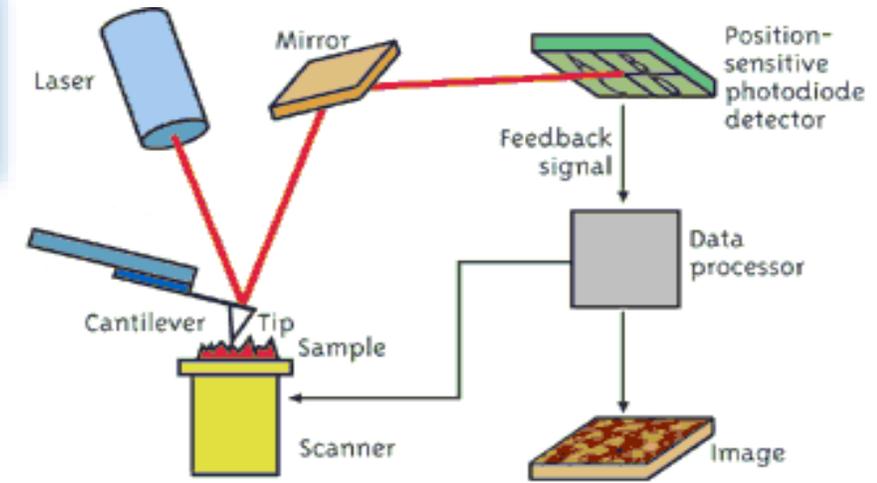
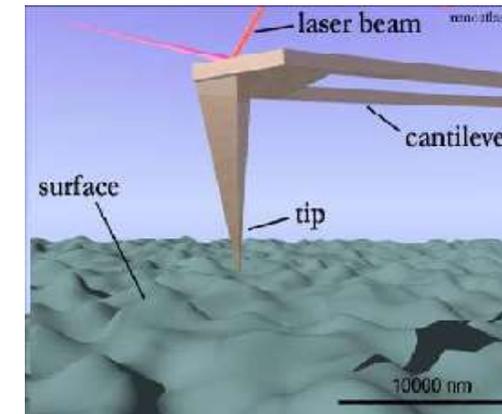
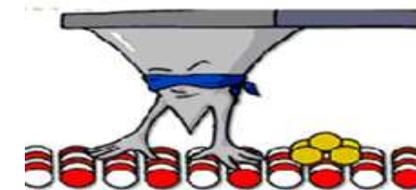


FIG 7; AFM setup



Left: Image of AFM tip

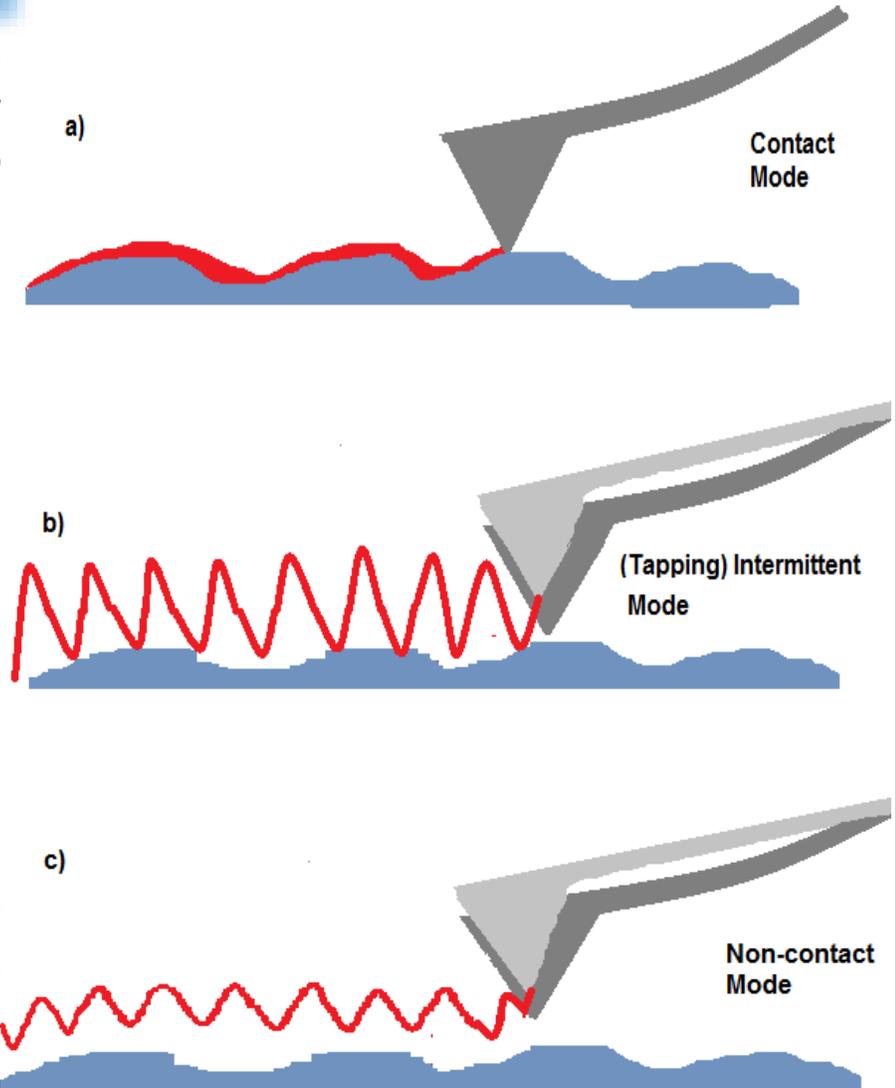


Right: A cartoon of AFM tip blindly feeling the surface.

FIG 8

Three Modes Of Operation

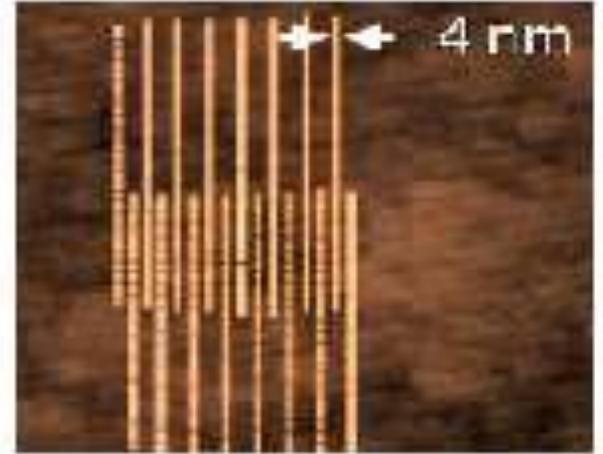
- Contact mode (*static mode*): AFM tip makes soft physical contact with the sample. The tip is attached to the end of a cantilever with a low spring constant. The contact force causes the cantilever to bend to accommodate changes in topography.
- Intermittent contact mode (*Tapping mode*): The cantilever is driven to oscillate up and down. The amplitude of this oscillation is greater than 10nm, typically 100 to 200nm.
- Non-contact (NC) mode (*Dynamic mode*): The cantilever is vibrated near but not contact to the sample surface at a frequency slightly above its resonance frequency (typically, 100 -400 kHz) where its amplitude is typically a few nm.



Conclusions

AFM is the versatile tool for investigate;

- ✓ Topography of surface.
- ✓ Properties of surface.
- ✓ Properties of single molecules.
- ✓ Force within molecules.



Parallel array of polymer wires fabricated by AFM

Soft Lithography (*Micro-contact printing*)

- Soft lithography has been developed as an alternative to photolithography and a replication technology for both micro and nanofabrication. Soft lithography uses the designs on a PDMS (*poly dimethyl siloxane*) stamp.
- This technique has wide range of application in cell biology, microelectronics, surface chemistry, micromachining, Designing cells, Designing DNA and Designing protein.

Nanoimprint Lithography (NIL)

Nano-imprint lithography (NIL) is a lithography technique that combines the speed of optical lithography with the resolution of EBL, we use NIL to make nanostructured substrates.

Special stamps contain the nanoscale designs to be fabricated on the substrate *fig: a*).

- ✓ The stamps are pressed into a polymeric material (*resist*) that was previously deposited on the substrate *fig: b*).
- ✓ When the stamp is filled with polymer, it is treated by UV light through the stamp, obtaining the stamps shape *fig: c*).
- ✓ A residual layer of resist is left and can be removed *fig: d*).



Fig: a)



Fig: b)

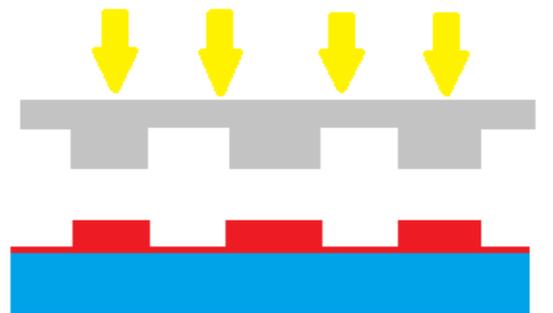


Fig: c)



Fig: d)

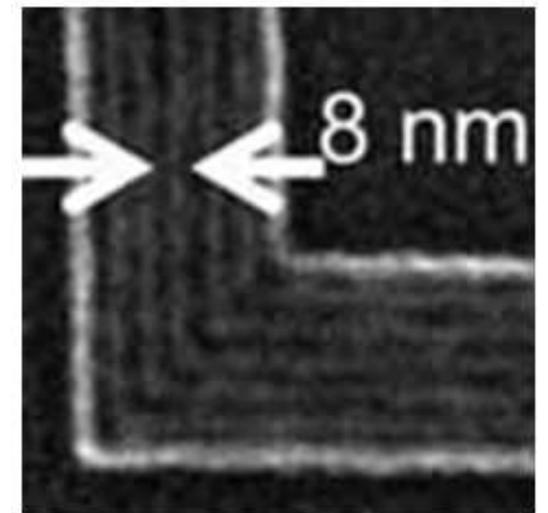
- ✓ A metal layer can be deposited on the sample as shown in *fig: e)*
- ✓ When the resist is removed, the nanoscale metal structures are left on the substrate *fig: f)*.



Fig: e)



Fig: f)



Sample fabricated by nanoimprint lithography

Applications

- It can be used to make optical, photonic, electrical and biological devices.
- Advances in mould manufacturing will have wide application of NIL in smaller devices.

Dip-pen Nanolithography

- DPN is a new AFM based direct write soft-lithography technique, which is used to create nanostructures on a substrate of interest by delivering collections of molecules thiols (*are the sulfur equivalent of alcohols, and the word is a combination of "thio" + "alcohol,"*) via capillary transport from an AFM tip to a surface gold.
- In DPN the tip of AFM cantilever as a “pen,” which is coated with chemical compound acting as an “ink,” and put in contact with substrate, the “paper”
- Note that "liquid inks" are governed by a very different deposition mechanism when compared to "molecular inks".
- Molecular ink diffusing from a nanoscale tip to a surface through a water meniscus.

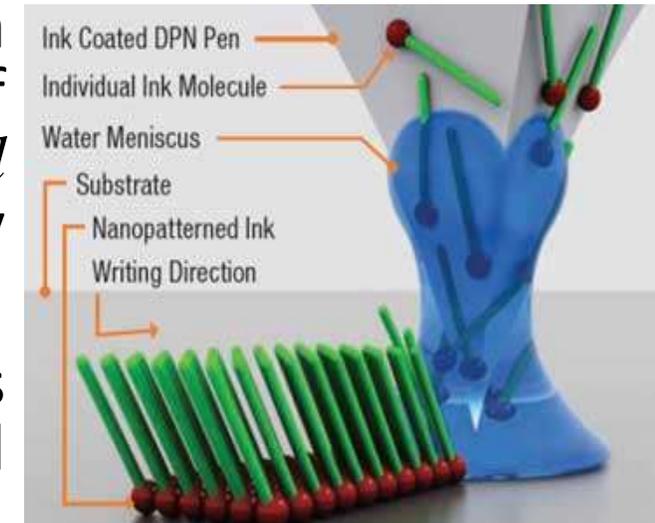
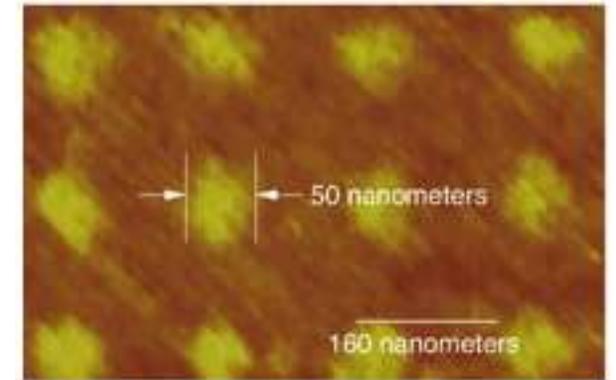


Fig: 9

Applications

- ✓ DPN is specially advantageous to bio molecular guidance.
- ✓ DNA and protein arrays are being fabricated as detection chips.
- ✓ DPN resolution is four to five orders of magnitude greater than other lithographic techniques.



Sample fabricated by
Dip pen nanolithography

Chemical Characterization

- Chemical characterization is to determine the surface and interior atoms and compounds as well as their three-dimensional distributions. Many chemical analysis methods have been developed for the surface analysis or thin films, but our discussion will be limited to the most popular techniques;
- ✓ Optical spectroscopy
- ✓ Electron spectroscopy
- ✓ Ion spectrometry.

Optical Spectroscopy

- ❑ Spectroscopy is method of “*Seeing the Unseenable.*” Using electromagnetic radiation to obtain information about atoms and molecules that are too small to see.
- ❑ Optical spectroscopy has been widely used for the characterization of nano- materials, and the techniques can be generally categorized into two groups: absorption and emission spectroscopy and vibrational spectroscopy.

Absorption and emission spectroscopy:

- As electrons move between the energy levels of an atom they can emit or absorb light energy. If the electron moves from a lower energy level to a higher energy level, the atom must absorb the energy. If the electron falls from a higher energy level to a lower energy level it will release energy by emitting light.
- By absorbing specific wavelengths of light, an electron moves from a lower energy level to a higher energy level. Since every kind of atom has a different electronic configuration, the wavelengths of light absorbed or emitted by an atom are unique to that element.
- By measuring the unique wavelengths and intensities of light an atom absorbs is called the Atomic Absorption Spectrum.
- We can directly observe the lines in the “*visible*” spectrum with our eyes, but many other lines outside the “*visible*” region exist and can be detected by specially designed spectrometers.

Optical Spectroscopy Cont.

Vibrational / Infrared Spectroscopy:

- Molecules and crystals can be thought of as systems of atoms or ions connected by springs (*chemical bonds*). These systems can be set into vibration, and vibrate with frequencies determined by the atomic weight and by bond strengths.
- They are at very high frequencies ranging from 10^{12} to 10^{14} Hz, which is in the infrared (IR) regions of the electromagnetic spectrum.
- The oscillations combine with an impinging beam of infrared electromagnetic radiation and to exchange energy with it when the frequencies are in resonance.
- In the infrared experiment, the intensity of a beam of infrared radiation is measured before and after it interacts with the sample.
- The identities, atomic arrangements, and concentrations of the chemical bonds that are present in the sample can be determined.

Electron Spectroscopy

- The electron spectroscopy depends on energy levels of the emission of photons (*X-ray*) or electrons. As schematically shown in Fig:10
- when an incident electron or photon strikes an unexcited atom, an electron from an inner shell is ejected and leaves a hole or electron vacancy in the inner shell (Fig:10b). An electron from an outer shell fills the hole by lowering its energy, and the excess energy is released through either emission of an X-ray (Fig:10c) or ejection of a third electron that is known as an Auger electron (Fig:10d).
- By measuring the energies of the X-rays and Auger electrons emitted by a material, its chemical compositions can be determined.

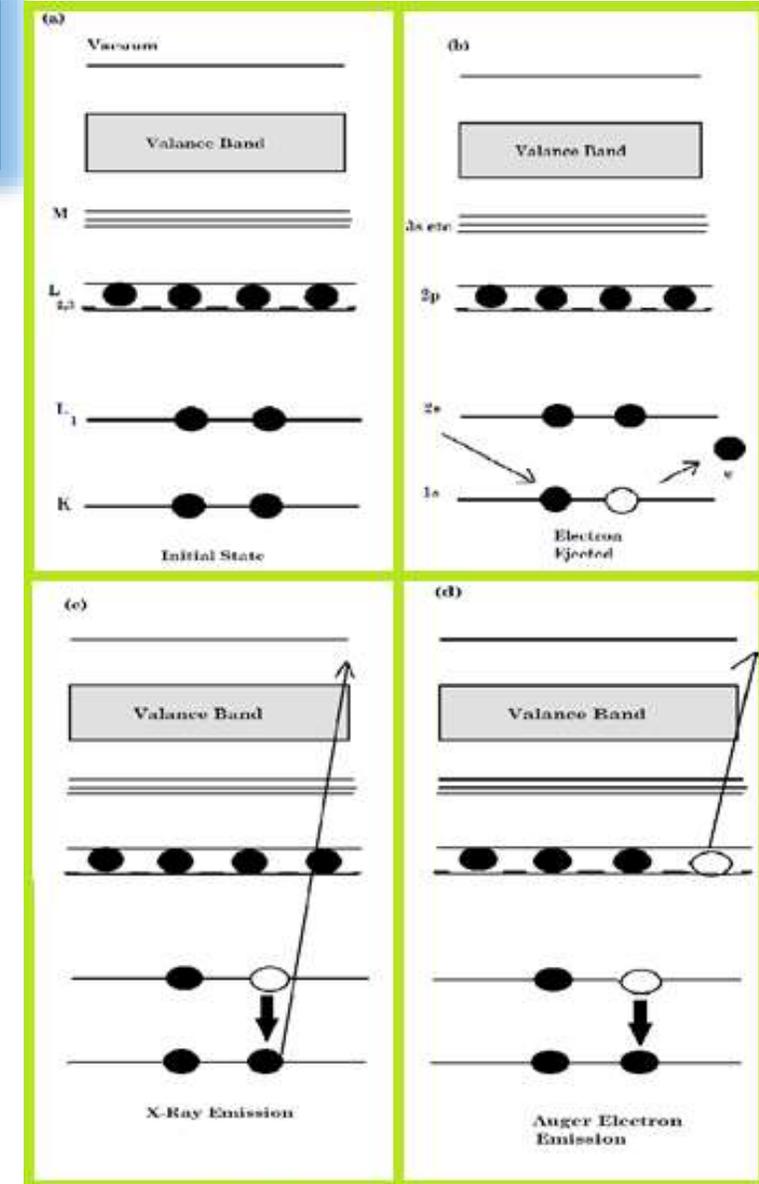


FIG 10

Ionic spectrometry

- Ionic spectrometry is a popular thin film characterization technique which depends on the use of very high-energy beams (MeV) of low mass ions. Such ions can penetrate hundreds of nano meters deep into samples and lose their energies through electronic excitation and ionization of target atoms.
- With known mass and energy of incident ions and angular position of the ion detector, their concentrations and depth distribution can all be simultaneously determined by measuring the number and energy of backscattered incident ions.

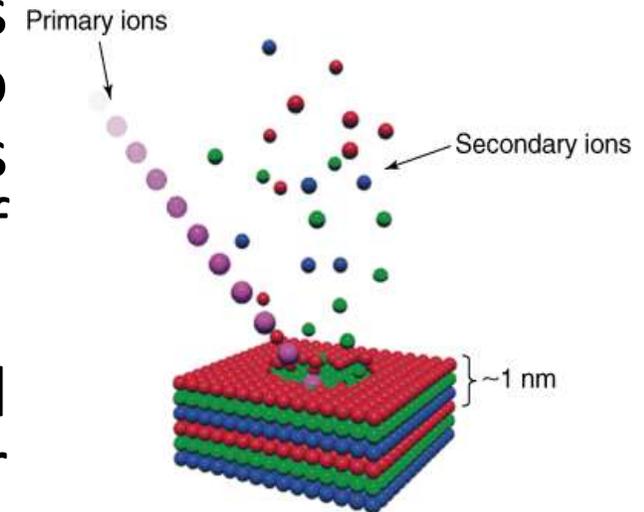


FIG: 11

Ionic spectrometry Cont.

A basic instrument will, consist of:

- A primary beam source (*usually O^{2+} , O^- , Cs^+ , Ar^+ , Ga^+ or neutrals*) to supply the bombarding types.
- A target or sample that must be solid and stable in a vacuum.
- A detector for collecting the ejected secondary ions.
- An ion detection system to record the magnitude of the secondary ion signal.

Secondary Ion Mass Spectrometry (SIMS)

- ❑ Secondary Ion Mass Spectrometry (SIMS) is capable of detecting an extremely low concentration in a solid. In SIMS, a source of ions bombards the surface and sputters neutral atoms, for the most part, but also positive and negative ions from the outermost surface layer. SIMS can be further distinct as “static” and “dynamic” SIMS.
- ✓ Static SIMS collect data before ion bombardment, and is well suited to surface analysis.
- ✓ Dynamic SIMS is operated with high sputtering rates, and thus enables depth profiling.

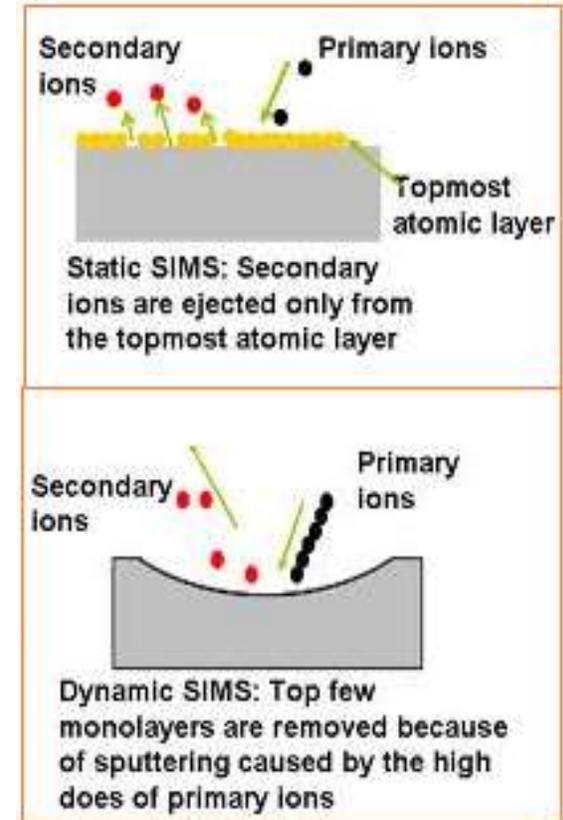


FIG: 12

**THANK
YOU!**

