Clean-Room microfabrication techniques

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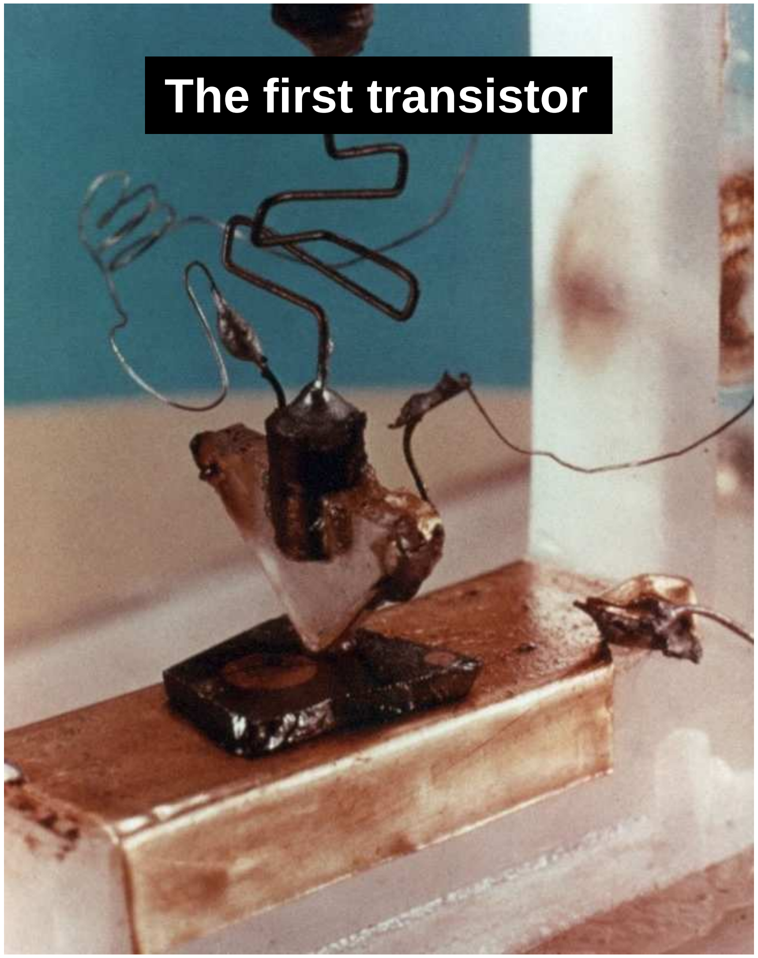
Miniaturization



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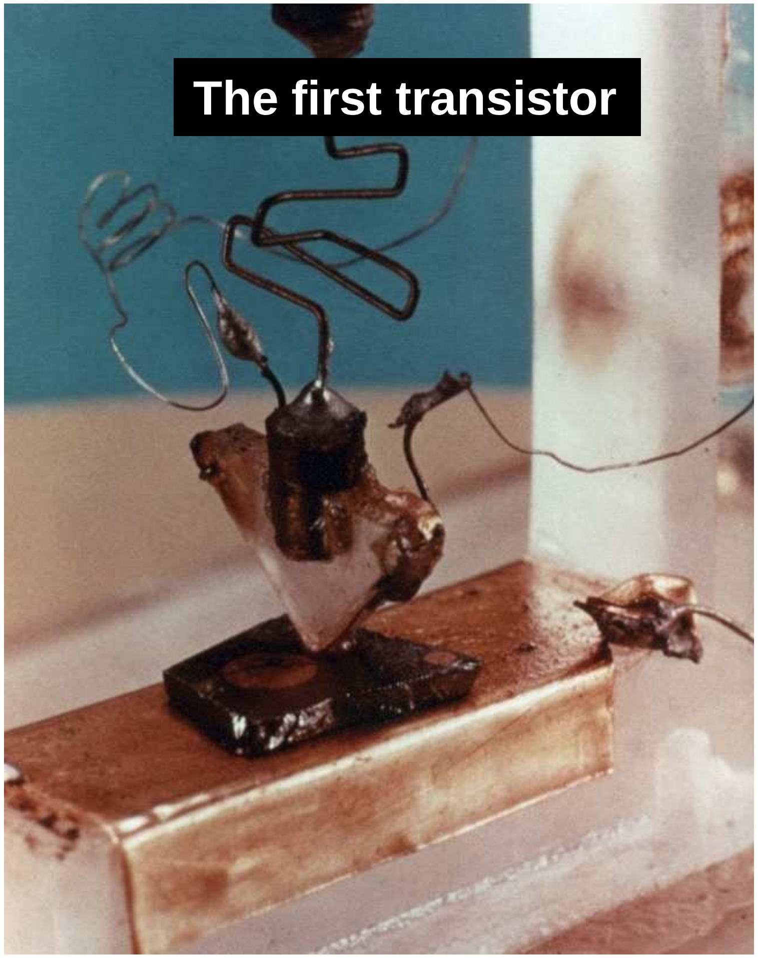

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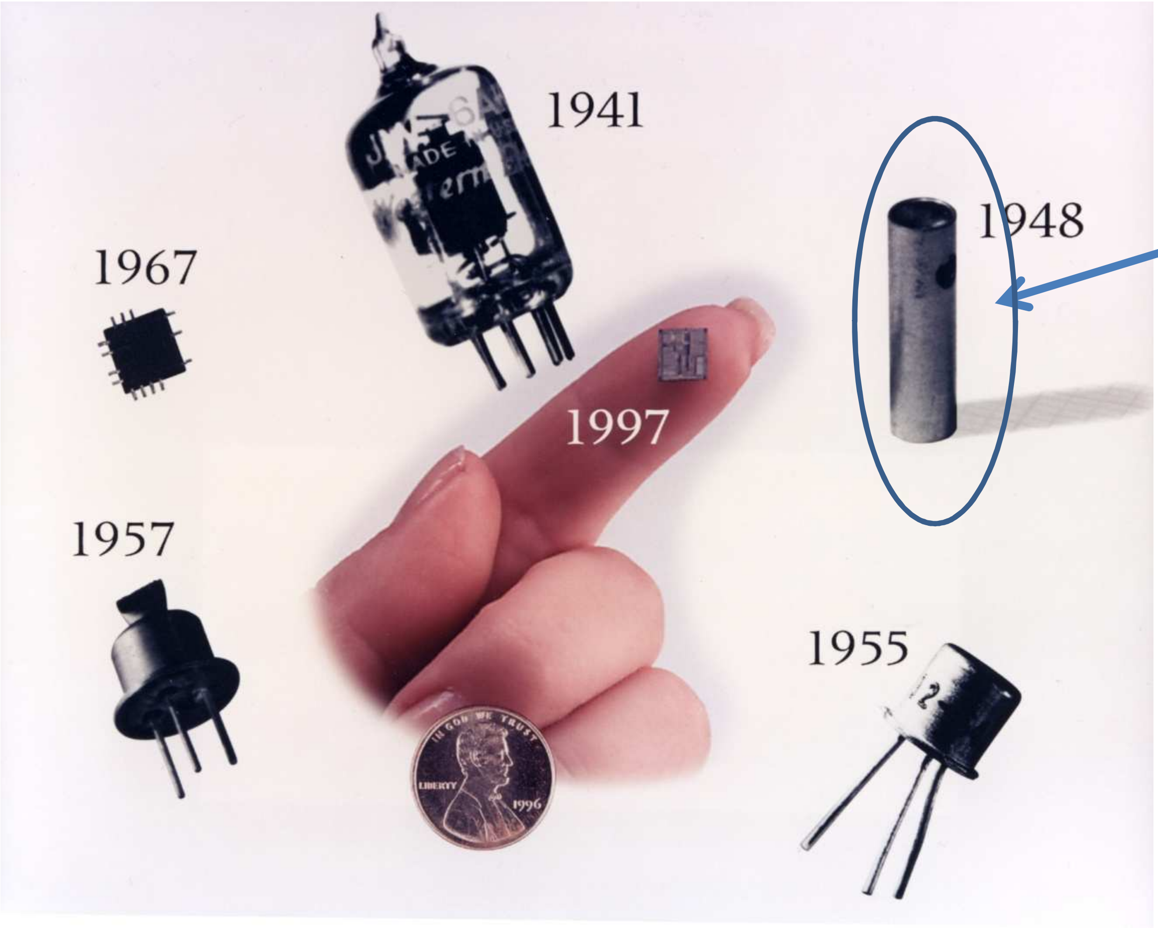

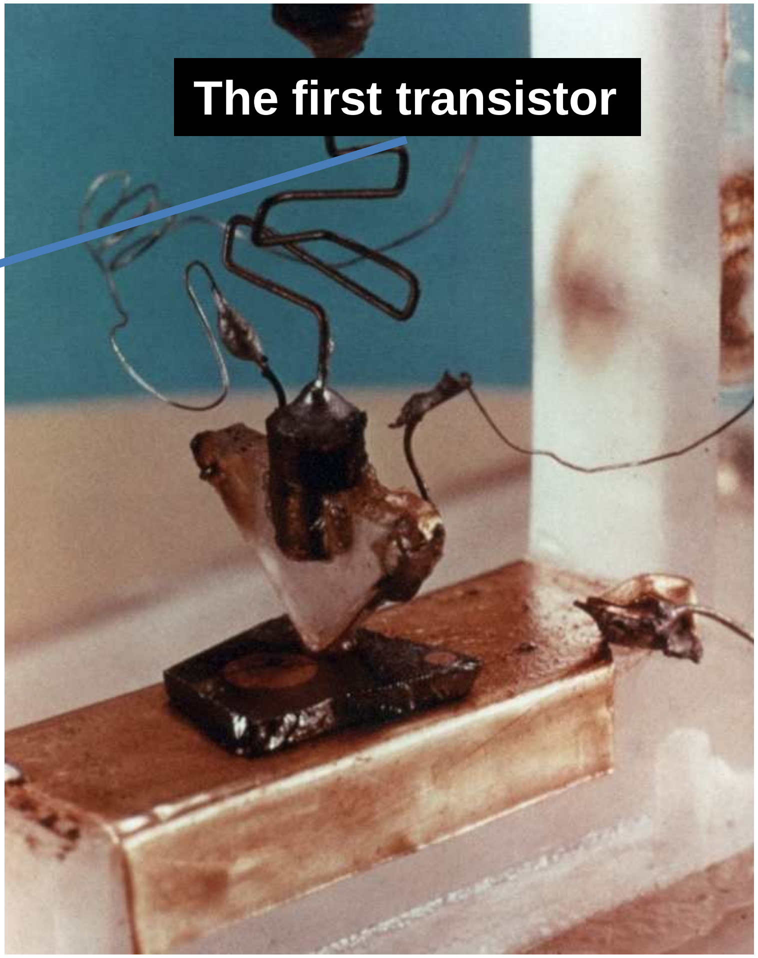

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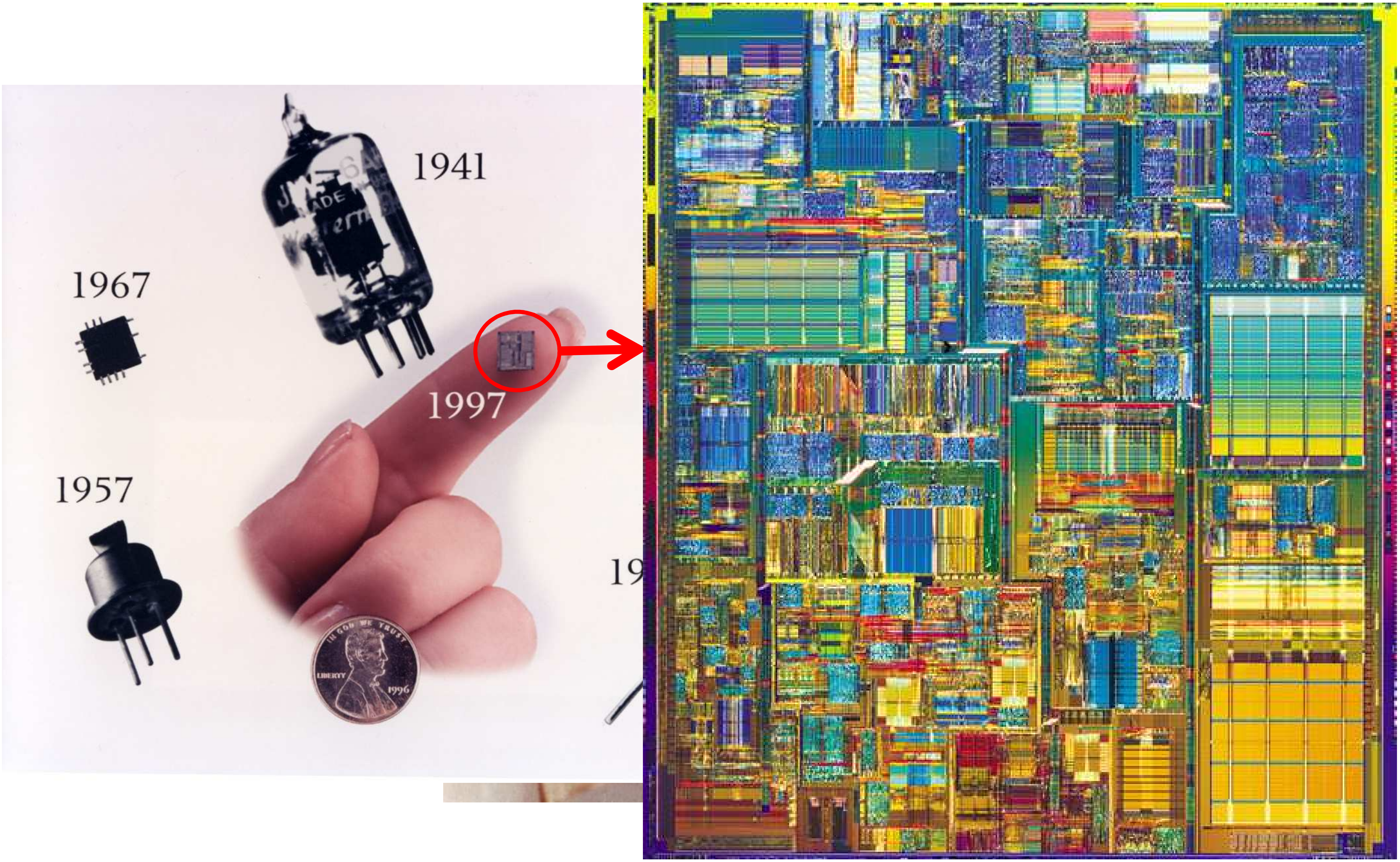
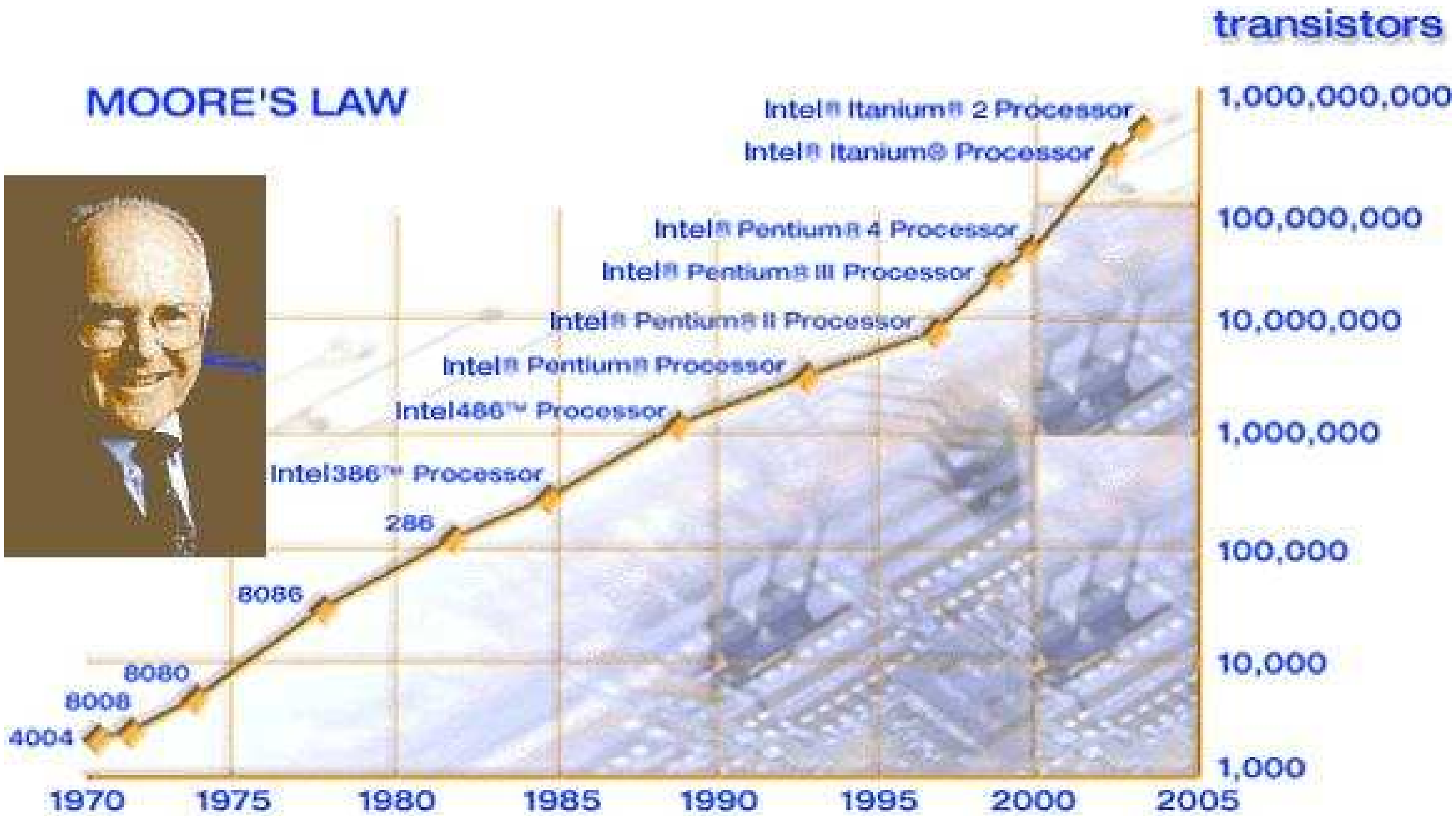
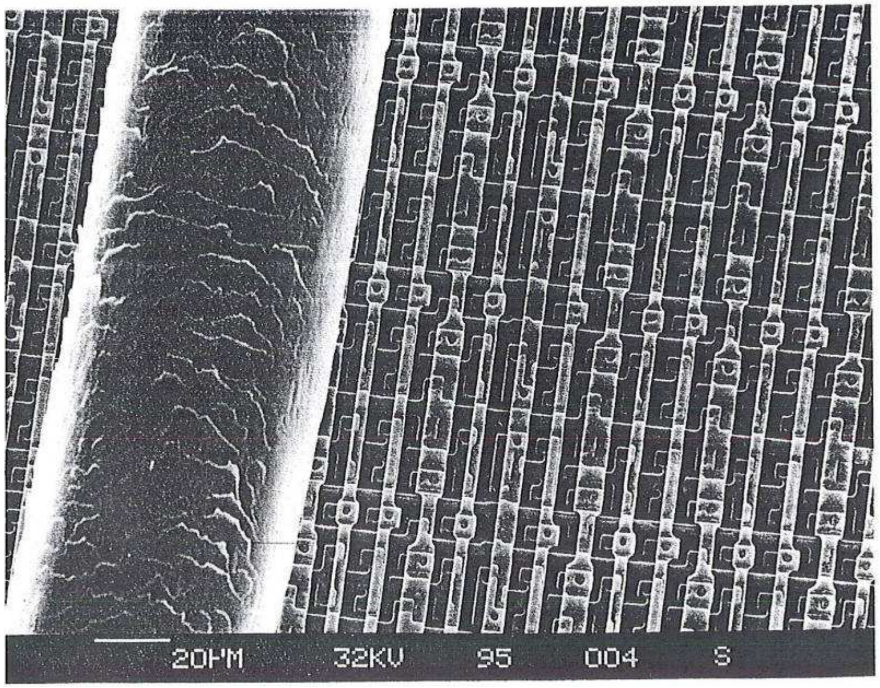


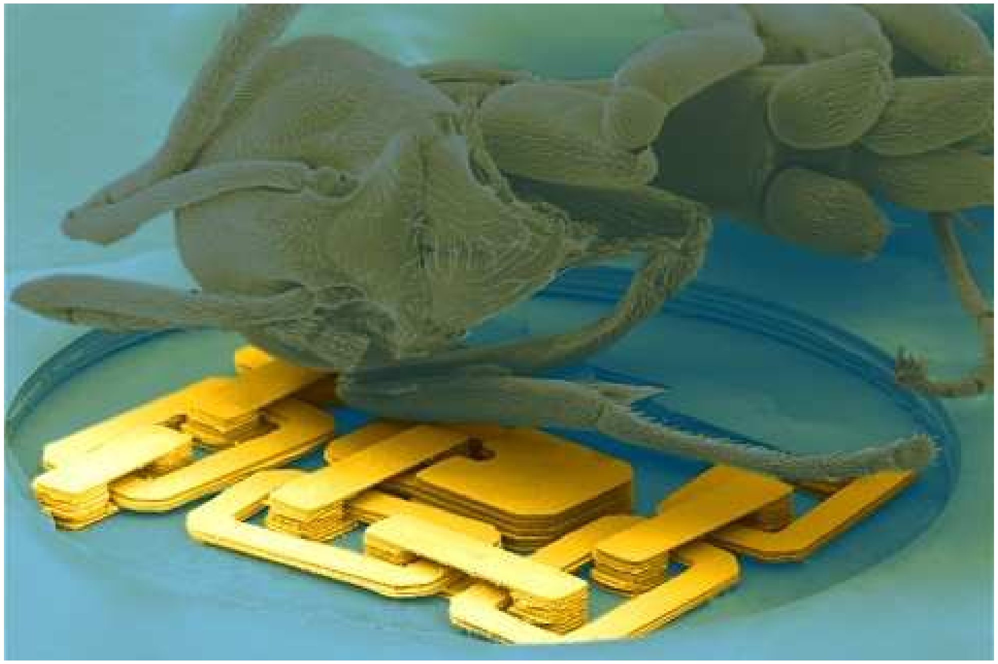
The Moore Law



Moore's Law :
the number of transistors that can be placed on an integrated circuit is increasing exponentially, doubling approximately every two years.

Microtechnology dimensions





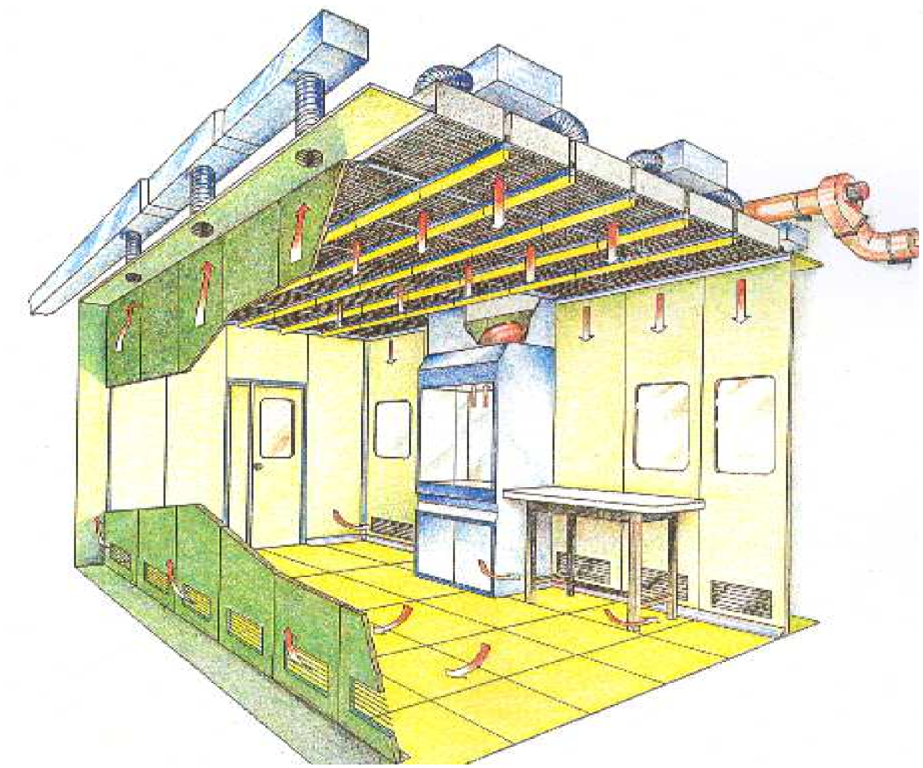
Needs for micro- structures (100 nm – 100 µm) realization :

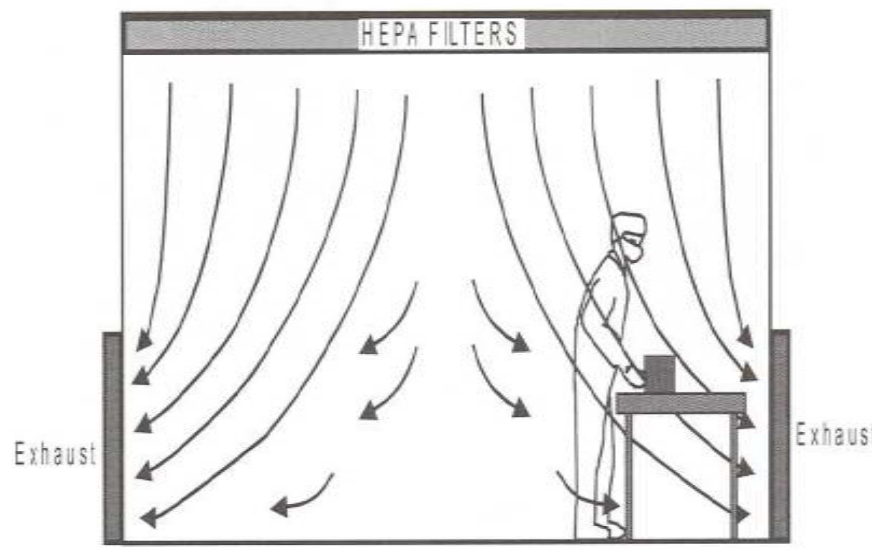
1. **Dimensions lower than airbor particles in atmosphere.**

2. **Thermal expansion and humidity in atmosphere inside laoratory have a “dramatic impact” on microstructures.**

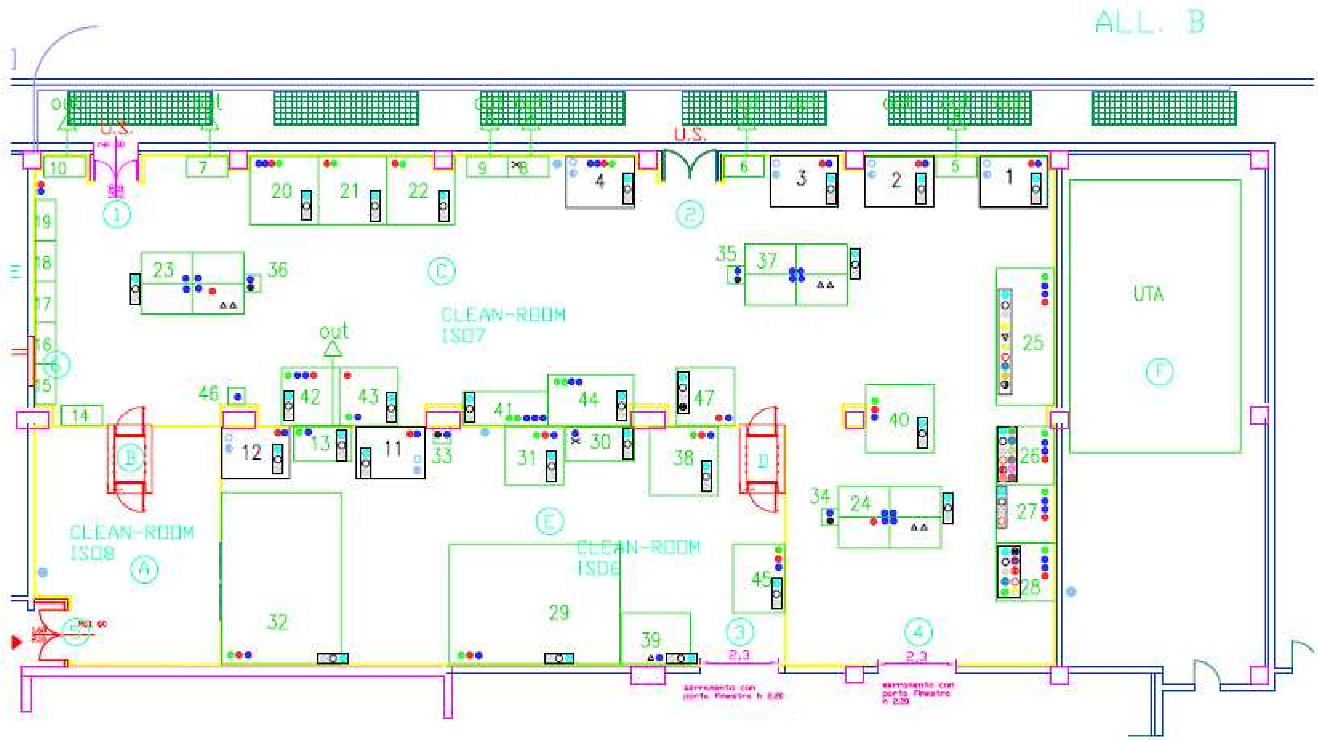
Clean Room:

Laboratory where air fluxes, conditioning and filtering, building materials and operational protocols, are ruled such as "environment cleanliness" and "thermo-hygrometric parameters" are under control.





IIT Clean Room



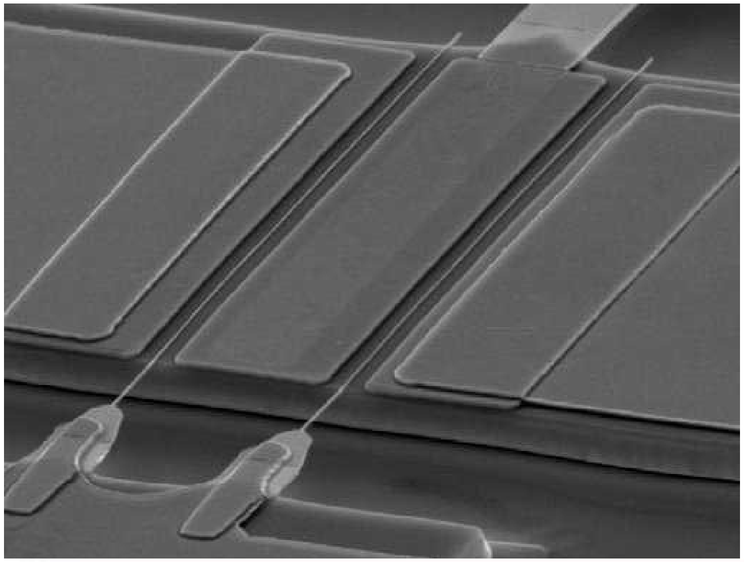
1 – 4) Cappa Chmica
5 – 10) Armadi Aspirati
11 – 12) Cappe Litografia
13) Spinner alta precisione
14 – 19) Armadi Consumables – Vetreria
20) e-beam evaporator 1
21 – 22) Predispisizioni e-beam evaporator
23 – 24) Banchi da lavoro
25) ICP
26) RIE
27) Plasma oxygen
28) PECVD
29) EBL
30) Mask Aligner
31) Injection molding
32) Laser Writer
33 – 36) Stufe
37) Banchi da lavoro
38) Imprinting
39) Polymer Ink Jet
40) Bonder
41) Profilometro + 2 microscopi
42 – 43) Evaporatori termico
44) Glove Box
45) Rapid Prototyping
46) Frigo
47) Vapour Primer Oven

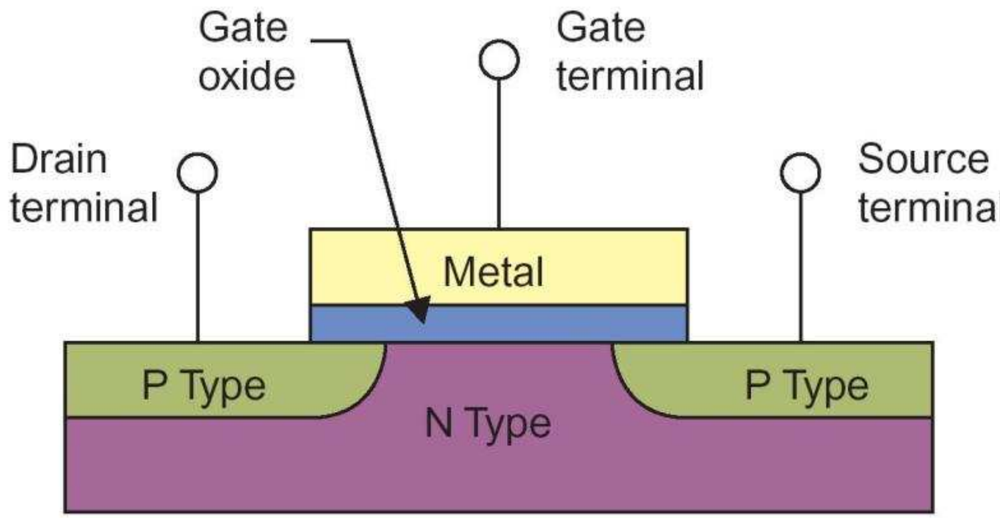
Technical Characteristics
Controlled Temperature : 20 ± 1 °C
Humidity: 50 ± 5 %
Air changes: 10 / hr
120 m² ISO 6
300 m² ISO 7
30 m² ISO 8 (pre-chamber)

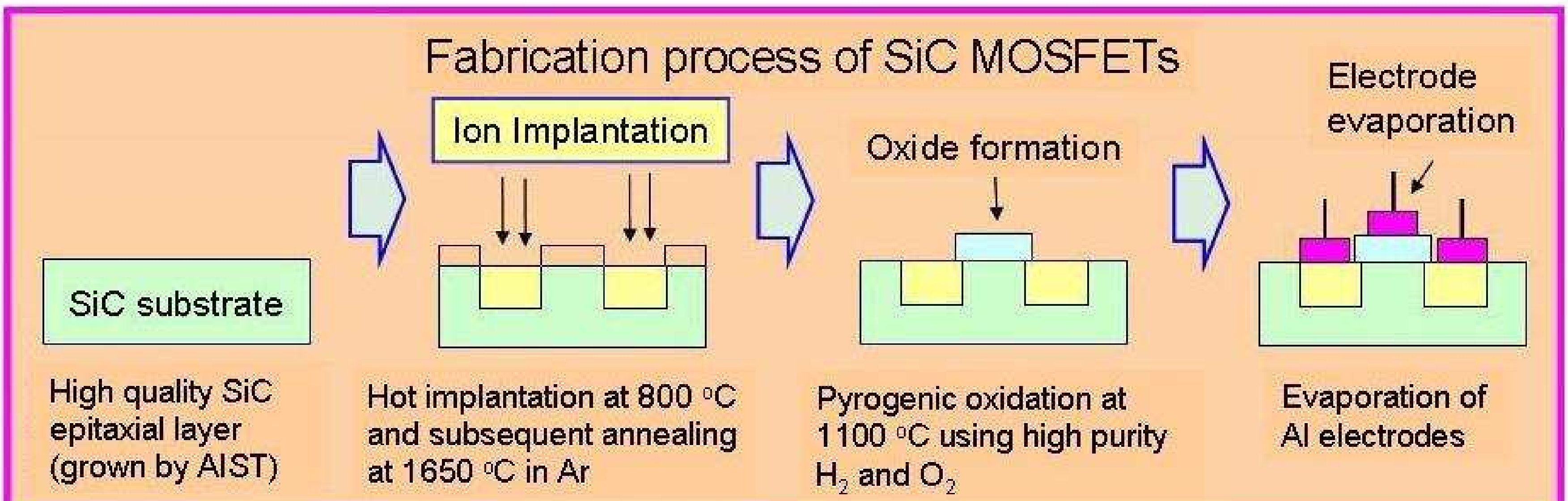
Services:
Deionized Water
Compressed Air
Nitrogen
Vacuum
Chemical benches

Ultra-pure technical gases:
Cl_2, BCl_3, $SiCl_4$, HBr, SiH_2Cl_2,
He, SF_6, SiH_4, NH_3, N_2O, CHF_3, CF_4,
Ar, O_2, H_2, CH_4, miscela $CH_4/H_2/Ar$, C_4F_8

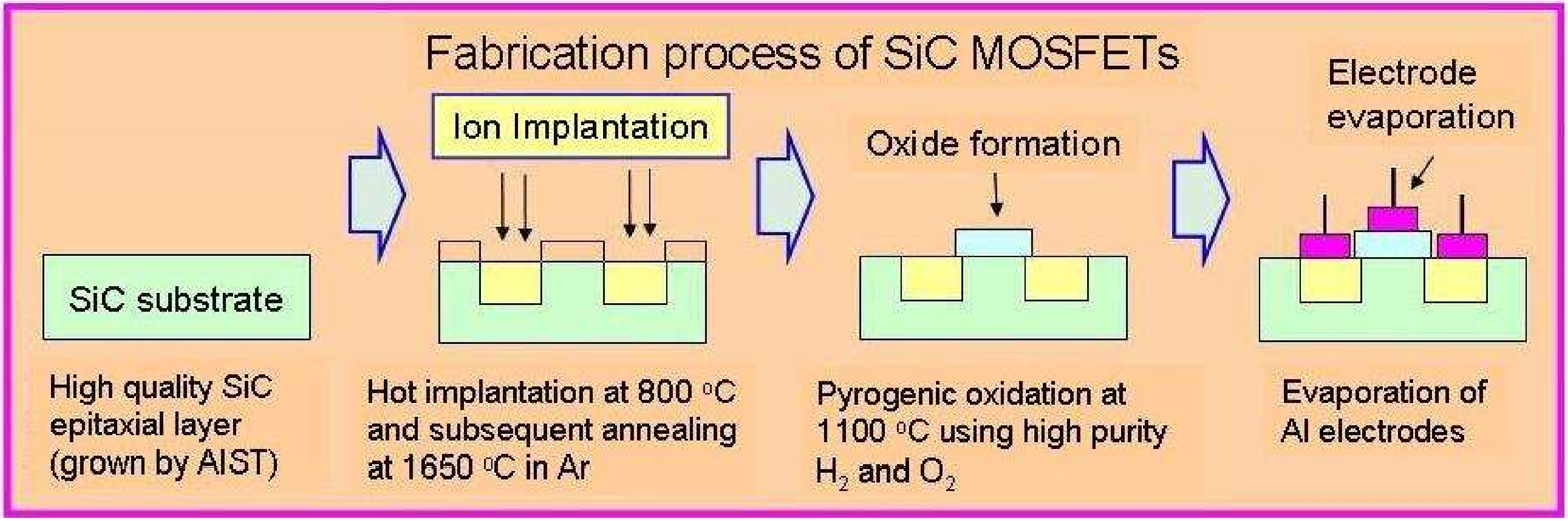
MOSFET realization







The planar processing



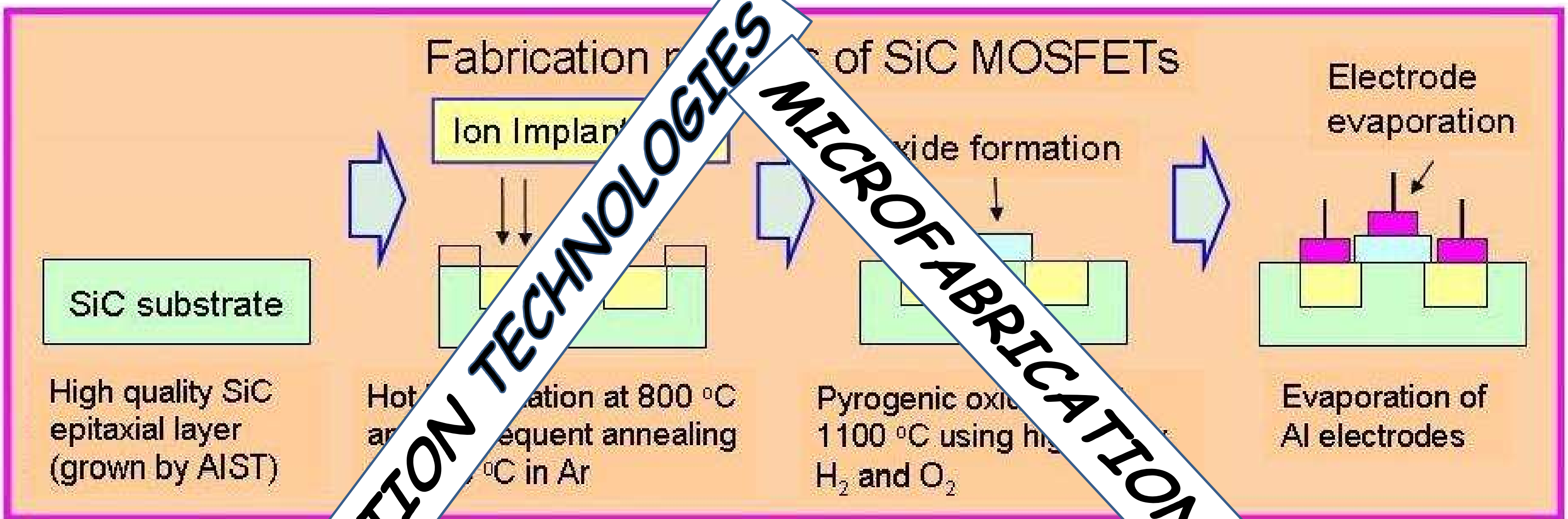
1) Material growth

2) Ion implantation

3) Thin Films deposition

4) Pattern transfer

The planar processing



MATERIAL PRODUCTION TECHNOLOGIES

MICROFABRICATION TECHNOLOGIES

1) Material growth

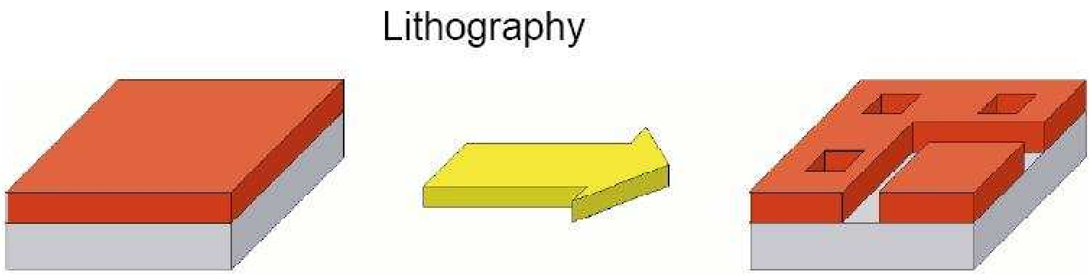
2) Ion implantation

3) Thin Films deposition

4) Pattern transfer

The Microfabrication Technologies

- **Optical Lithography**



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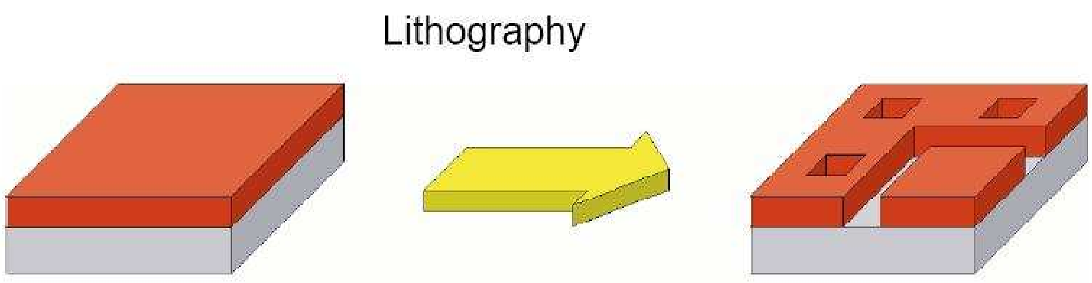
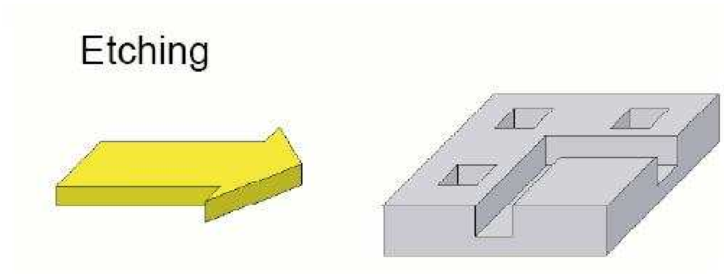


- Etching of materials



The Microfabrication Technologies

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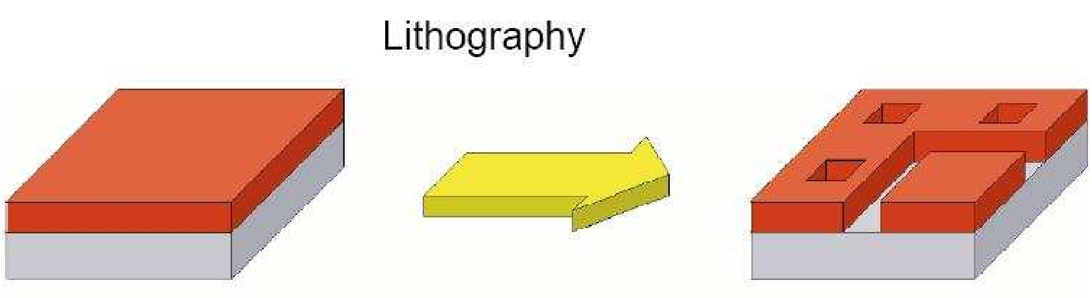

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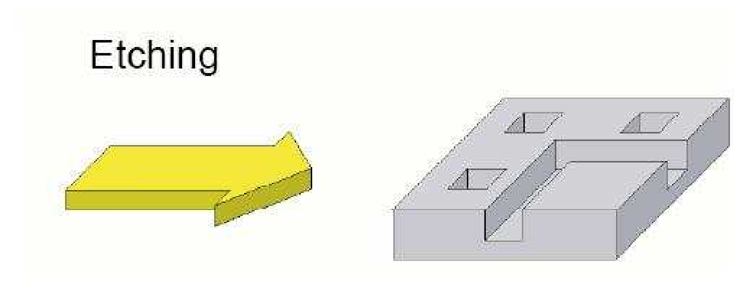
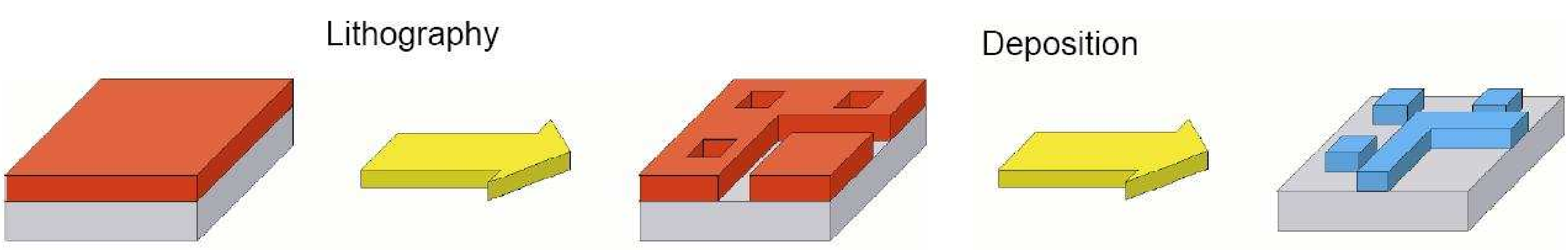
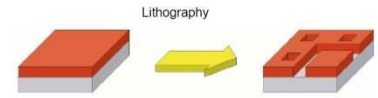


- **Thin Films depostion methods**



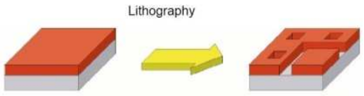


Optical Lithography

Reproduction of a pattern:

Expose a resist to open windows in a controlled way

The origin of the lithographic process is linked to the original process invented by Nicephore Niepce in 1826 for the photography



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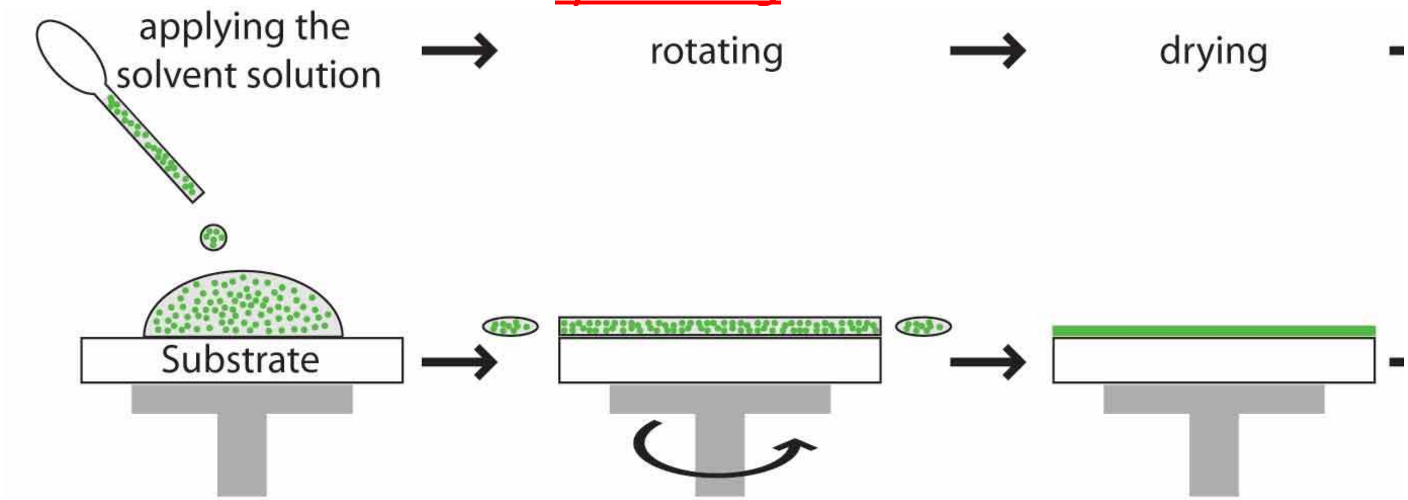
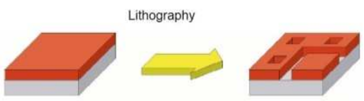
Photoresist : photon sensitive polymer made of long or short chains; applied by <u>spin coating</u>





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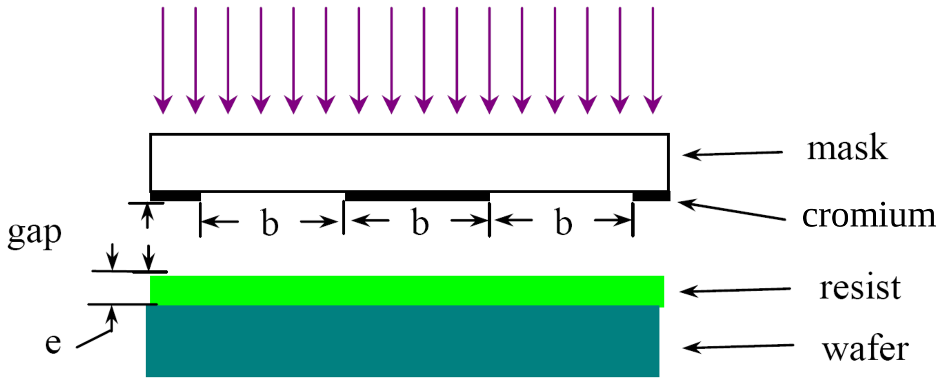

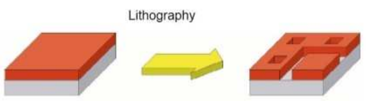

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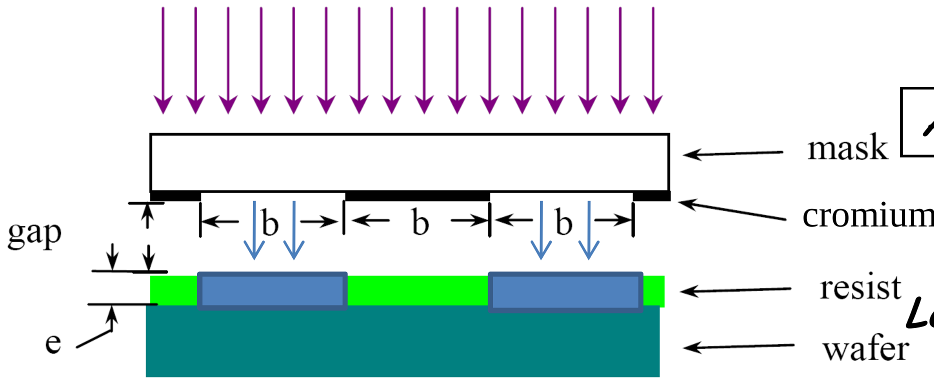


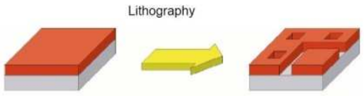
Photoresist : photon sensitive polymer made of long or short chains

After UV light interact with polymer chain:

Positive photoresist:
Long chain molecules are broken in short chain

Negative photoresist:
Short chain molecules are joined in long chain

PAY ATTENTION: Long chain are insoluble in developer



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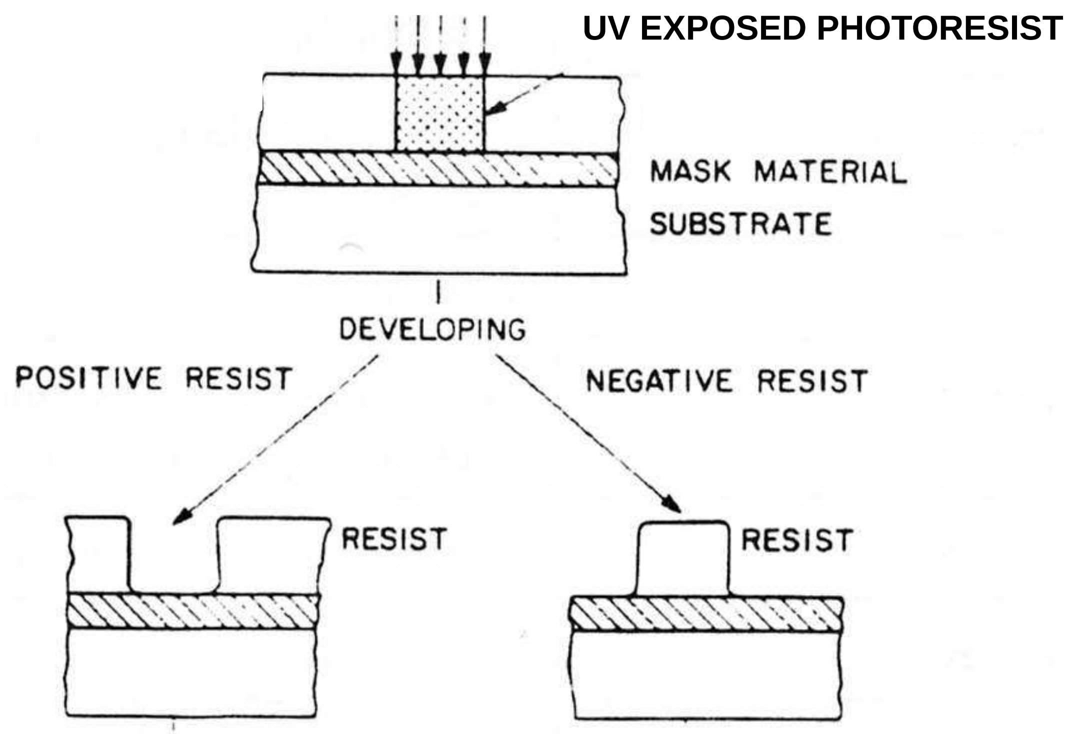

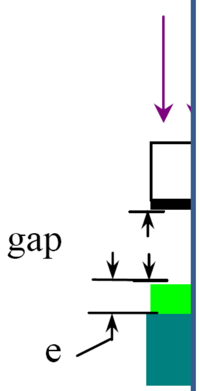

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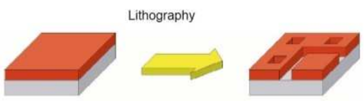
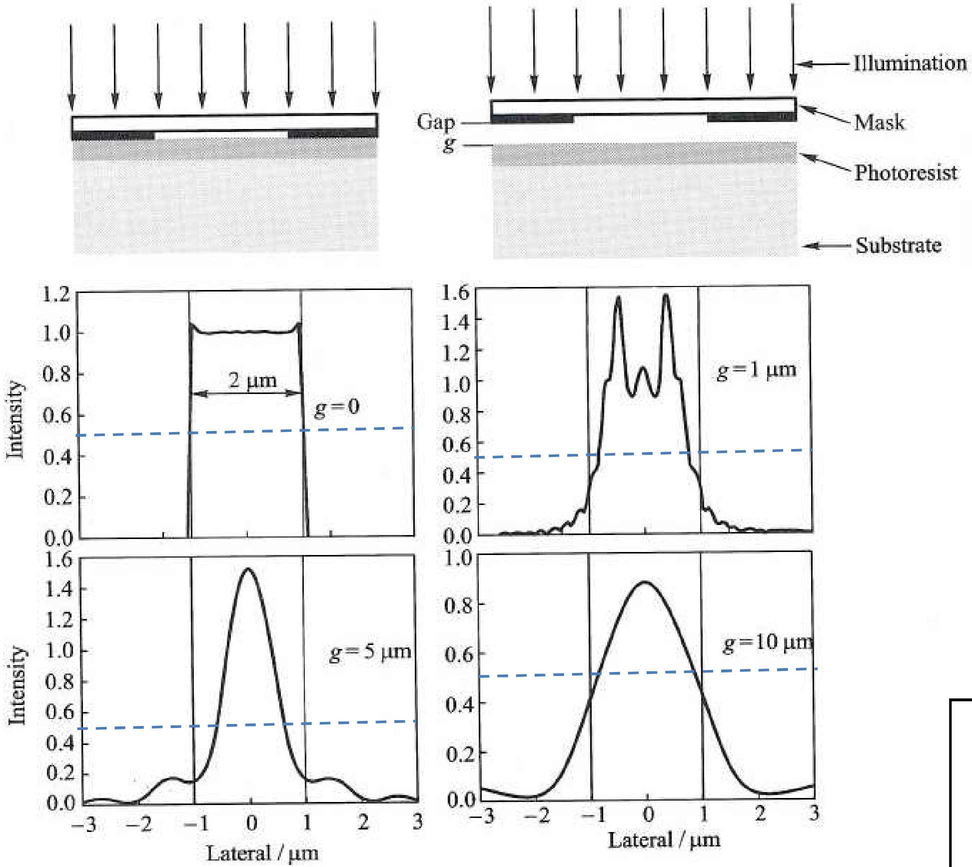


Lithography: Critical Dimensions



Intensity ≈ 0.5:
minimum dose for development

- resolution limited by diffraction:

$$t=\sqrt{\lambda g}$$

- gap minimum=resist thickness

***Minimize** t = difference between real transfer image and ideal transfer image*

Find a tradeoff between the gap g and the diffraction peak to repeat inside the photoresist the mask pattern

Lithography: Critical Dimensions

436nm, Hg-Xe Lamp + Optical Filter: CD ≈ 650 nm

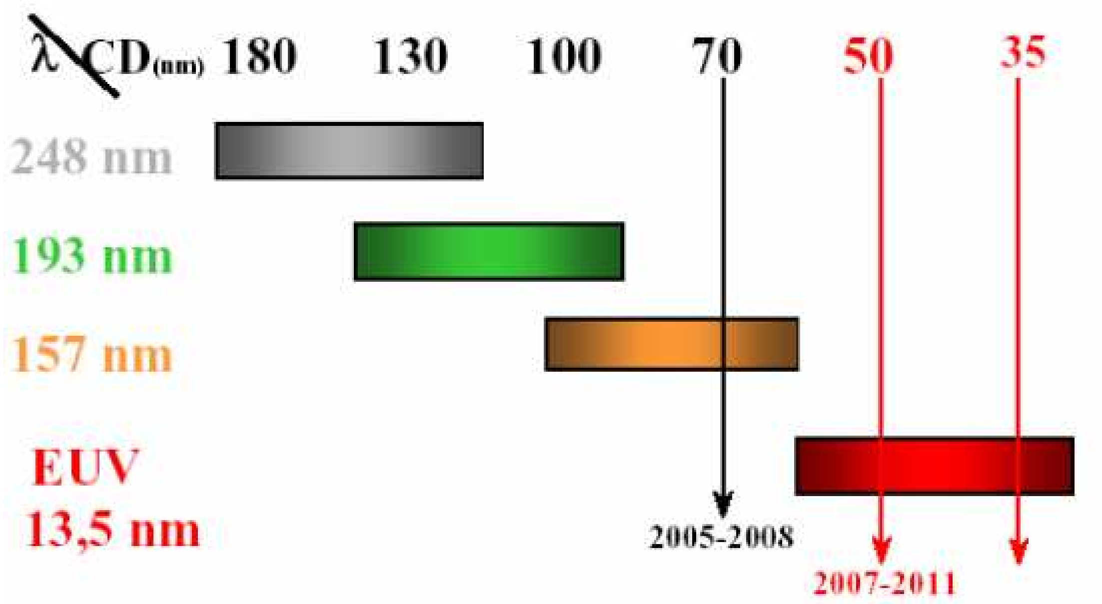
365nm, Hg-Xe Lamp + Optical Filter : CD ≈ 350 nm

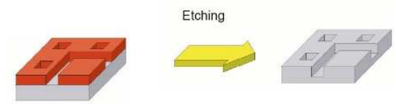
248nm, KrF Excimer Laser

193nm, ArF Excimer Laser

F2: 157nm, F2Laser

EUV : 13.4nm, Soft X-ray



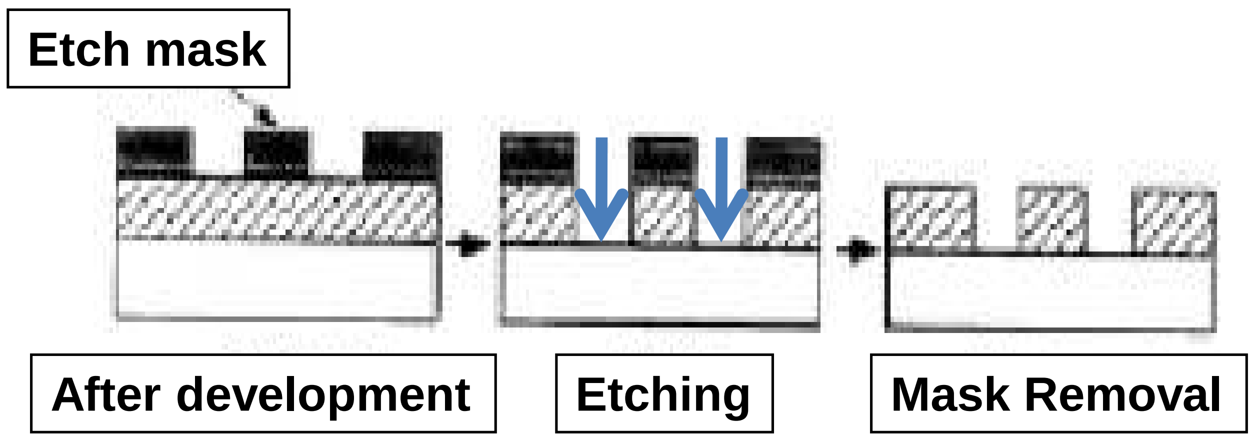


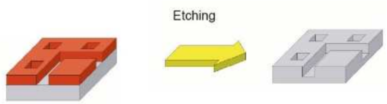
Etching

Selective removal of thin film(s) resulting in a desired thin film(s) pattern

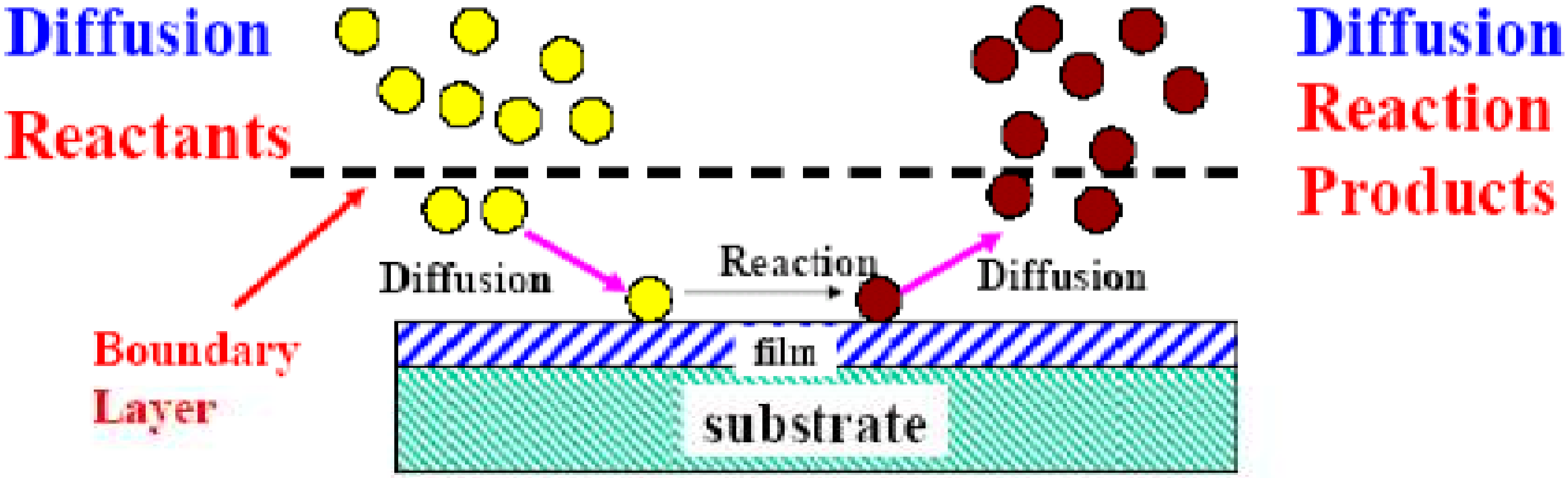
Etch mask

photoresist or oxide/nitride material patterned by optical lithography and resistent to the etchant agent



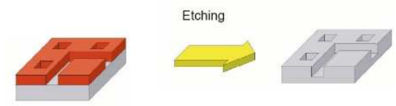


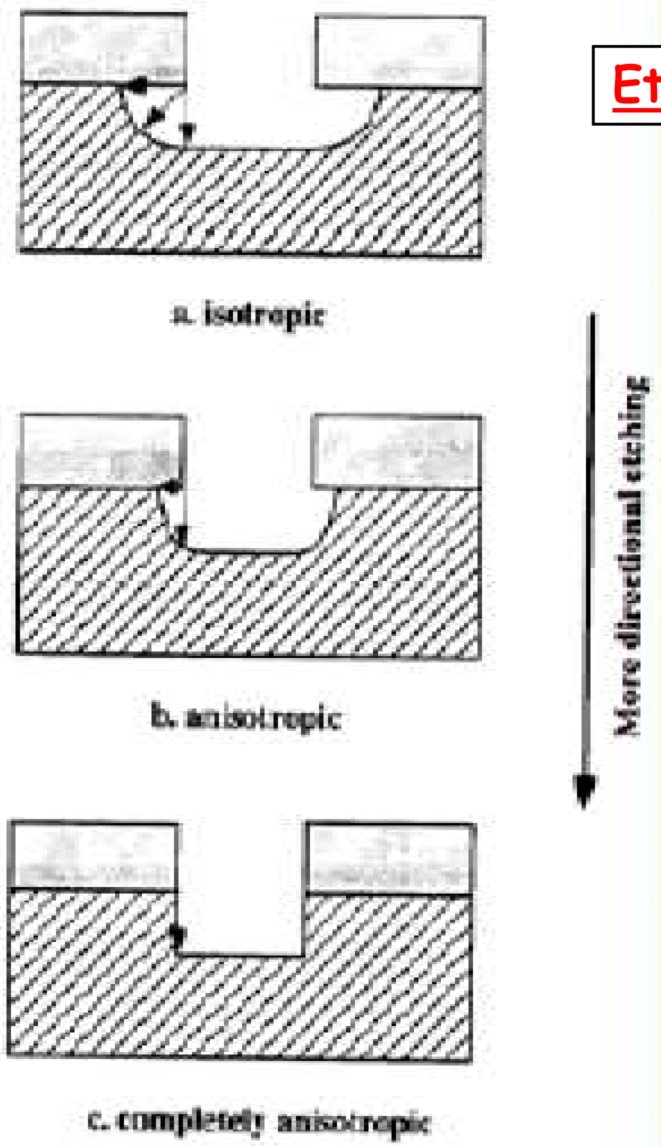
Basic Concepts



- Etching process consists of three steps
  - Mass transport of reactants (through a boundary layer) to the surface to be etched
  - Reaction between reactants and the film(s) to be etched at the surface
  - Mass transport of reaction products from the surface through the boundary layer
- Etching is usually done using liquid phase or gas phase reactants
  - **liquid phase (wet) etching** —reaction products soluble in solvent or gaseous
  - **gas phase etching** — reaction products gaseous / sublimation temperature

Etching figure of merit





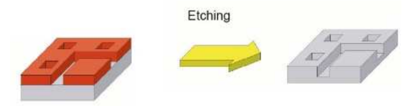
Etch rate: rate of film removal, typically 100 nm/min

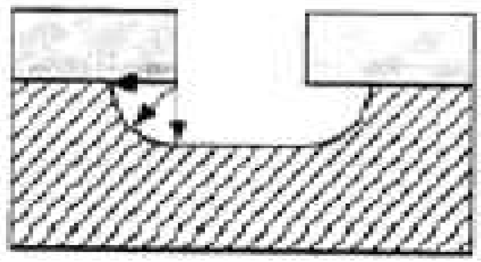
Etch Directionality	Measure of relative etch rates in different directions usually vertical vs. lateral
Isotropic Etching	Etch rates are same in all directions. It is usually related to chemical processes
Anisotropic Etching	Highly directional etching with different etch rates in different directions. It is usually related to physical processes such as ion bombardment and sputtering

Anisotropy:

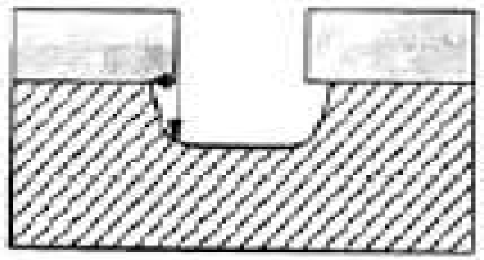
Anisotropyic etching is the preferred process

Etching figure of merit

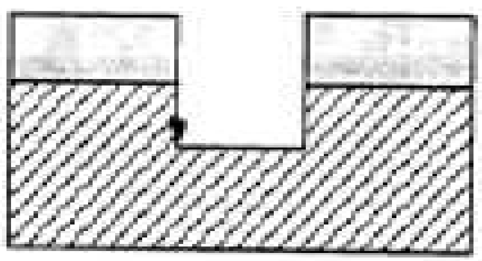




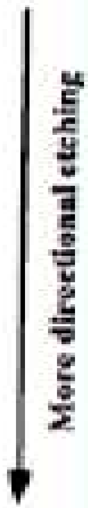
a. isotropic



b. anisotropic



c. completely anisotropic



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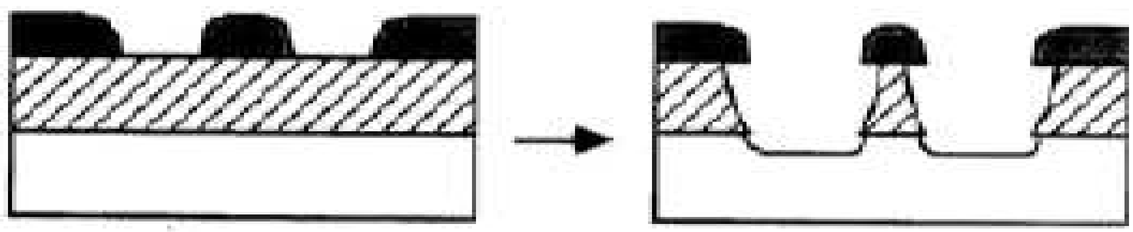
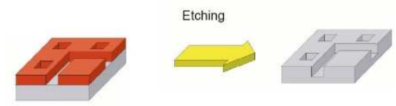


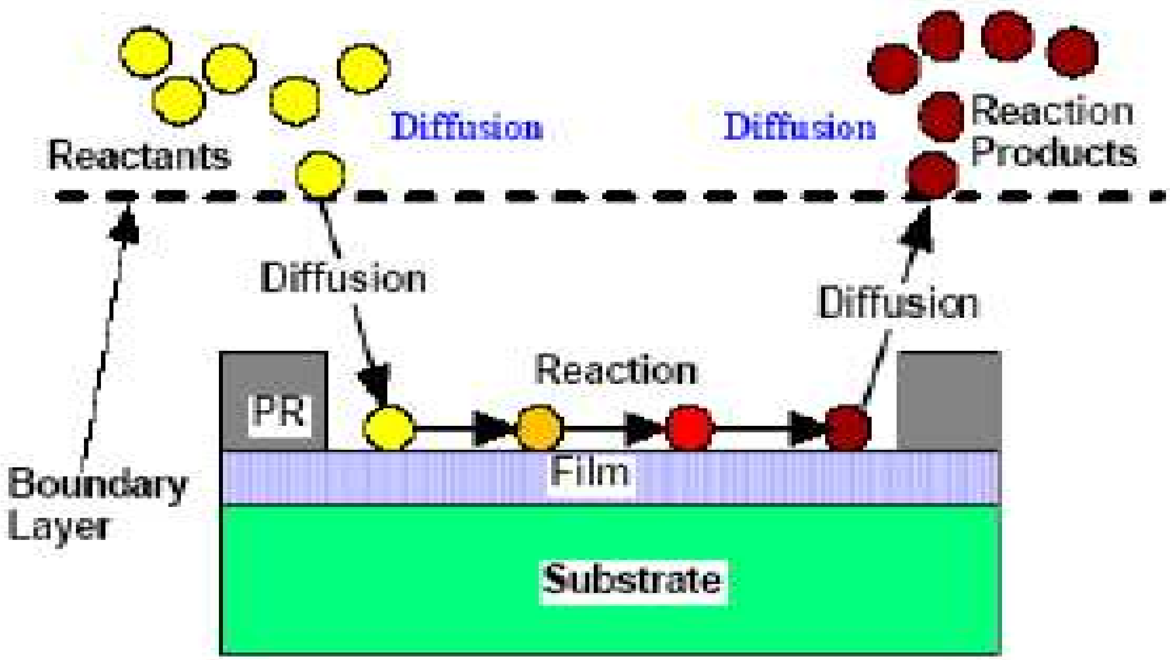
Selectivity: Etchant could attack substrate, not only film

Wet Etching



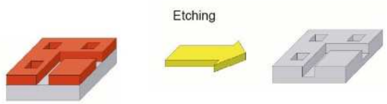
How?

Simply place the wafer in solution that attacks the film to be etched but not the mask (resist).



- Diffusion reactive species from the liquid bulk through the boundary layer to the surface of wafer
- Reaction of species at the surface to form solvable species
- Diffuse reaction products away from the surface through the boundary layer into the bulk of the liquid

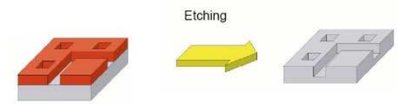
Advantages	High selectivity because it is based on chemical processes
Disadvantages	Isotropic, poor process control and particulates



Etching Chemistry

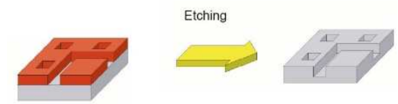
- Key ingredients in any wet etchant:
  - Oxidizer
    - examples: H_2O_2, HNO_3
  - Acid or base to dissolve oxidized surface
    - examples: H_2SO_4, NH_4OH
  - Dillutent media to transport reactants and products through
    - examples: H_2O, CH_3COOH

Drawback of Wet Etching



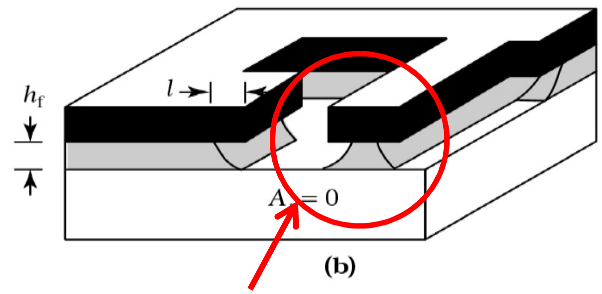
- Lack of anisotropy
- Poor process control
- Excessive particulate contamination

=> Wet etching used for **noncritical** feature sizes



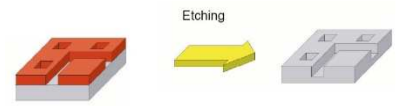
Dry Etching Overview

- Feature-sizes smaller-than 1-μm cannot be well defined with isotropic wet-etching processes.
- Anisotropic-etching is necessary to form submicron-sizes.



Critical dimension feature disappear

Dry Etching Overview



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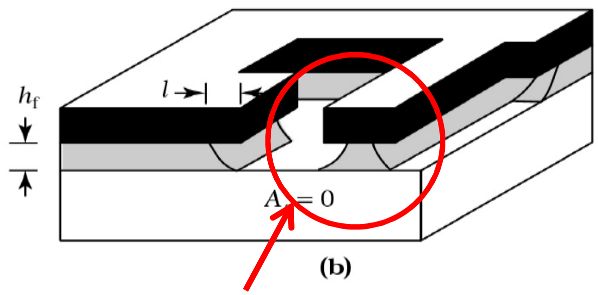
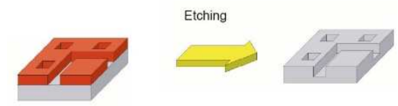


Critical dimension feature disappear

Dry Etching

<u>Material removal reactions occur by a gas phase etchant.</u>



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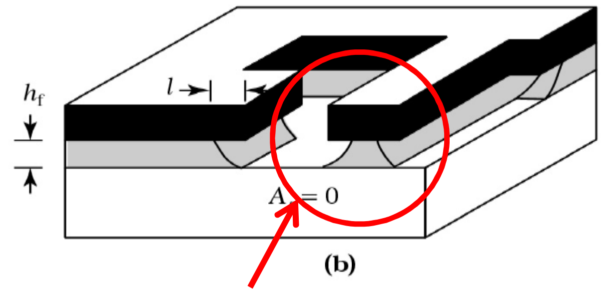


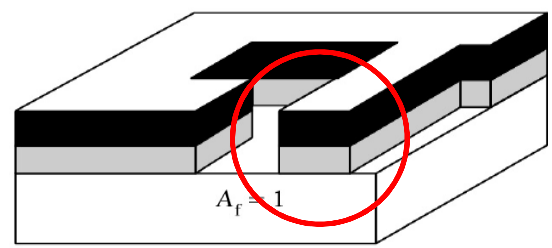
(b)

Critical dimension feature disappear

Dry Etching

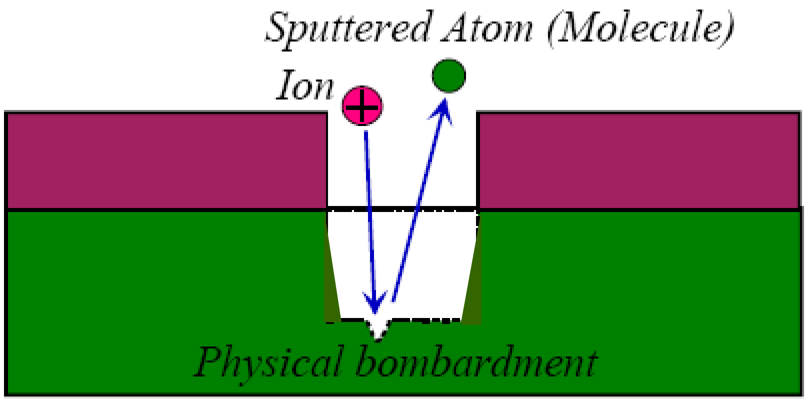
Material removal reactions occur by a gas phase etchant.

- Dry-etching can be anisotropic.
- It also eliminates handling, consumption, & disposal of large quantities of dangerous acids & solvents.

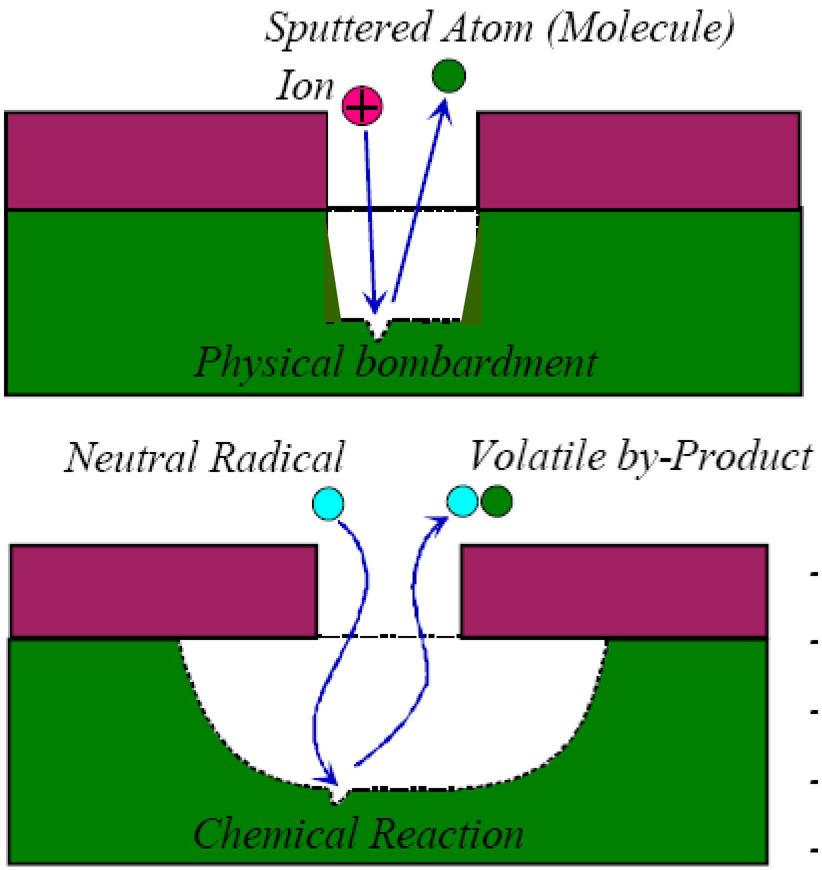


(c)

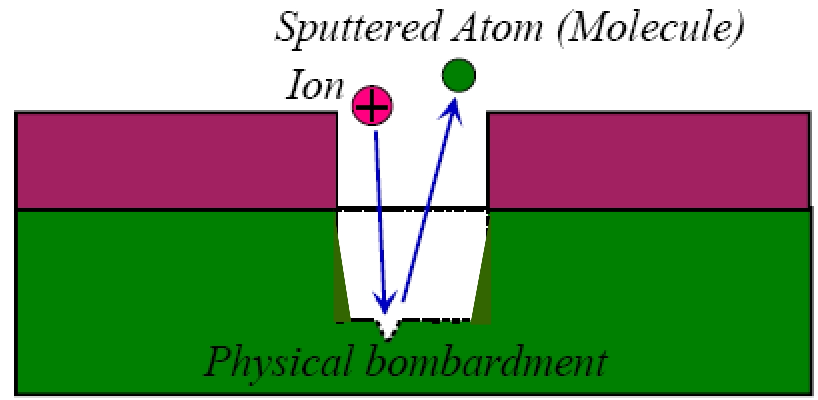
- ***Physical Etching***
  - ***<u>The gaseous ion, accelerated to the substrate, mechanically ejects substrate material</u>***
  - ***Highly Anisotropic***
  - ***Non-Selective***



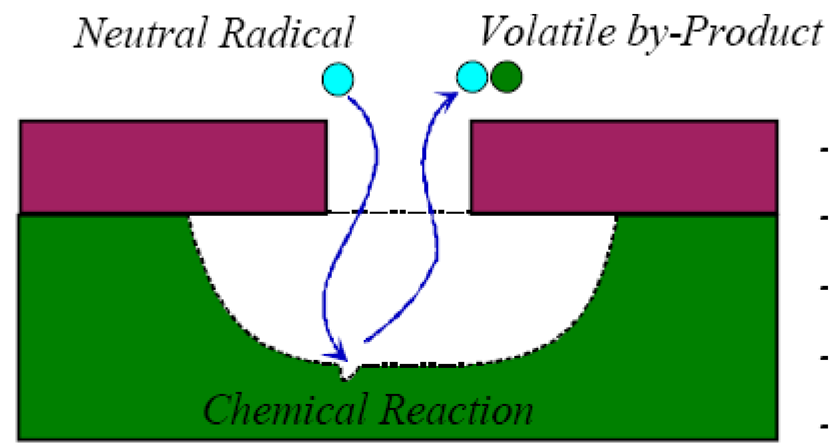
- ***Physical Etching***
  - ***<u>The gaseous ion, accelerated to the substrate, mechanically ejects substrate material</u>***
  - ***Highly Anisotropic***
  - ***Non-Selective***
- ***Chemical Etching***
  - ***<u>Thermalized neutral gaseous radicals chemically combine with substrate material forming volatile products</u>***
  - ***Highly-Selective***
  - ***Isotropic***



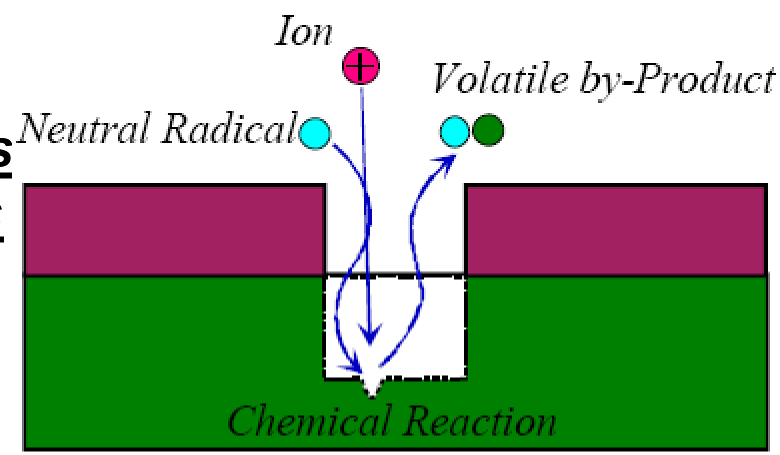
- ## *Physical Etching*
  - ***The gaseous ion, accelerated to the substrate, mechanically ejects substrate material***
  - ***Highly Anisotropic***
  - ***Non-Selective***



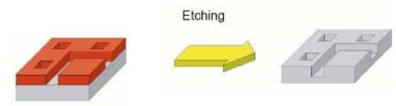
- ## *Chemical Etching*
  - ***Thermalized neutral gaseous radicals chemically combine with substrate material forming volatile products***
  - ***Highly-Selective***
  - ***Isotropic***

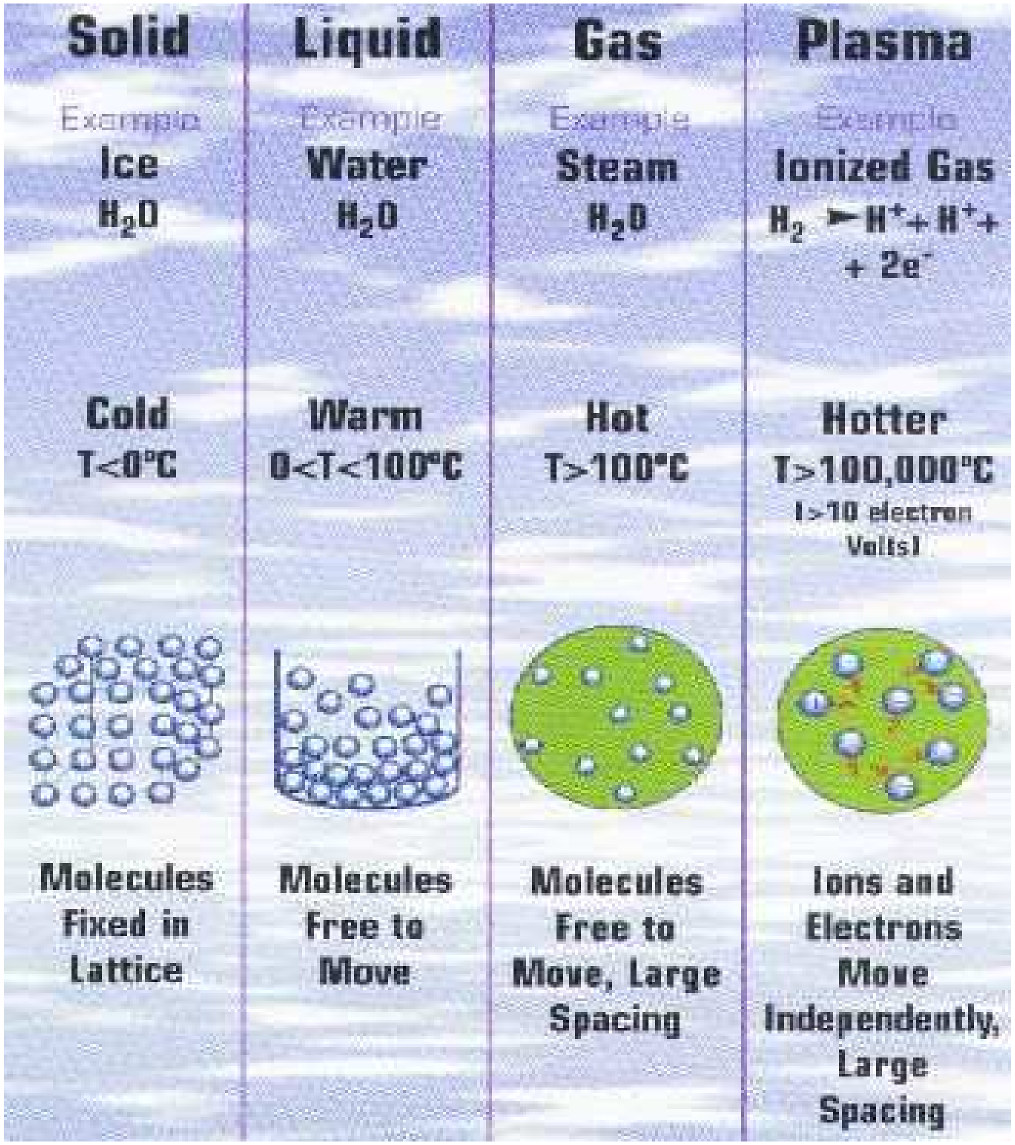


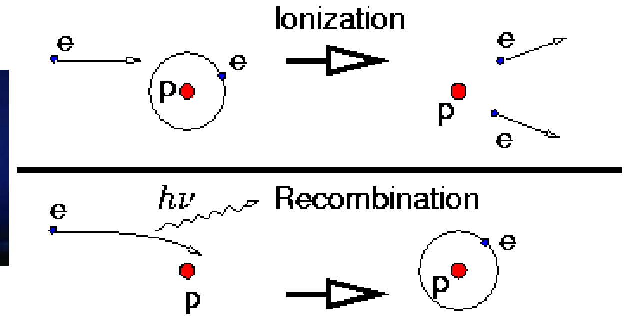
- ## *Combination of the two*
  - ***Ion bombardment enhances or promotes the reaction between an active species and the substrate material***
  - ***Controlled Anisotropy***
  - ***Adequate Selectivity***



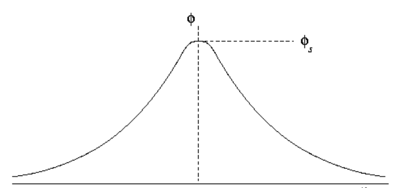
Plasma: the 4th state of matter





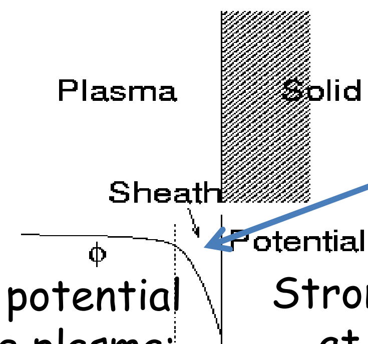


Screening potential near a point charge



Plasma particles are free to move; don't feel each other

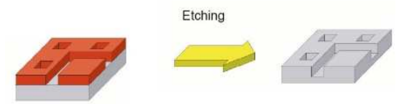
Plasma-solid interface



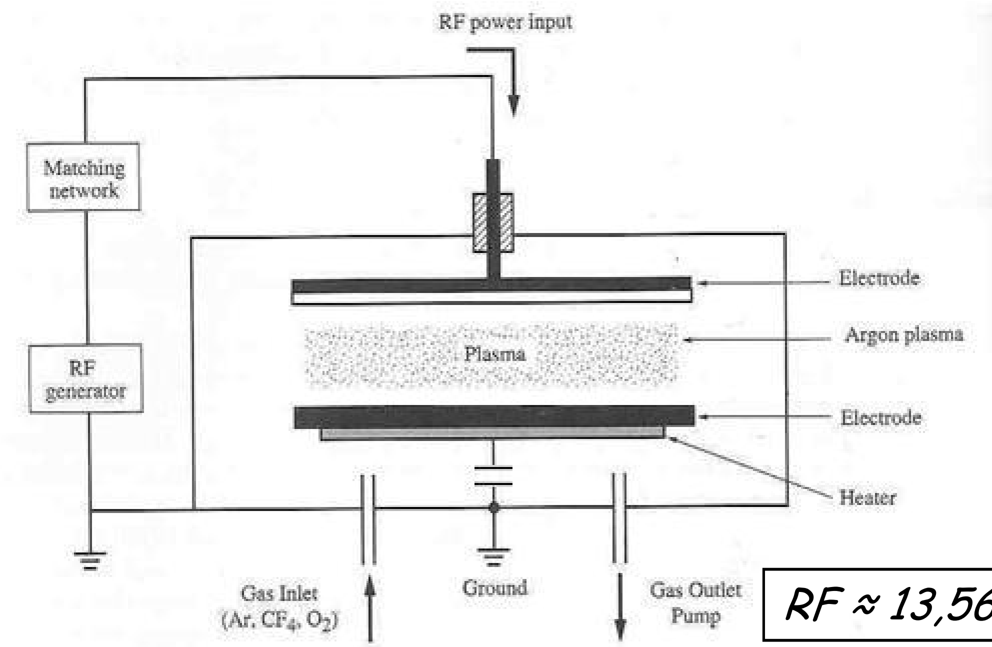
Decreasing Pressure **increase** the sheath area

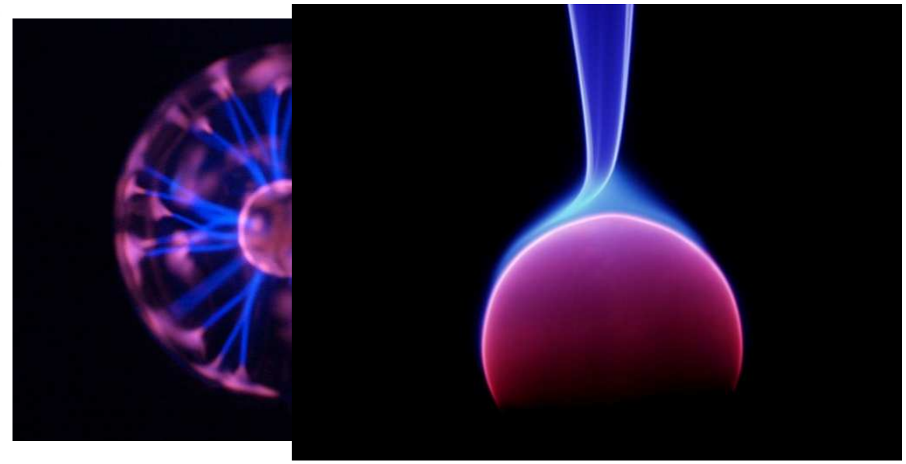
Constant potential inside the plasma; **Plasma is on**

Strong electric field at the boundary; **Plasma is off**

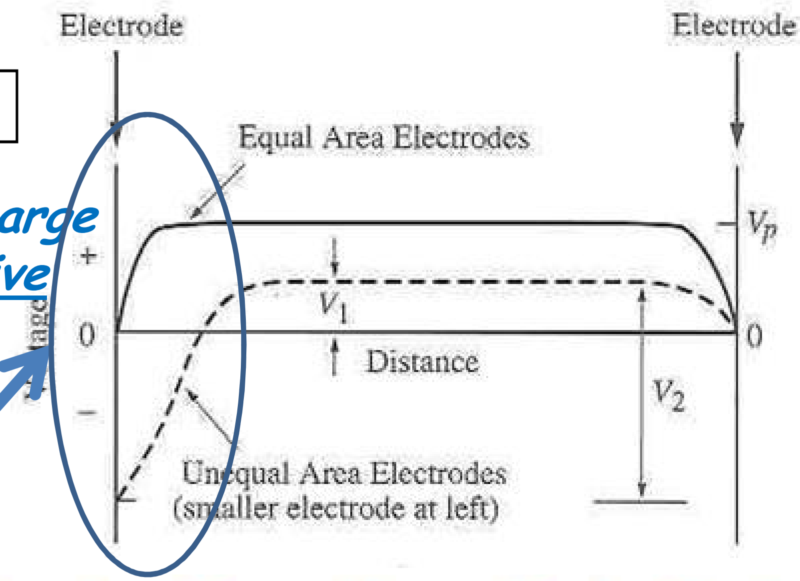


The RF gas chamber





RF ≈ 13,56 MHz



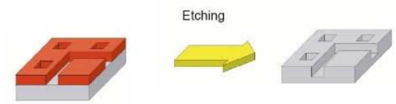
RF Electric field produce plasma by glow discharge

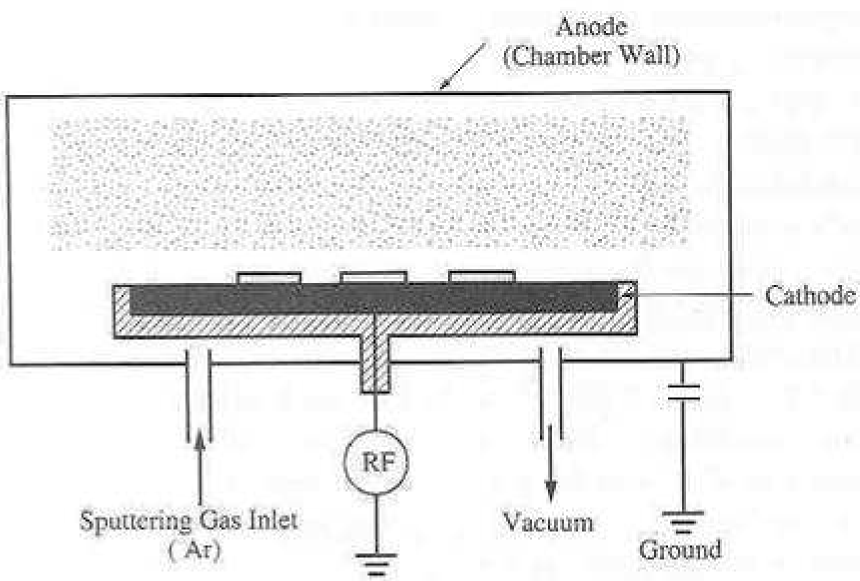
Plasma is used to crack molecules and/or drive chemical reactions useful for dry etching

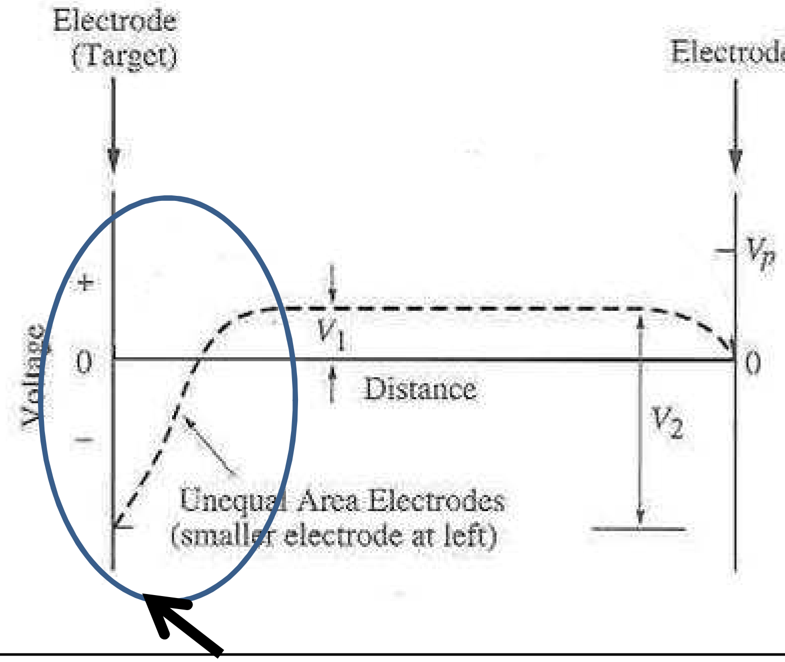
Electric potential is constant inside the bulk of plasma. The voltage drop is mostly across the sheat area, where the plasma is off, and ions are accelerated towards electrodes.

Steady-state voltage distribution in RF-powered plasma chamber

Physical Etching: the Ion Sputtering system

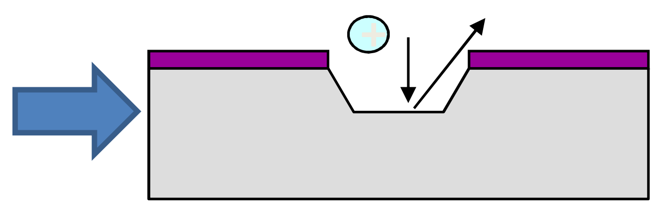


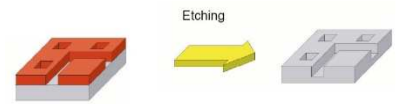




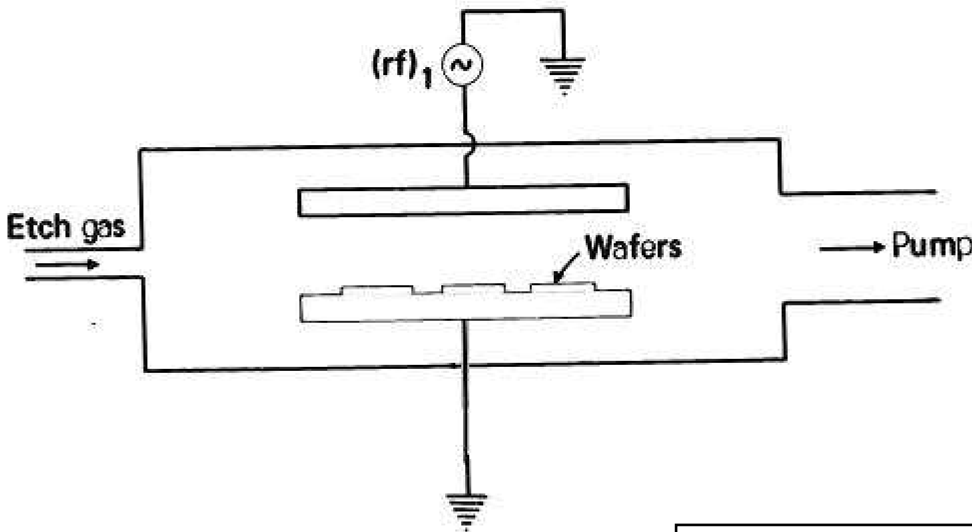
In this process all of the RF voltage is applied to a smaller target electrode. A neutral gas is injected in a low pressure environment.

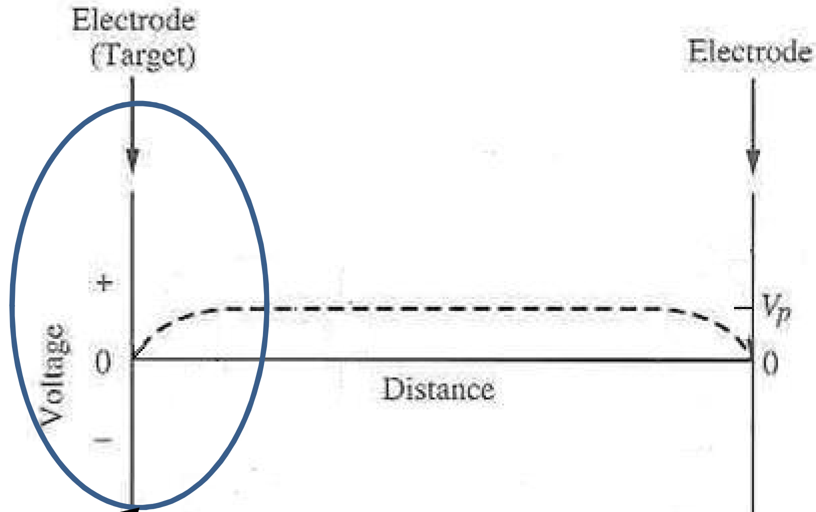
Glow discharge is used to energize chemically inert ions or atoms (e.g., Ar). Atoms close to the sheat area are strongly accelerated bombarding the wafer.





Chemical Etching: the Plasma Etching system

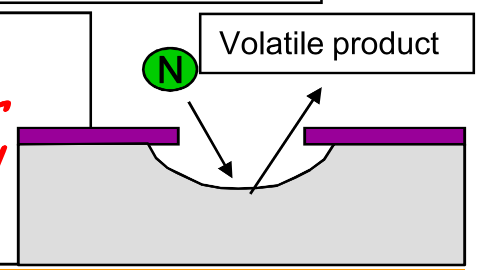




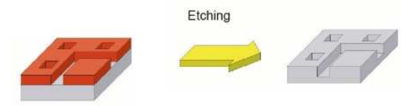
The opposite of Sputtering

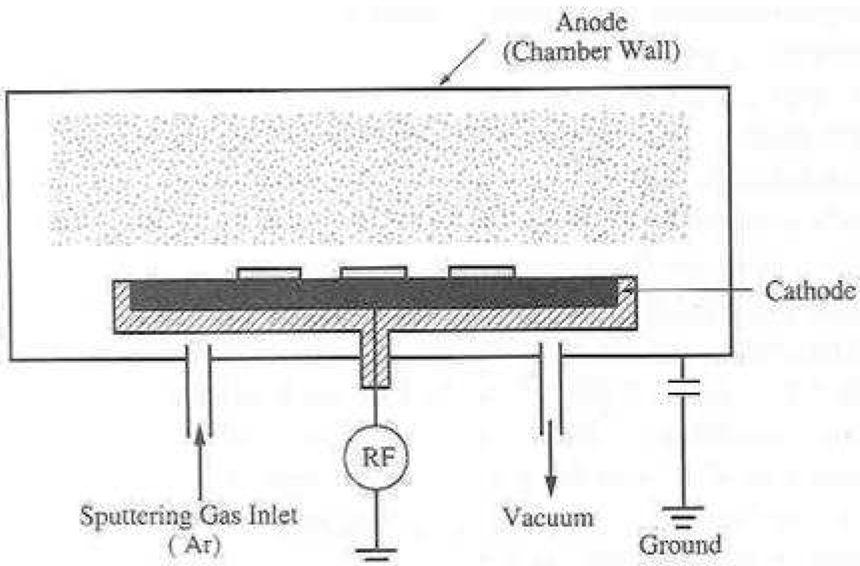
In this process RF voltage is applied to a separate electrode while the target electrode is grounded. A gas is injected in a high pressure environment

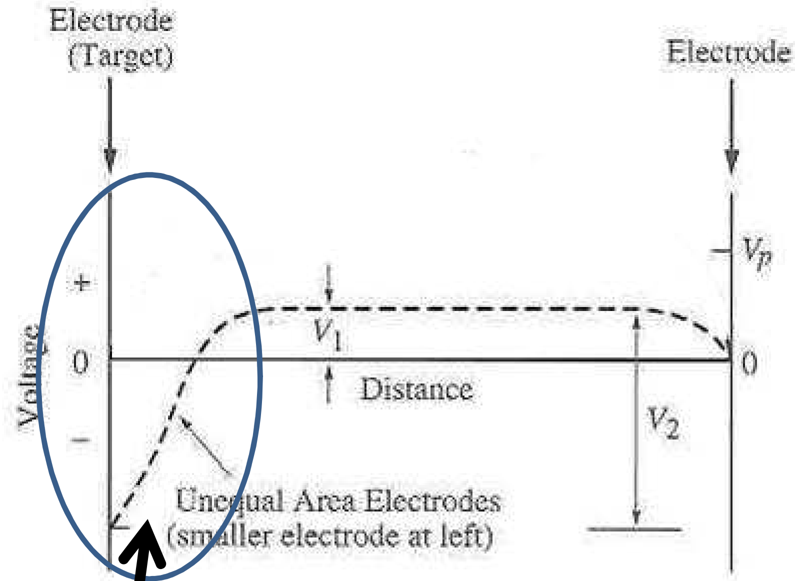
Glow discharge is used to produce chemically reactive species; the sheat field tend to be negligible: radicals or ions diffuse towards the wafer with low acceleration and remove material from the substrate by chemical means



Combination of Physical and Chemical: the Reactive Ion Etching system

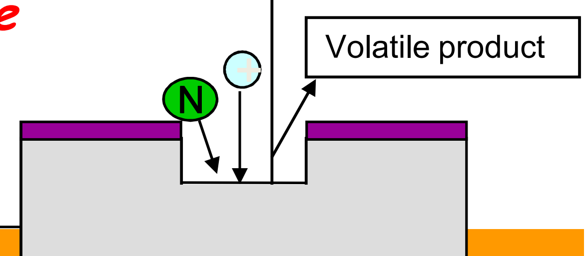




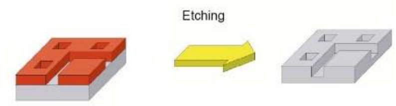


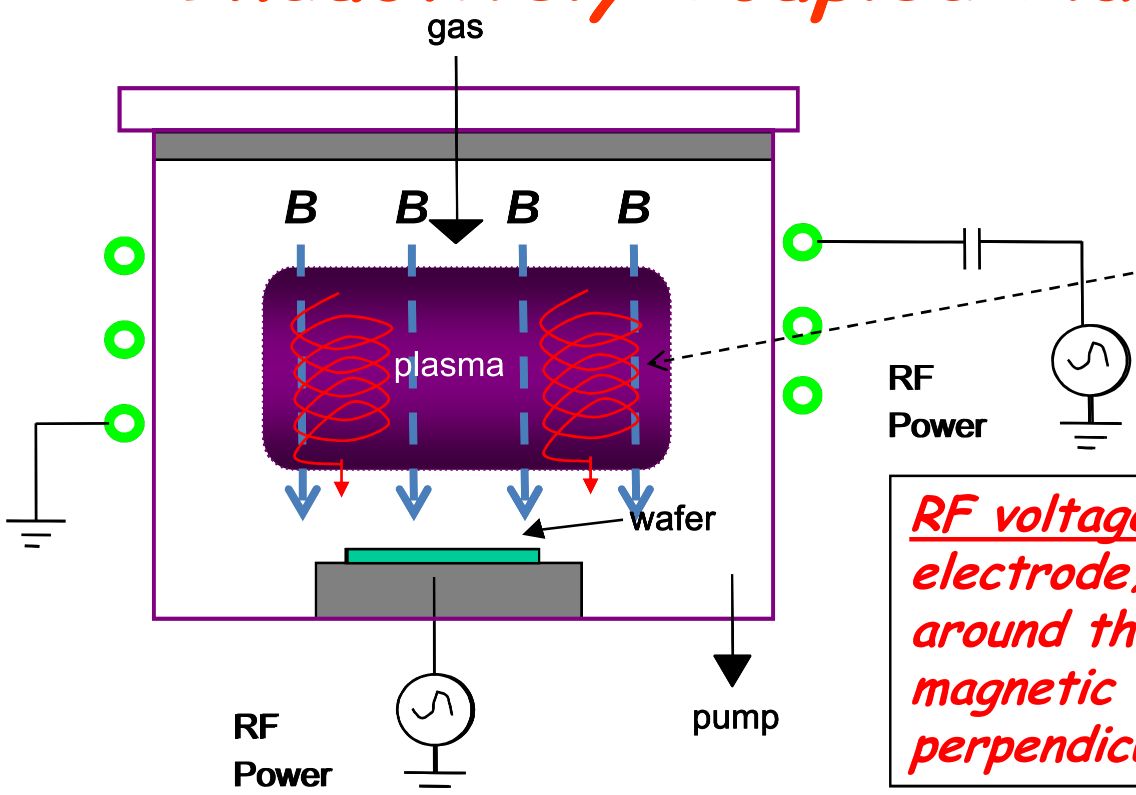
In this process all of the RF voltage is applied to a smaller target electrode; neutral gas is replaced by one or more halogen-rich chemical species at low pressure environment.

Glow discharge is used to produce chemically reactive species and chemically inert ions; neutral ions bombards the substrate surface while radicals diffuse towards the wafer with negligible acceleration and remove material from the substrate by chemical means.



High density plasma: Inductively Coupled Plasma Etching



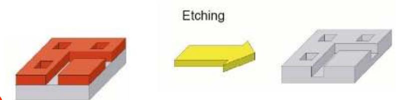


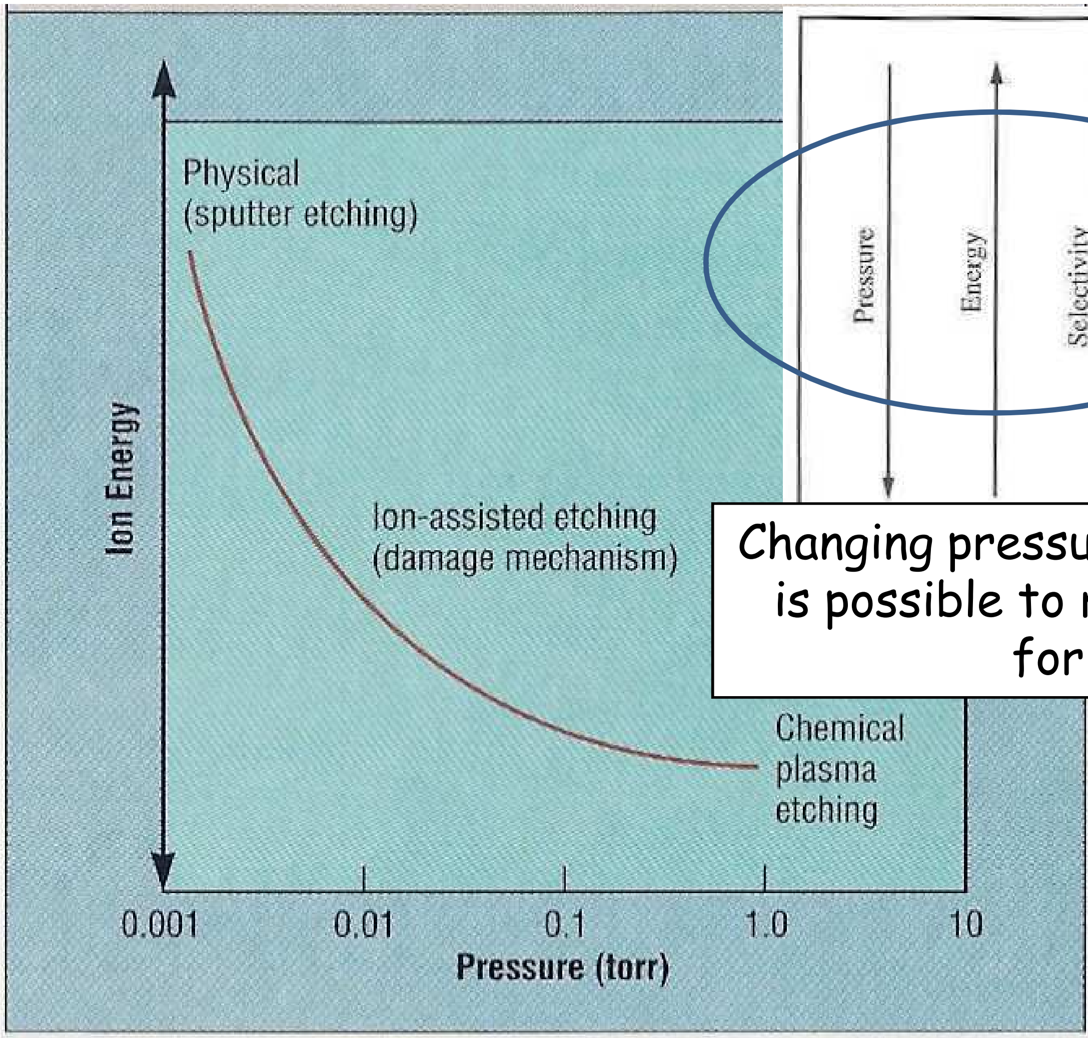
Ions and reactive species spiral around B field in the plasma going towards the wafer; this act on the plasma density, even at low pressure, changing the sheat area.

RF voltage applied on the target electrode; RF current in the coil around the chamber induces a magnetic field in the chamber perpendicular to the target electrode.

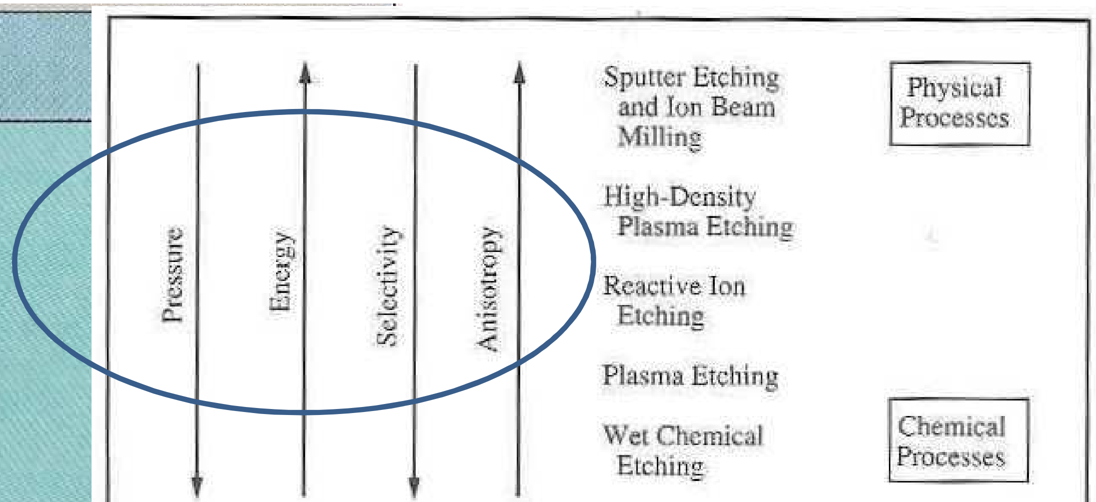
Glow discharge is used to produce chemically reactive species and chemically inert ions; Magnetic field controls the plasma density in the chamber; Electric field controls the ion energy; Control of ion energy and ion density select and balance independently the physical and chemical mechanism for etching

Ion Energy vs. Pressure for a Plasma

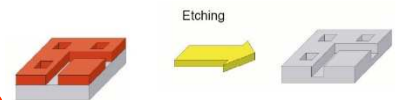




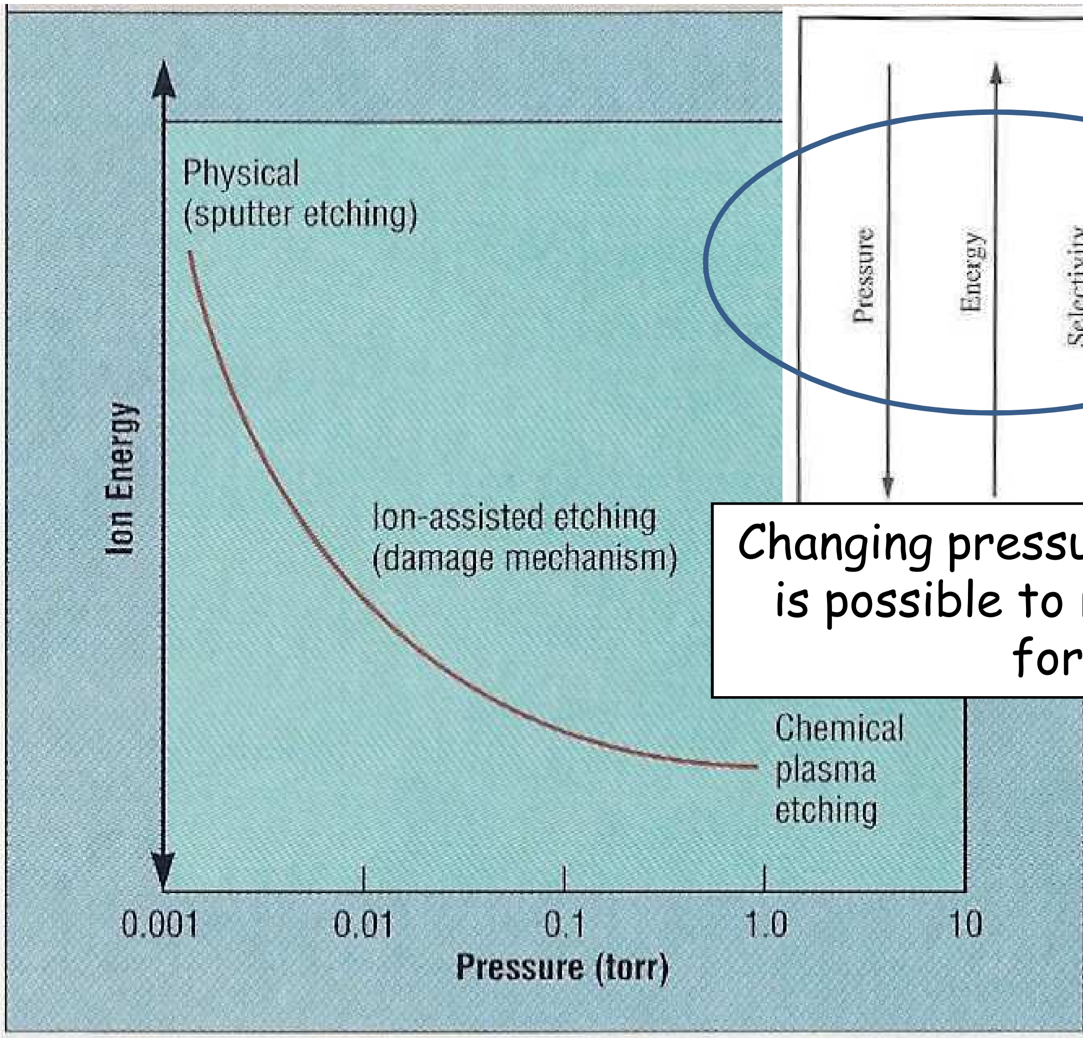
Ion Energy vs. Pressure for a plasma.



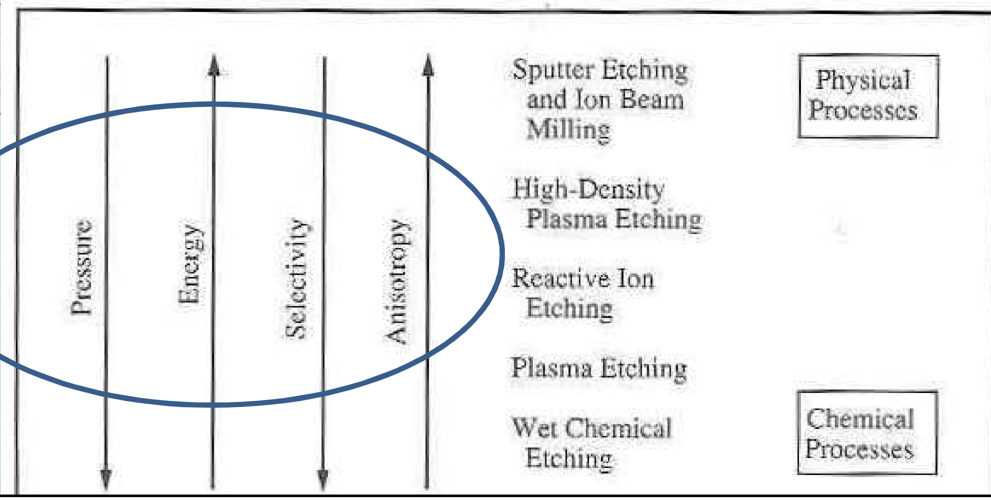
Changing pressure and RF voltage for E and B field is possible to realise the most suitable process for each fabrication need.



Ion Energy vs. Pressure for a Plasma

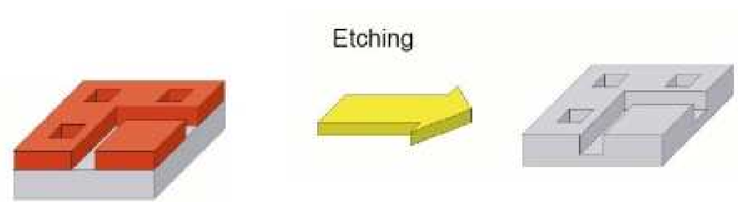


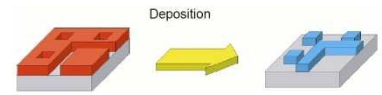
Ion Energy vs. Pressure for a plasma.



Changing pressure and RF voltage for E and B field is possible to realise the most suitable process for each fabrication need.

Once finished the etching process, Mask etching photoresist is removed by Acetone





Thin Film Deposition techniques

- Vacuum deposition Methods

  Ultra High Vacuum ($<10^{-8}$ mTorr)

- Physical Deposition:

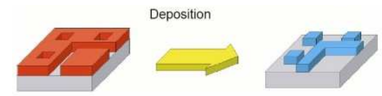
– *Material to be deposited is ready in pellet or disk*

1. Magnetron Sputtering deposition (metal, dielectrics);
2. Thermal deposition (metal, dielectrics);
3. Electronic beam deposition (metal);

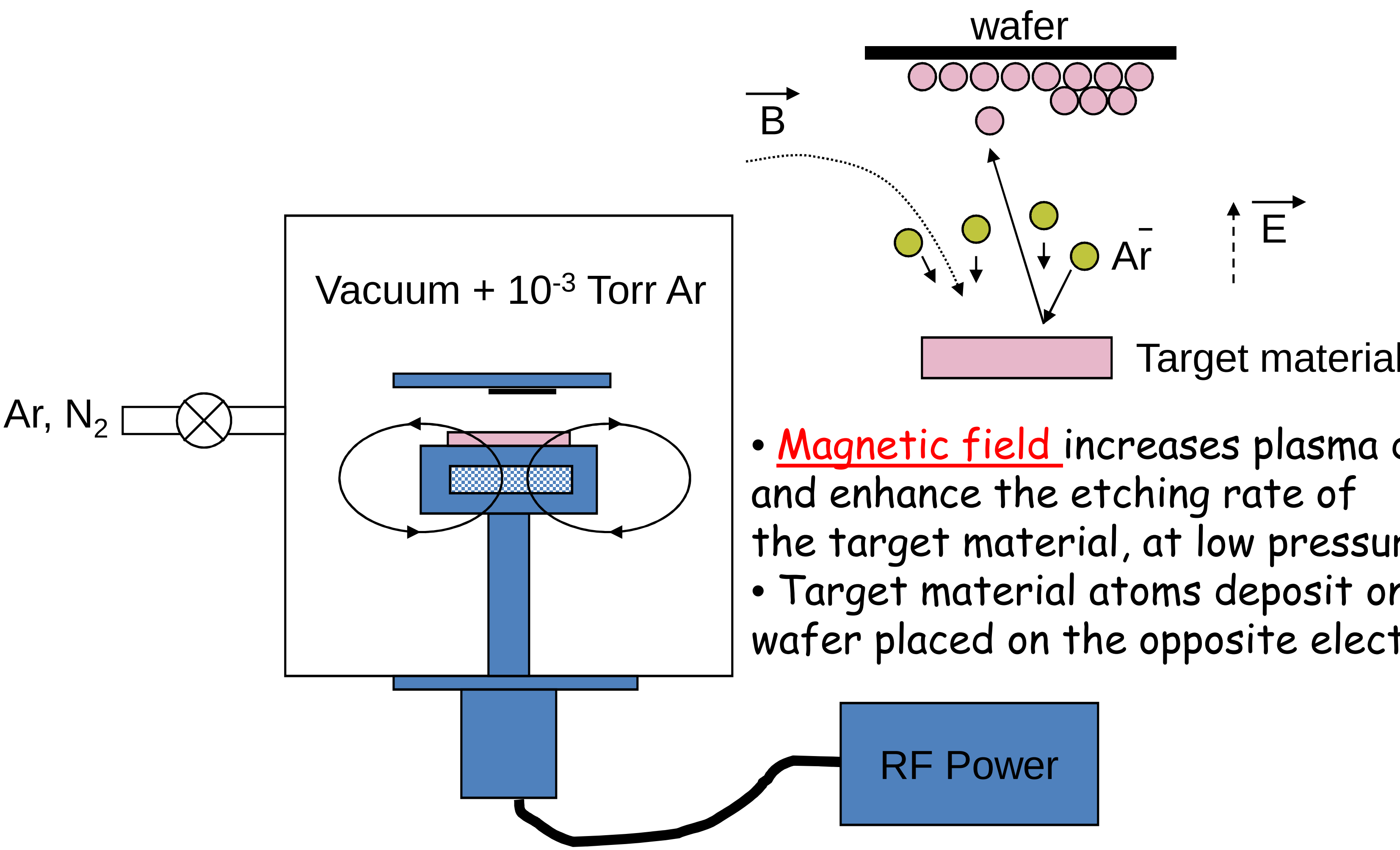
- Chemical Deposition:

– *Material to be deposited is product of a chemical reaction*

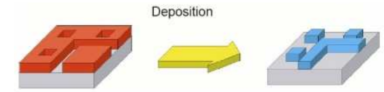
1. Electrodeposition (metal);
2. Chemical Vapor Deposition (CVD) (dielectrics);



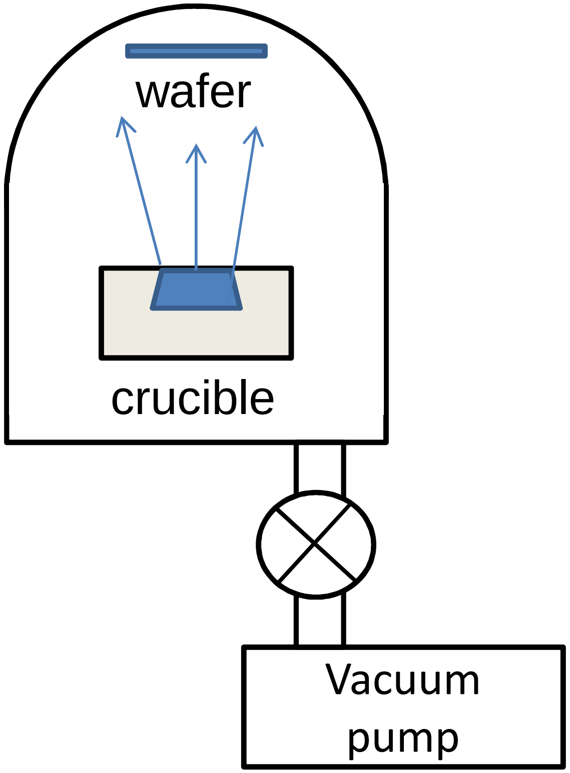
Magnetron Sputtering

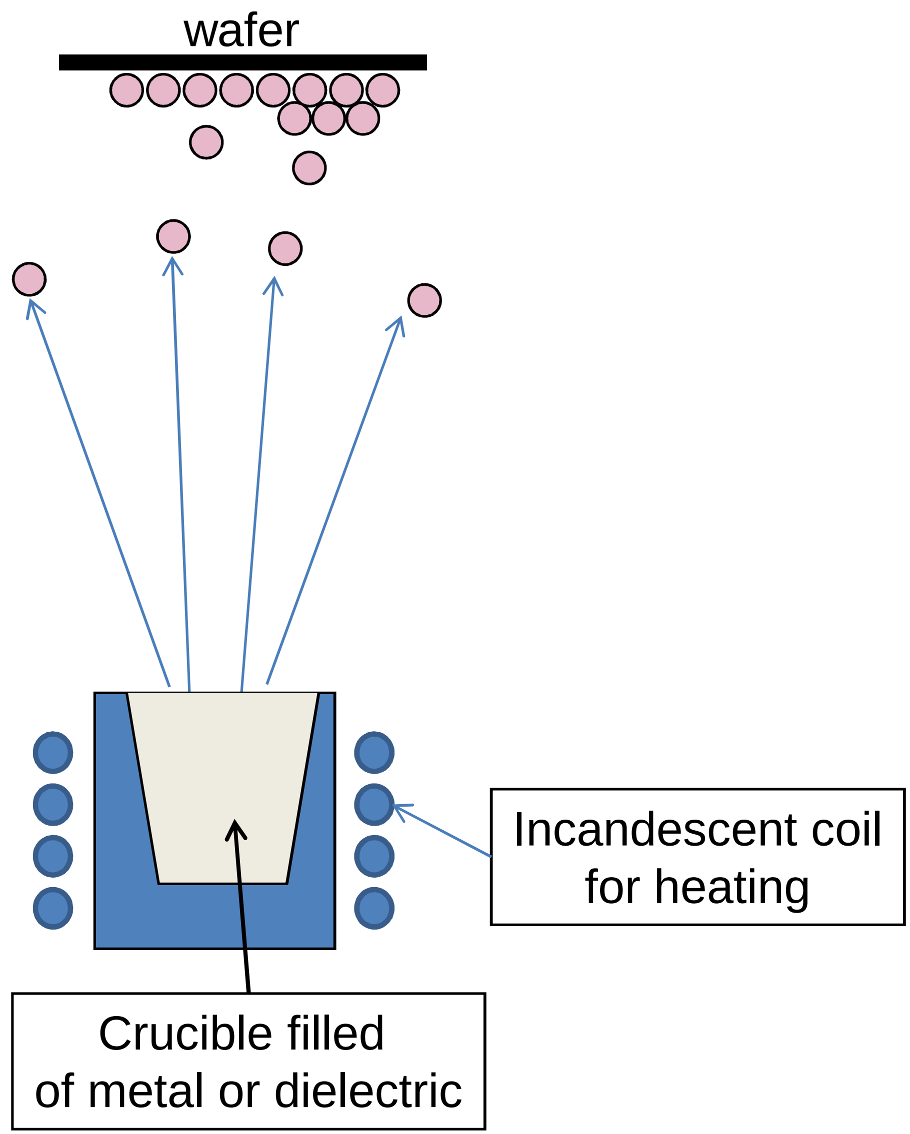


- Magnetic field increases plasma density and enhance the etching rate of the target material, at low pressure.
- Target material atoms deposit on the wafer placed on the opposite electrode.



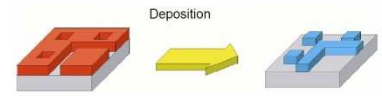
Thermal Evaporation



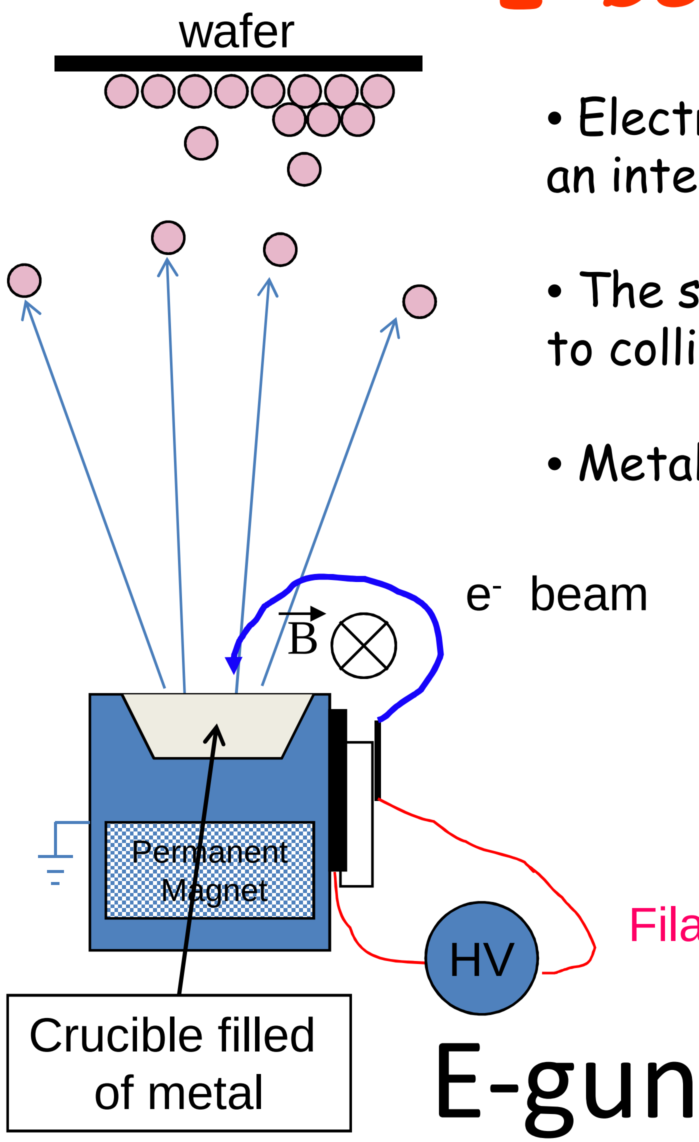


- A resisitively heated coil increase the temperature of material inside the crucible up to the sublimation point.

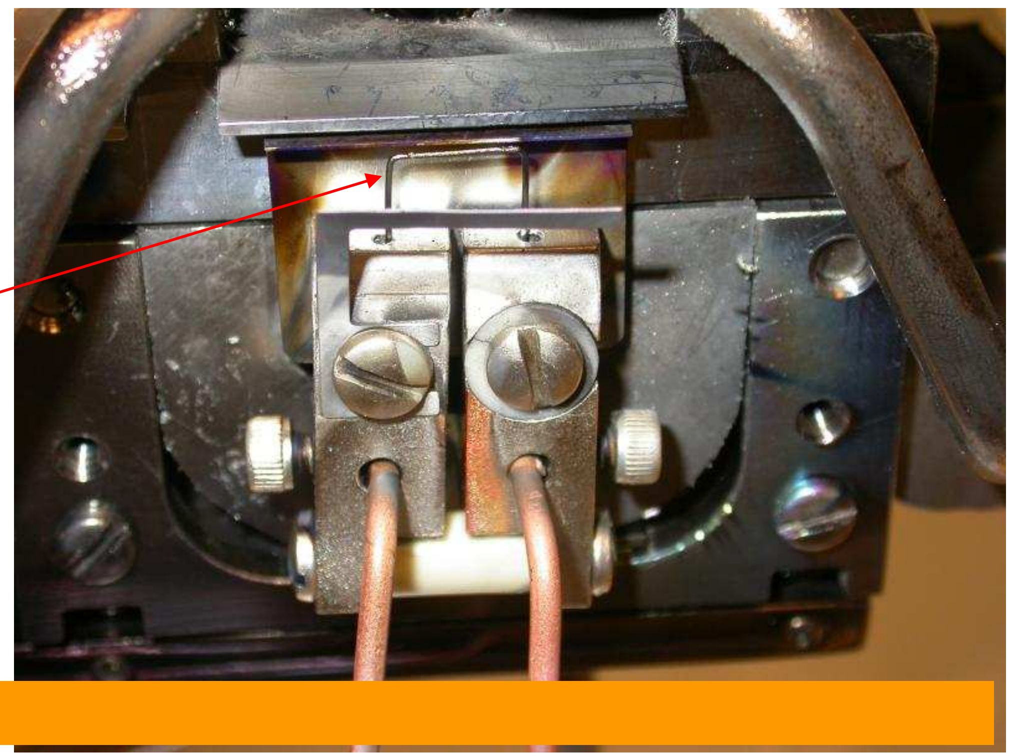
- Metallic or dielectric atoms evaporate towards the wafer.

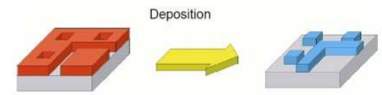


E-beam Evaporation



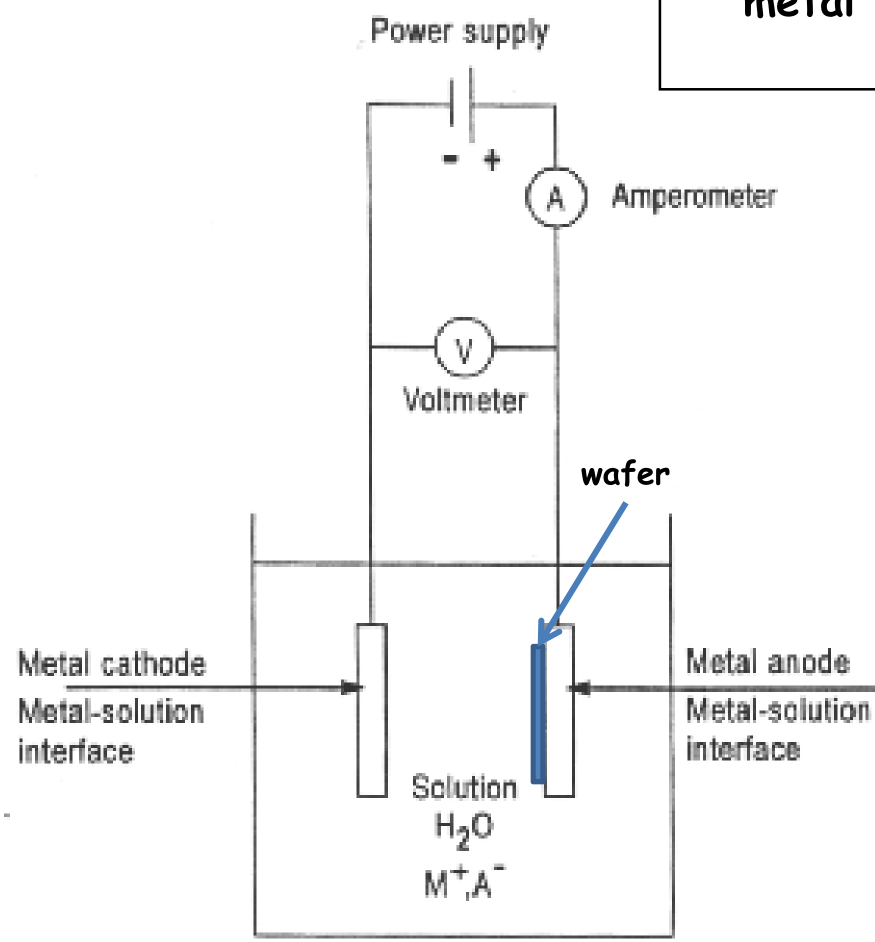
- Electron gun, under the crucible, ejects an intense, high energy beam, by thermionic effect.
- The strong magnetic field bends the beam causing it to collide on the surface of the crucible, filled by metal.
- Metallic atoms evaporate towards the wafer.

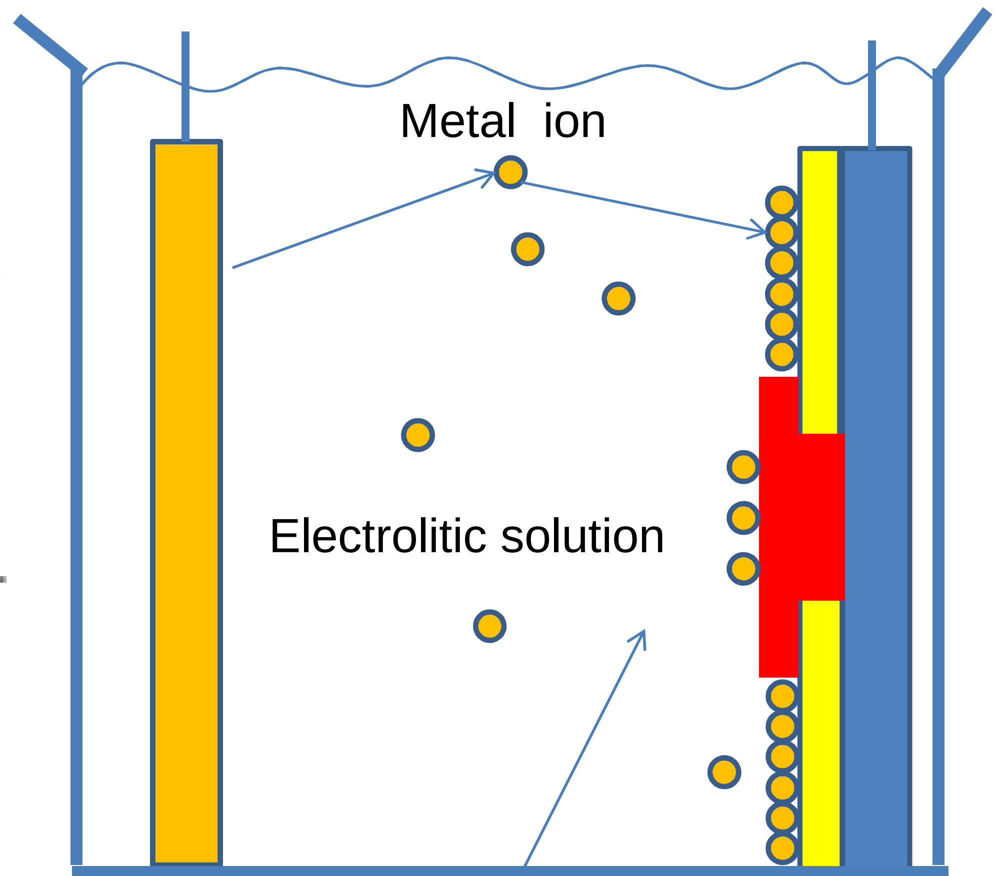




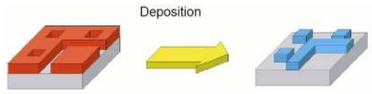
Electrodeposition

Electrodeposition is the process of coating a thin layer of one metal on top of a different metal by deposition of metallic ions in acid solution from one electrode to the opposite.

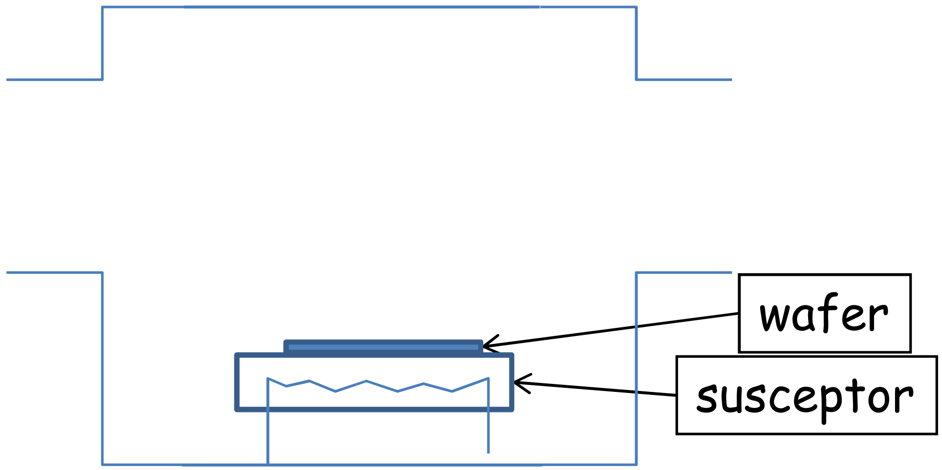


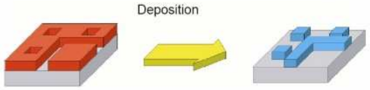


Photoresist (insulator) to be removed

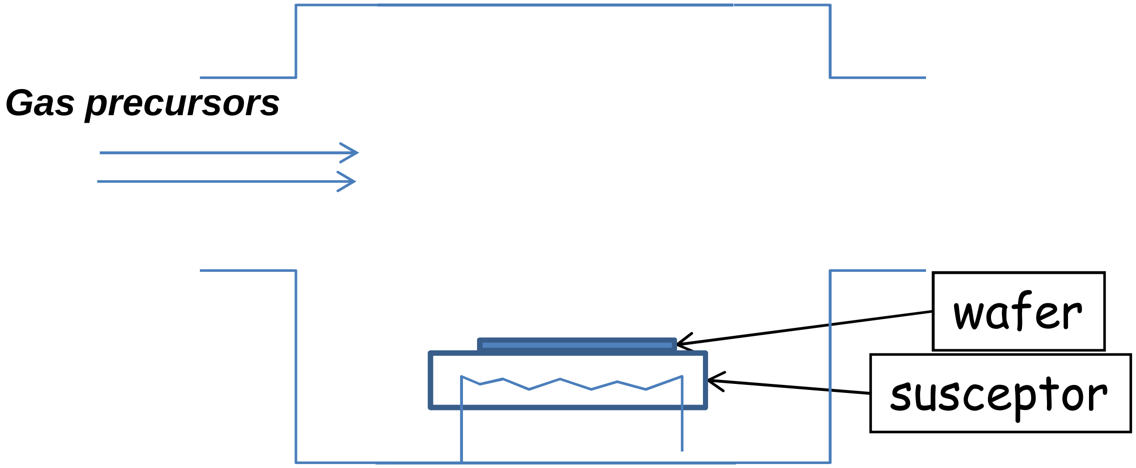


Chemical Vapor Deposition

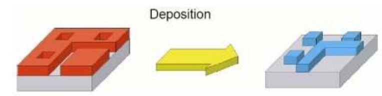




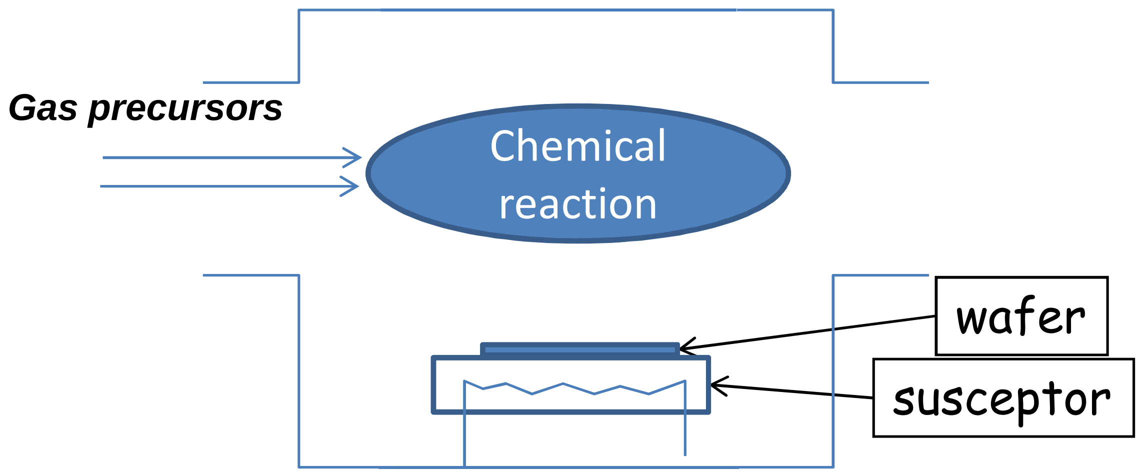
Chemical Vapor Deposition



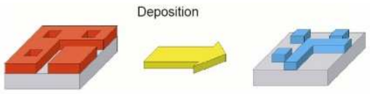
• In Chemical Vapor Deposition (CVD) the substances to be deposited (**precursor**) enters a chamber in a gaseous state.



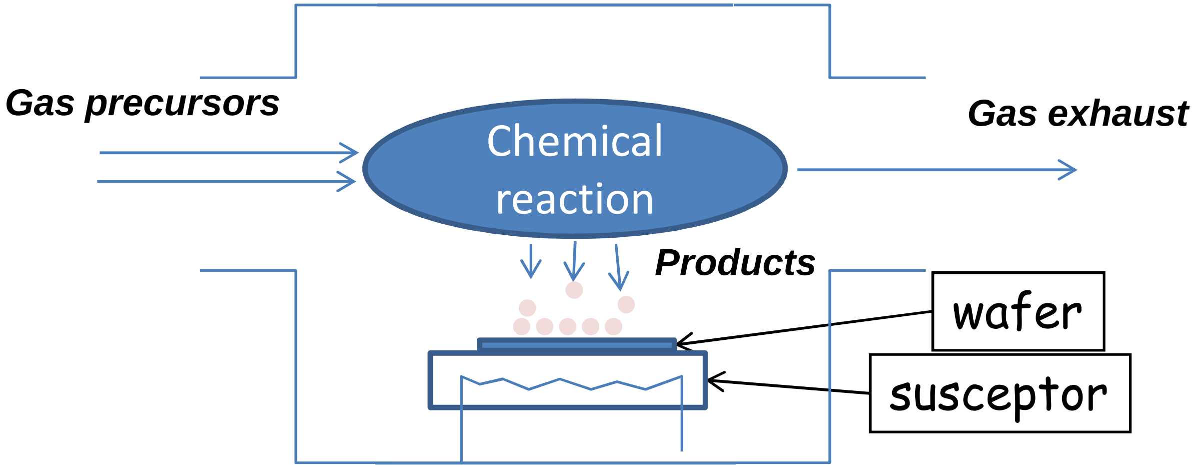
Chemical Vapor Deposition



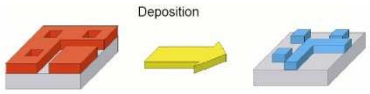
- In Chemical Vapor Deposition (CVD) the substances to be deposited (**precursor**) enters a chamber in a gaseous state.
- These gases can undergo reactions in this vaporous state before reaching the substrate.



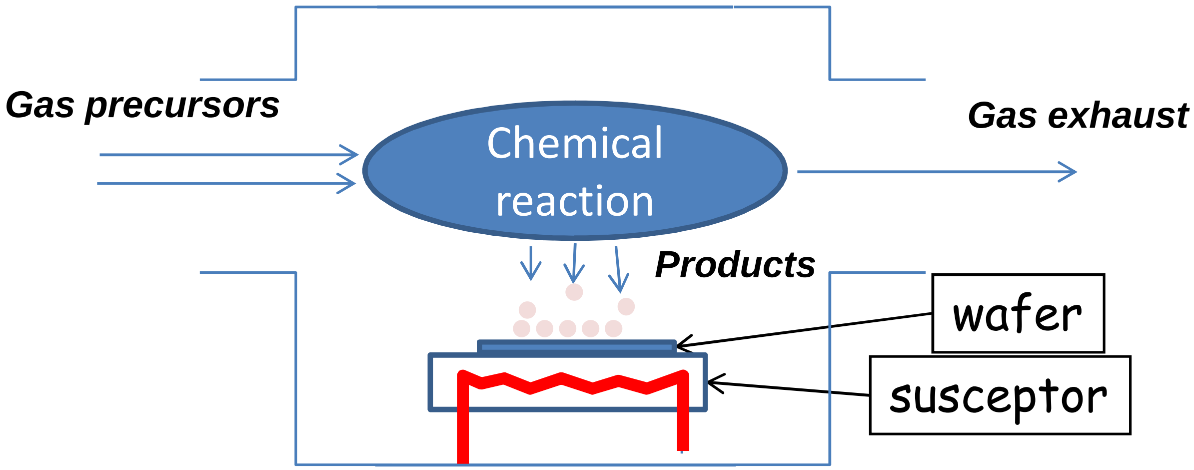
Chemical Vapor Deposition



- In Chemical Vapor Deposition (CVD) the substances to be deposited (**precursor**) enters a chamber in a gaseous state.
- These gases can undergo reactions in this vaporous state before reaching the substrate.
- As the gases approach the substrate, the molecules are **adsorbed** onto the surface; undergo a surface reaction with the substrate and products **diffuse** on the surface along the surface and form a stable thin film.



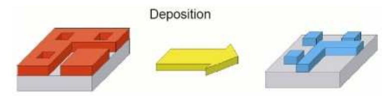
Chemical Vapor Deposition



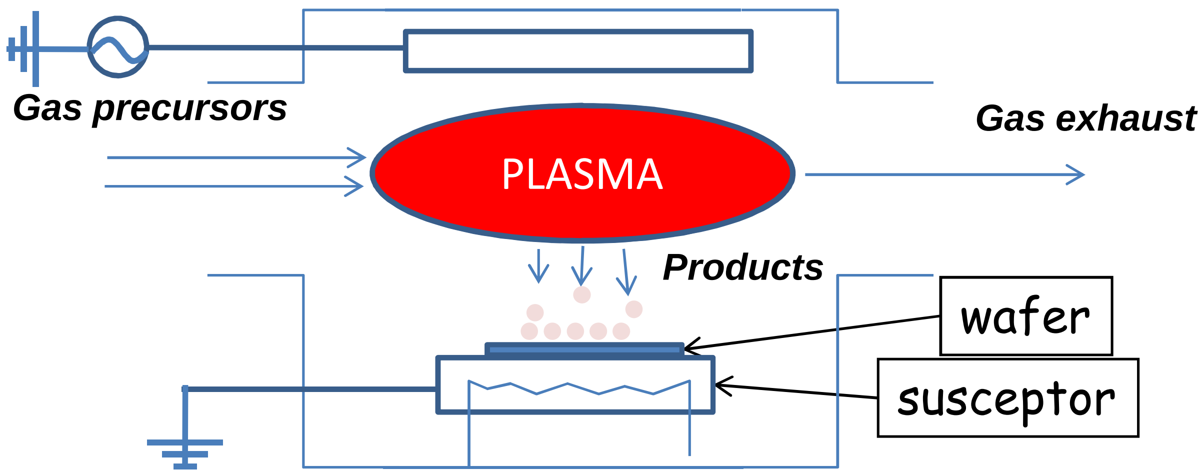
- In Chemical Vapor Deposition (CVD) the substances to be deposited (precursor) enters a chamber in a gaseous state.
- These gases can undergo reactions in this vaporous state before reaching the substrate.
- As the gases approach the substrate, the molecules are adsorbed onto the surface; undergo a surface reaction with the substrate and products diffuse on the surface along the surface and form a stable thin film.

Parameters to favor reactions if more energy is needed:

- ***Increase temperature of wafer by resitive heater inside the susceptor (LPCVD).***



Chemical Vapor Deposition



• In Chemical Vapor Deposition (CVD) the substances to be deposited (precursor) enters a chamber in a gaseous state.

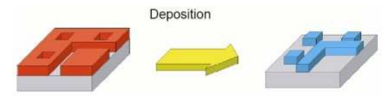
•These gases can undergo reactions in this vaporous state before reaching the substrate.

•As the gases approach the substrate, the molecules are adsorbed onto the surface; undergo a surface reaction with the substrate and products diffuse on the surface along the surface and form a stable thin film.

Parameters to favor reactions if more energy is needed:

•*Increase temperature of wafer by resitive heater inside the susceptor (LPCVD).*

•*Apply a RF voltage to create a plasma if low temperature is needed (PECVD)*

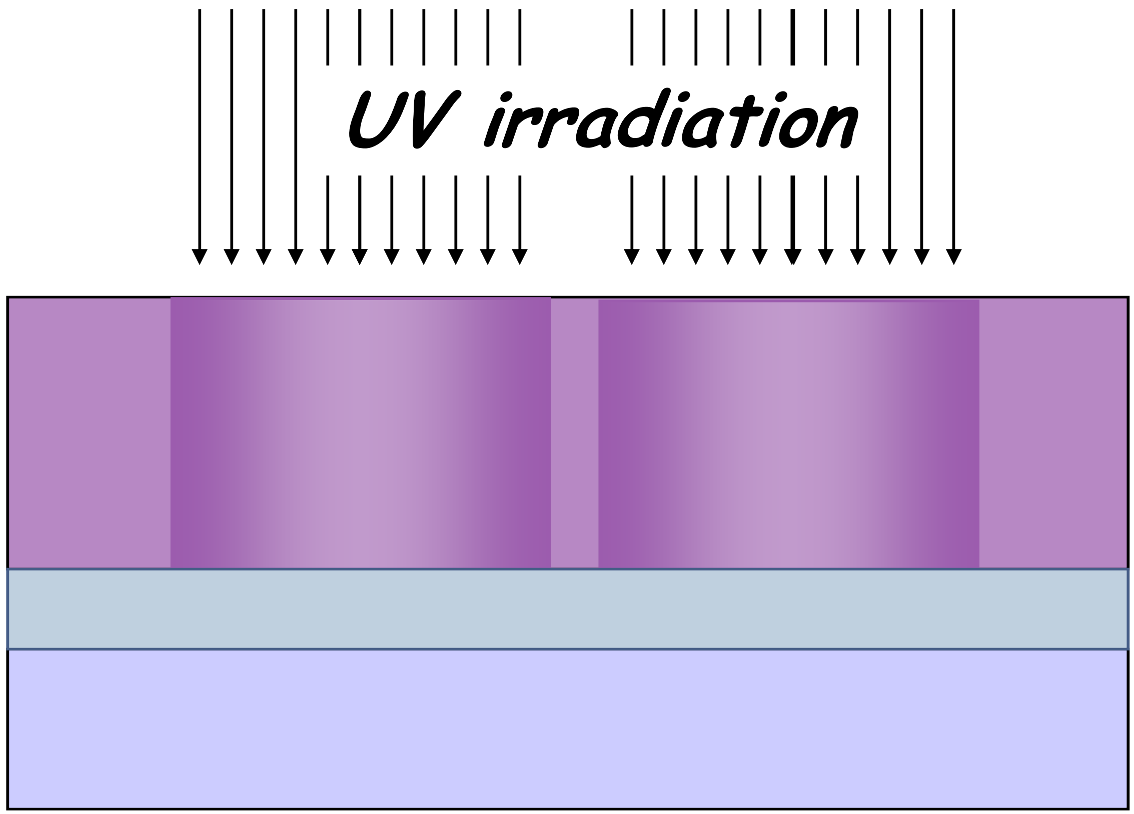


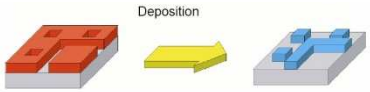
Shadow evaporation and Lift-off

Lift off: the process to remove the mask deposition photoresist after deposition.

Problem:

if there is a continuous deposition layer, it's difficult to remove the photoresist. It's completely covered by coating; difficult to desolve by acetone.





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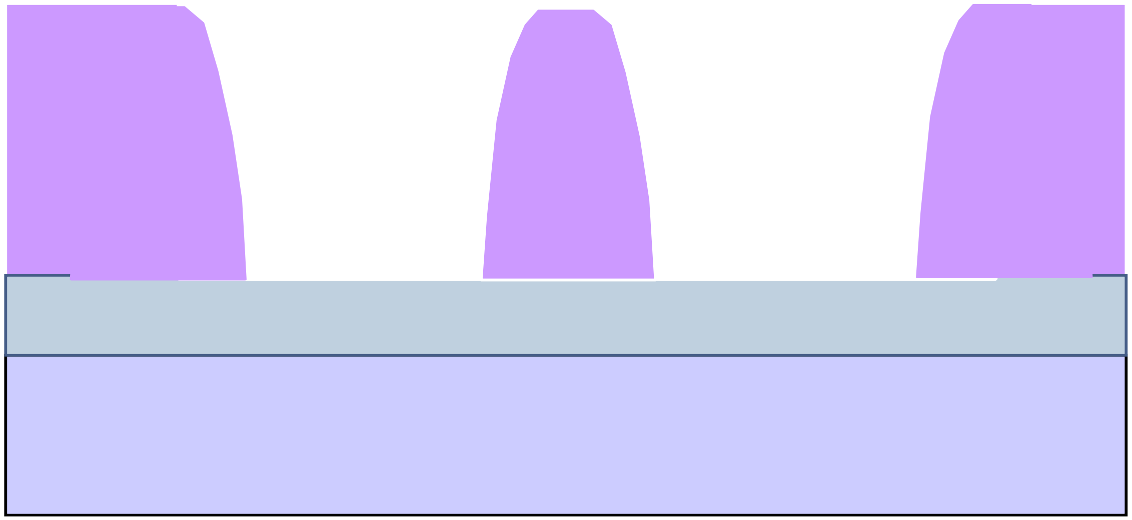
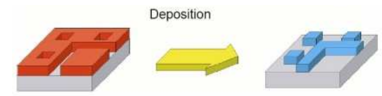
Developement



Shadow evaporation and Lift-off



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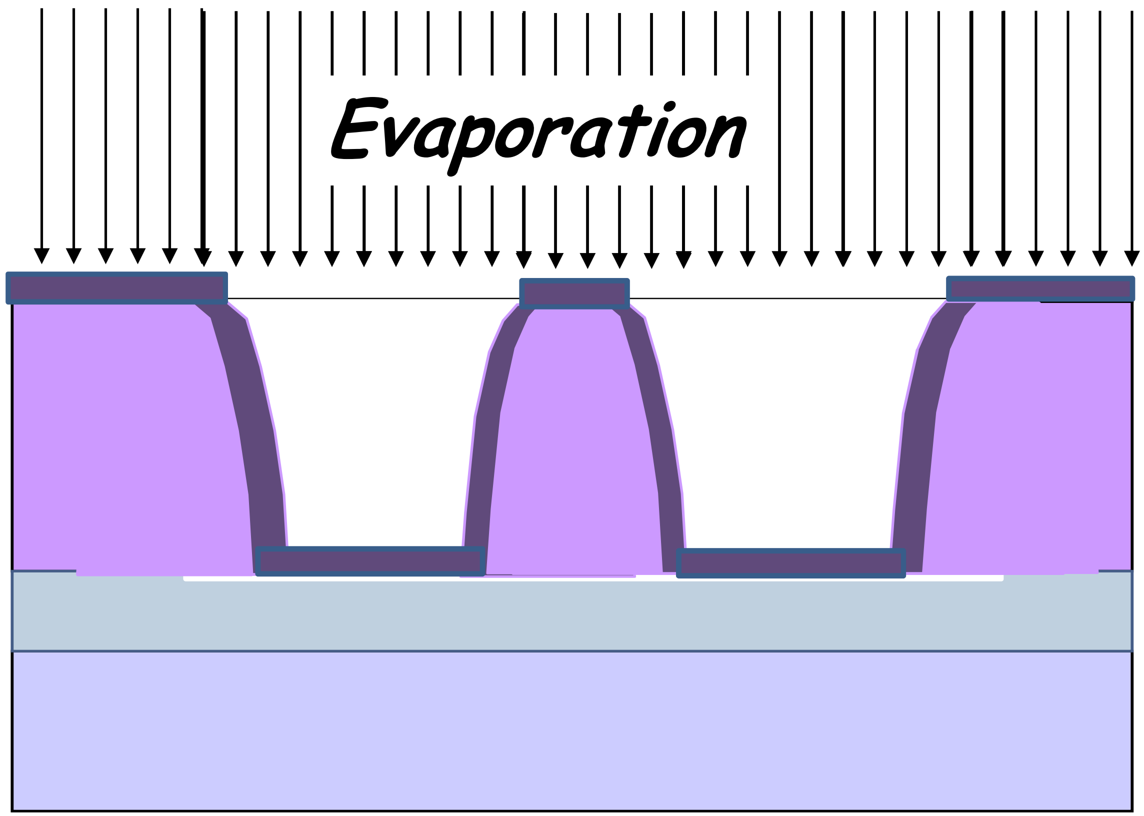
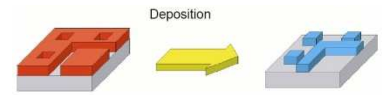
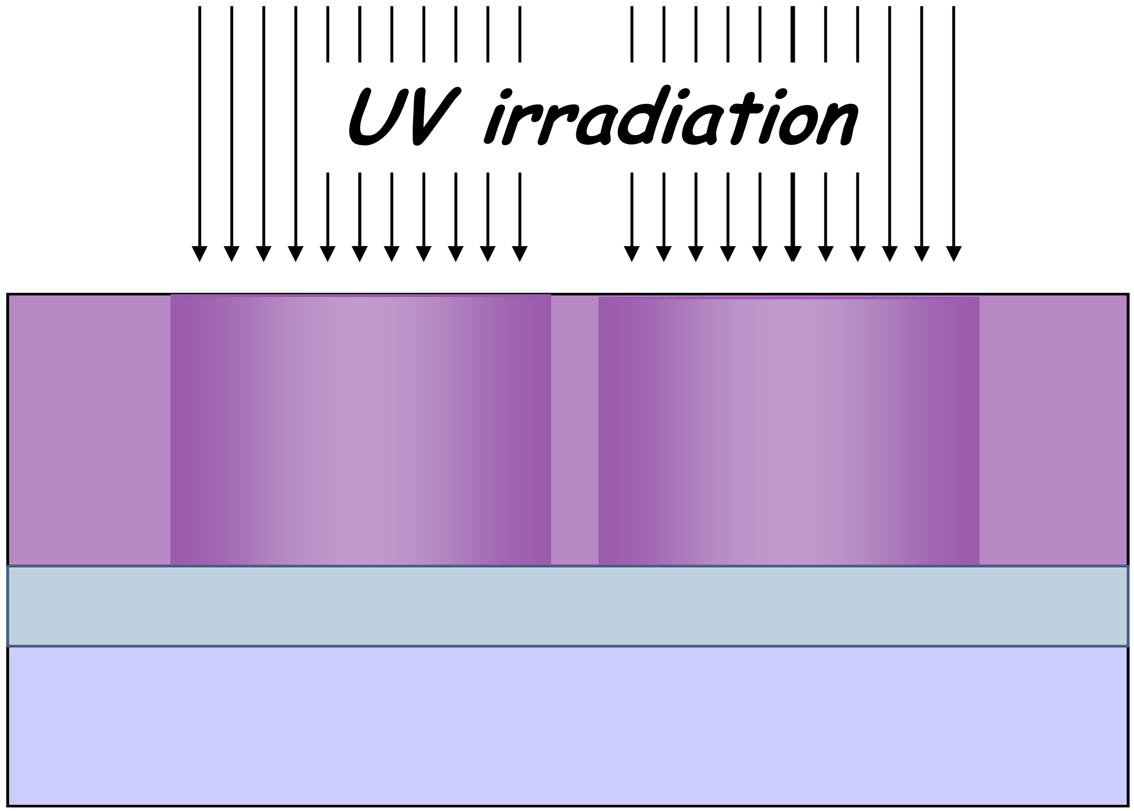


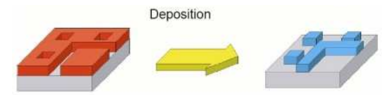


Shadow evaporation and Lift-off

Lift off: the process to remove the mask deposition photoresist after deposition.

As opposite of etching, we need the photoresist to give a shadow effect to ease remotion of deposited film on it. It is possible using some chemicals before devolopment to make the unexposed photoresist stronger to development.





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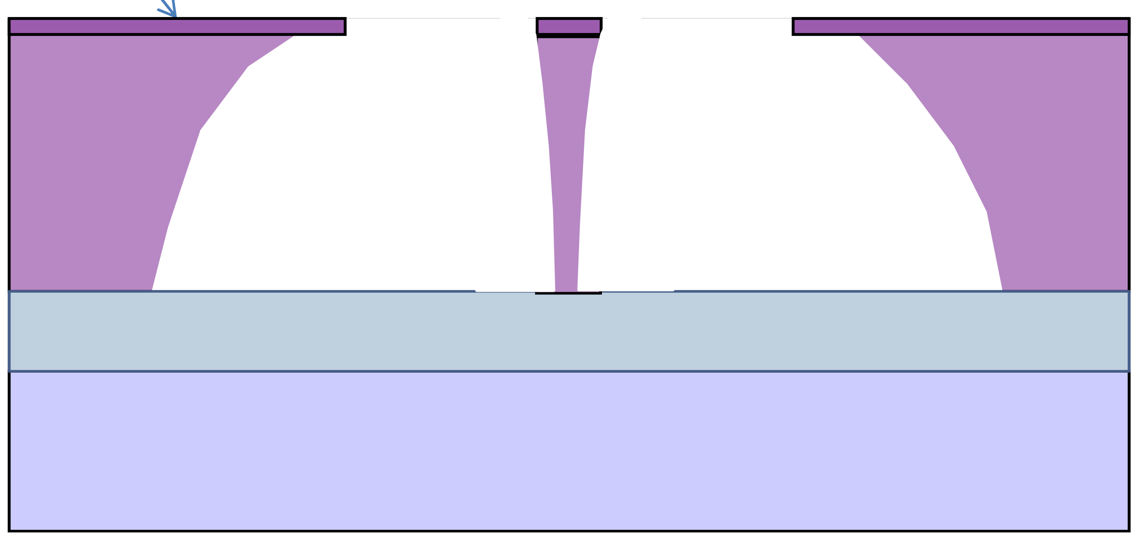
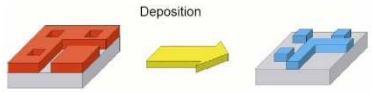
Chlorobenzene and developer

Hardned photoresist layer by chlorobenzene: re-entrant profile.





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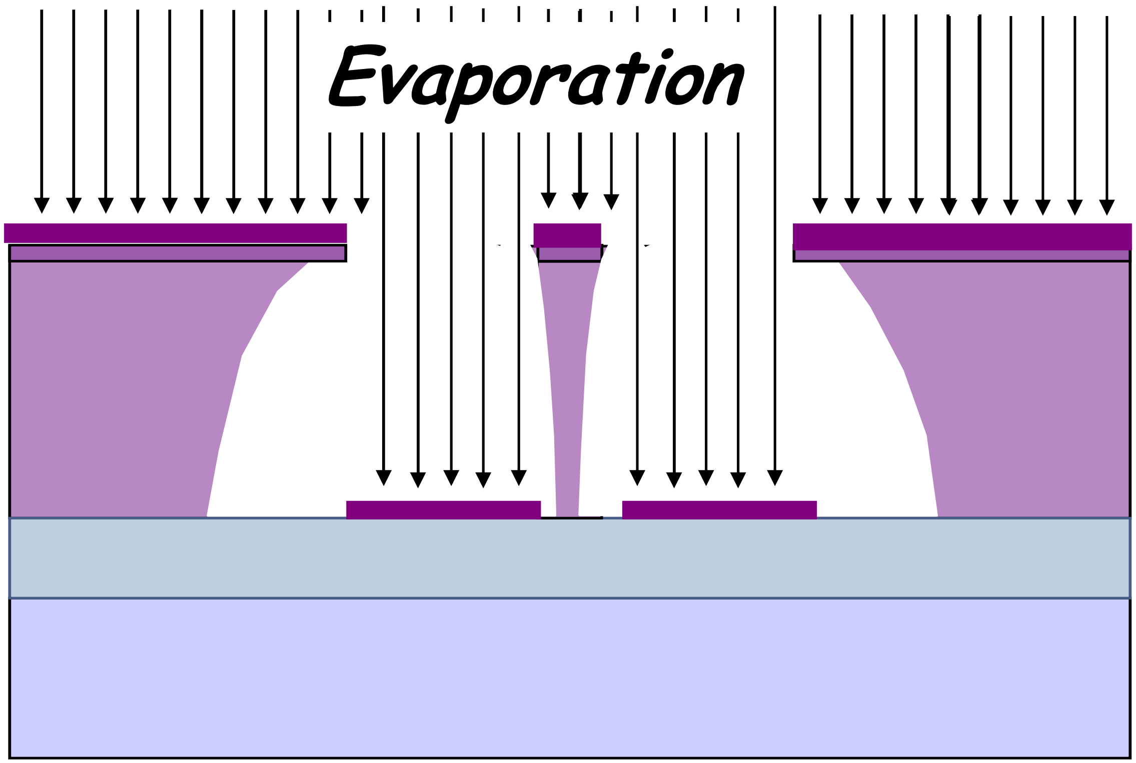

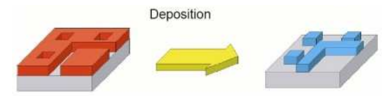

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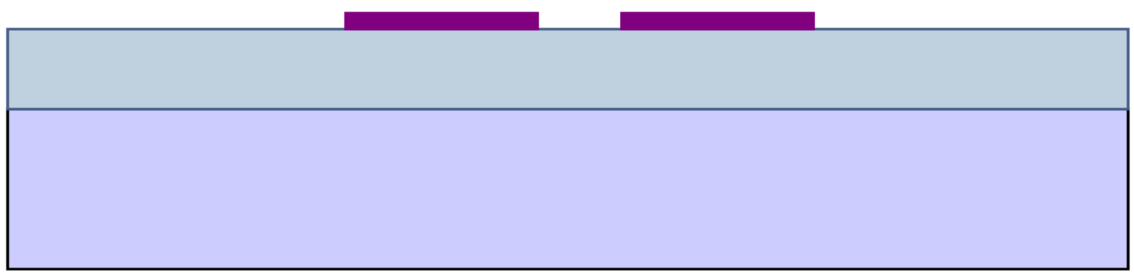
As opposite of etching, we need the photoresist to give a shadow effect to ease remotion of deposited film on it. It is possible using some chemicals before devolopment to make the unexposed photoresist stronger to development.

Lift off the resist and excess metal



1959 Feynmann's talk

annual meeting of the American Physical Society

http://www.zyvex.com/nanotech/feynman.html

There's plenty of room at the bottom

[…] I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. [...]

What I want to talk about is the problem of manipulating and controlling things on a small scale.[…]

Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin? […]

- ***Information on a small scale***
- ***Miniaturizing the computer***
- ***The marvelous biological system***
- ***Rearranging the atoms***
- ***Atoms in a small world***

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There's plenty of room at the bottom

[…] I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. […]

So, Guys, there is a plenty of job in your doctorate.

Have fun and Good luck!!!!

the head of a pin? […]

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- *Atoms in a small world*