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It is important to remember that the difference between a NMOS and a PMOS is the type of channel that appears between the drain and the source. Namely in a NMOS we have the appearance of a n-channel (electrons) among a P-type doped silicon.

Most schematics of this course are not *up to scale* ! so it is important to remember some typical values :

- Wafer diameter & Thickness:
 - 4" : $400 \mu m$
 - 8"-12" : $1200 \mu m$
- Thickness of a layer : $1-3 \mu m$

A good comparison for this scale is a single hair which is approximately $75 \mu m$.

Basic steps of IC fabrication

We always start from a wafer, either P-type or N-type. Here we will discuss the fabrication of a NMOS type of transistor so we will need a P-type Si wafer.

1. Oxidation : We deposit a layer of SiO_2 by either *growing* or *depositing* it at high temperature.
2. Deposition of poly-Silicon : we will deposit some poly-crystalline silicon using cvd.
3. First photoresist : we use some organic photoresist and to evenly disperse it we will spin the wafer. This will help spreading evenly the photoresist and making it thinner. Many version and purity of this compound exists.
 - *Lithography* : we will shine UV light through a mask (why UV ? shorter λ so smaller features size possible). After this we will simply etched away the area that were exposed to UV light (so it gets smoother through UV exposure and stay harder otherwise)
4. Etching of Poly-Si : we will use some *dry* (plasma) or *wet* etching and then we remove the rest of photoresist.
5. Doping of Source and Drain region : we send ion at high speed on the wafer (ion implementation) and to repair the damage we "cook" it around 900° . It can easily traverse the thin SiO_2 layer but not the poly-Si.
6. Wrapping & Adding contact :
 - *Deposit of Oxide* : again with some cvd we put a layer of oxide. This result in unsmooth surface.
 - *Add photoresist* : then use UV mask and etch at specific spot over the Source and Drain.
 - *Remove photoresist*
 - *Add metal* : we do some pvd
 - *Remove metal over the gate* : we don't want any layer of metal over the gate or we will create more unwanted capacitance. So we again use photoresist, UV mask, etch photoresist, etch metal and finally remove the remainder of photoresist.

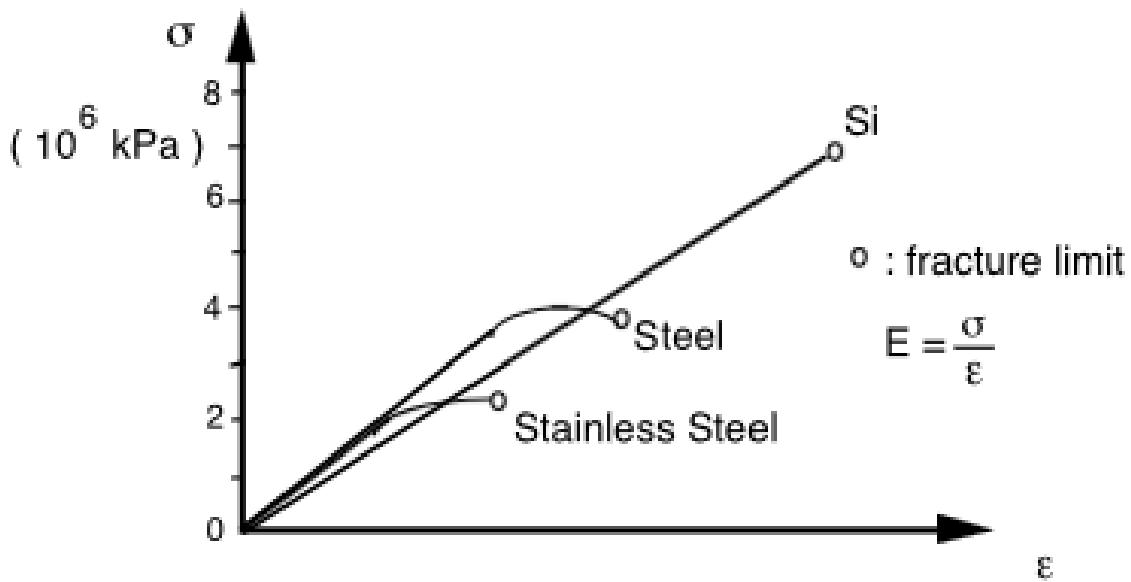
An important distinction to be made is when we are talking about mask they can be either :

- *Photo mask* : use of a blocking and non blocking UV light mask to make a photoresist compound react or not.
- *Etch mask* : the remaining photoresist (after etching of non hardened one) is used as a protective layer to not etch unexposed surfaces.

Mass producing and producing in batch is a key to bring down the costs of IC. We can produce a lot quickly and efficiently and with good design we can leave room for error and process variation meaning we can increase yields.

Silicon

r0.5

**Figure 1:** image

Silicon is one of the favorite material since it is :

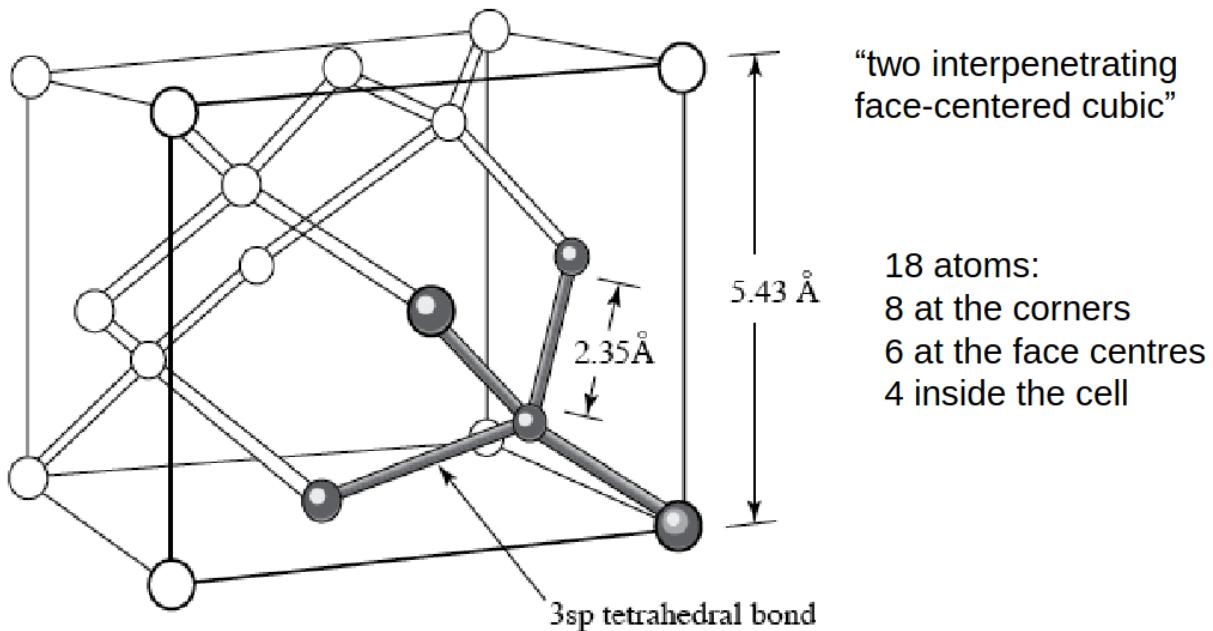
- Cheap, strong (and fragile)
- $0.001 - 20 \text{ } k\Omega/\text{cm}$
- Stable oxide (SiO_2) pretty inert (wow)
- various flavors of lattice, Silicon-Crystalline-Silicon, poly-silicon, amorphous silicon (unordered)

We can also use some GaAs, Quartz (which is just SiO_2 with other things), SiC, Al_2O_3 . On the figure [resistivity_Si]{reference-type="ref" reference="resistivity_Si": we can see how the Silicium can deform under pressure and come back to its original shape without breaking for large values. We can even make some wafer flexible using special processes to make it extra thin.

We mostly use crystalline like Silicon even though non-crystalline have become somewhat important in the industry. The doping plays a role regarding the resistivity of the material.

Dopant level	Designation	Dopant concentration (cm^{-3})	Resistivity n/p (ohm-cm)
Very lightly doped	n^{--}, p^{--}	$<10^{14}$	$>100/>30$
Lightly doped	n^-, p^-	$10^{14}-10^{16}$	$1-100/0.3-30$
Moderately doped	n, p	$10^{16}-10^{18}$	$0.03-1/0.02-0.3$
highly doped	n^+, p^+	$10^{18}-10^{19}$	$0.01-0.03/0.005-0.02$
Very highly doped	n^{++}, p^{++}	10^{19}	$0.001 < 0.01/0.005$

Figure 2: Resistivity for various doping level



r_{0.5}

Silicon Lattice constant = 5.43 Å

Silicon atoms have 4 valence electrons and their covalent bonds are in a pyramid like structure (**tetrahedron**).
For doping we can use :

- N-type : use 5a group : Arsenic, Phosphorous, ...
- P-type : use 3a group : Boron, Gallium, Aluminum, ...

We have 4 atoms completely inside of a unit cell, the 8 ones on the corner are shared with other cell (and count as 1 atom inside cell) and the 6 remaining atoms on the faces are shared with 2 cells (count as 3 atoms inside cell). So we have $4 + 1 + 3 = 8$ atoms inside the cell and the cell volume is $(.543\text{nm})^3 = 1.6 \cdot 10^{-22}\text{cm}^3$ which leads to a density of $\frac{8}{1.6 \cdot 10^{-22}\text{cm}^3} = 5 \cdot 10^{22} \text{ atoms/cm}^3$.

To represent which angles we are viewing a cell, we are using the **miller indices**. Different orientations of the lattice impact the properties of the transistor due to different lattice form.

Miller Indices

To find the miller indices, we need to first draw a plane and see where it intercepts with any x,y,z axis. If we only intercept the x axis at a then we can write [1 0 0] if we normalize a as the *cubic cell constant*.

We have various notation each with its own rule:

- 100 : **direction** in crystal coordinate
- <100> : set of *symmetrically equivalent direction* in crystal coordinate
- (100) : **plane** perpendicular to a direction
- {100} : set of *symmetrically equivalent plane* in crystal coordinate

To find the angle between two crystallographic directions we use the equation with the two directions being

$[h_1 k_1 l_1]$ and $[h_2 k_2 l_2]$:

$$\cos(\theta) = \frac{h_1 h_2 + k_1 k_2 + l_1 l_2}{\sqrt{(h_1^2 + k_1^2 + l_1^2)(h_2^2 + k_2^2 + l_2^2)}}$$

Production of wafers

Single crystal silicon is one of the purest material made artificially with a purity of 99.99999999 %. We have a FCC lattices displaced by .25 Å in the 3 directions.

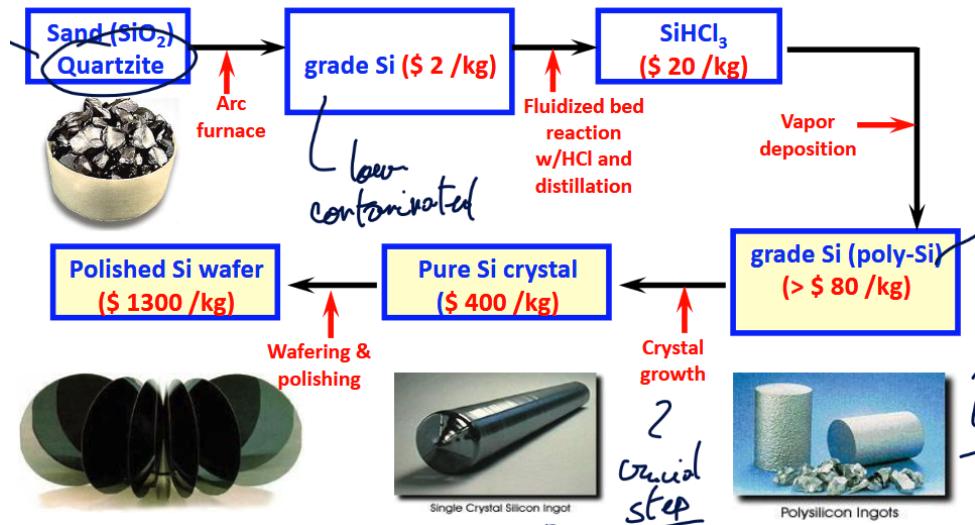


Figure 3: Cycle of Si production

We can have some defect and non-idealities in the boule. Typically we want a mono-crystalline structure where everything is ordered in the same direction. But we can have :

- Polycrystalline : multiple pockets named **grain** (or crystallites) where we find different direction of crystal
- Amorphous : unorganized structure and random

But first, we need to melt this *quartz sand* with carbon at over 1900°C. We have a purity of over 98 %.

Wafer processing

Czochralski Pulling To create the big boule we then use to slice into wafers, we need to use a specific machine. Typically, we need to use a *seed crystal* with a specific orientation which will make sure to give the same orientation to the boule. We dip it and rotate in counter direction the pot and the seed crystal. The rotation speed is important and the diameter is *inversely proportional to the pull rate*. The pull rate is in *mm/min* and it takes a lot of time to produce just one boule. We need 30 hours to create a 2m boule and another 30 hours for heating and cooling.

Slicing To indicate the orientation, we used to add a flat perpendicular to the < 110 > direction but now we simply use a notch. We mostly use the < 100 > with a precision of ±0.5° and sometimes we use the

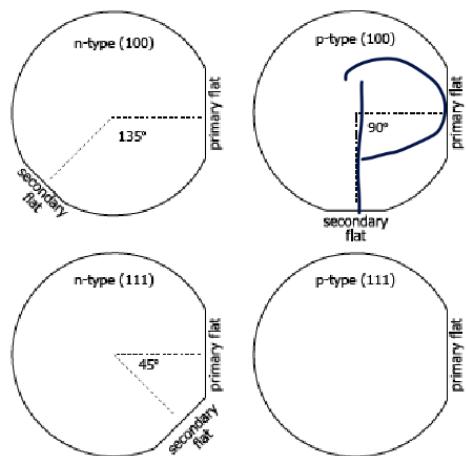
$<111>$ with $2^\circ - 5^\circ$ off axis.

The cutting is done with wires coated with diamond and we have one feeder spool and another one that takes the used wires.

Wafer after treatment

1. **Lapping** grind both sides, flatness around $2 - 3 \mu m$, removes $20 \mu m$ per side.
2. **Edge Profiling**
3. **Etching** chemical etch to remove *surface damage*, removes $20 \mu m$ per side.
4. **Polishing** chemi-mechanical polish, using a slurry composed of SiO_2 and some $NaOH$, removes $25 \mu m$ per side. Nice mirror finish.
5. **Cleaning and Inspection**

Silicon wafers cut parallel to one of the crystal planes.



Miller indices indicated by ground edges called "flats". "n"-type and "p"-type refer to "doping". N means "negative" (phosphorus) and P means "positive" (boron).



Figure 4: Crystal orientation

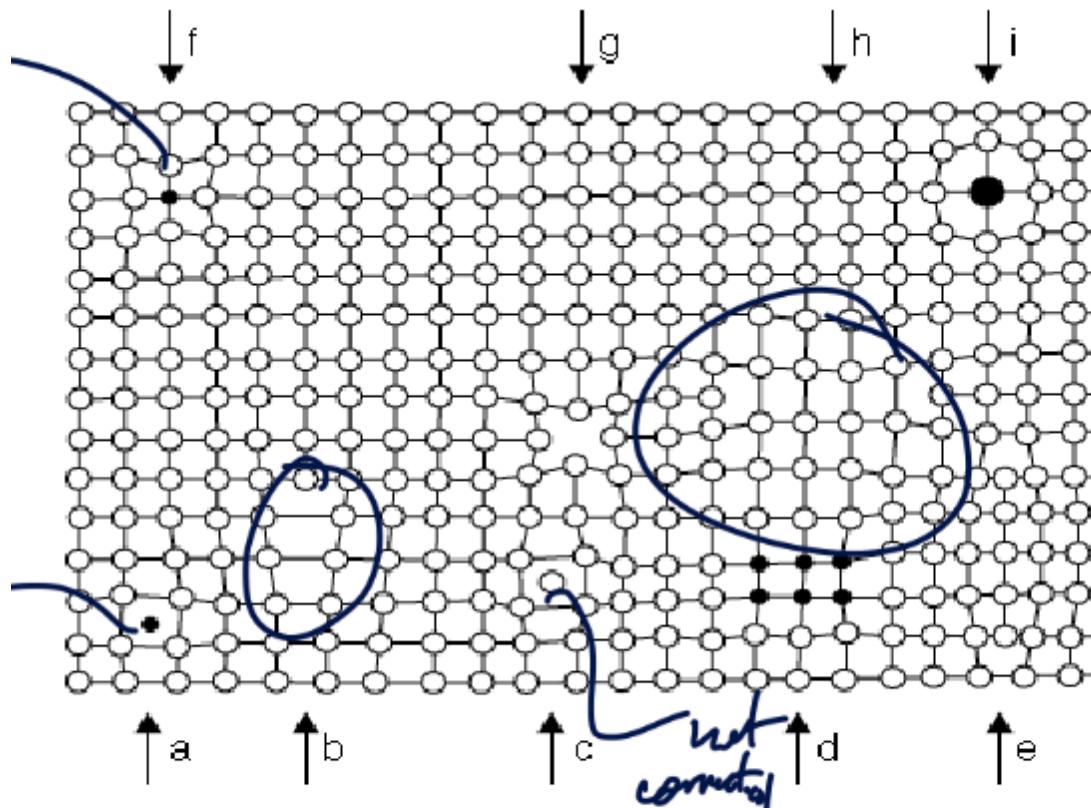


Figure 4.10 Schematic defects. (a) Foreign interstitial; (b) dislocation; (c) self-interstitial; (d) precipitate; (e) stacking fault (external); (f) foreign substitutional; (g) vacancy; (h) stacking fault (internal); (i) foreign substitutional. From Green, M.A. (1995), by permission of University of South Wales

Crystal Orientations r0.55

But nowadays, we are using notches and not really using fully doped wafer. We are doping locally the wafer. A notch indicates $a < 100 >$ n-type wafer.

We are processing the wafers in batches of 12 or 24 and they sit on a glass tray (quartz boat) so the support doesn't melt. We will oxidize the wafer to dope it which will tint the wafer. The color of the tint can be used to see what type of doping it is and how doped it is using some optics properties.

All those issues will lead to non-functional dies. We usually put some dye on those to clearly and visually indicate if they are good or not. We can't use the dies that are too close to the edge (*edge exclusion* 6 mm for 100-mm diameter wafers).

For this reason, we are wanting to use smaller chips to increase the yield. There exists an ideal size that is related to the yield and packaging cost. Now we have an optimum around 13cm^2 .

Packaging To do some packaging we need to dice the wafer, then use a pick and place arm and finally add some wire (wire bonding) from the chip and its pad to the housing of the chip.

Cleanroom

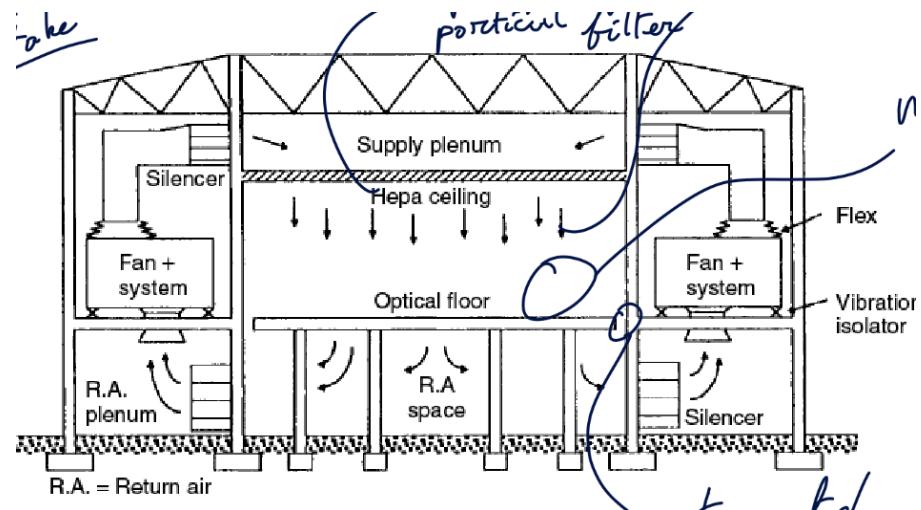


Figure 5: Cleanroom

The purified air comes from the ceiling where it needs to go through some *HEPA* (High efficiency particulate air) filter in the ceiling. We will usually only put one under the arrival of the air and over the crucial equipment to reduce cost.

We have various class where each number indicates the amount of particles $> 0.5\mu\text{m}$ in a cubic foot of air :

- Class 10000 : PCB, electronic packaging, medical devices
- Class 1000 : MEMS, electronic packaging, hard disk drives
- Class 100 : MEMS, RF/Photonic ICs
- Class 10 : ICs

We also use the ISO standard :

Table 1: Comparison of ISO and FS209 standard

Class	FS209	0.1 μm	0.2 μm	0.3 μm	0.5 μm	1 μm	5 μm
ISO1		10	2				
ISO2		100	24	10	4		
ISO3	1	1,000	237	102	35	8	
ISO4	10	10,000	2,370	1,020	352	83	
ISO5	100	100,000	23,700	10,200	3,520	832	29
ISO6	1,000	1,000,000	237,000	102,000	35,200	8,320	293
ISO7	10,000				352,000	83,200	2,930
ISO8	100,000				3,520,000	832,000	29,300
ISO9					35,200,000	8,320,000	293,000

The cost in chips is due to the lithography where one chip can go through 10 cycles and the more cycle we have the more expensive it is.

Lithography, photoresists, exposure, development

When we do the lift-off we can either use *positive* photo-resist or *negative* photo-resist. In positive, it is like usual, the photo-mask is used to protect area that shouldn't be etched away. But some compounds are not easy to etch. So sometimes, it is better to use negative process to first deposit the photo-resist and then do the blanket deposition of the compound. Then the lift-off is easy. We need some special trapeze shape that lays on the smaller side for this process.

Lithography: basic steps

The goal behind photolithography is to transfer a pattern into structure in a thin layers. By repeating this operation multiple time we can create some intricate and complex integrated circuits.

It mostly revolves around 3 major steps:

1. Resist coating: we deposit a light sensitive photoresist
2. Exposure: we expose some part of it through a structural mask
3. Development: we remove the photoresist

Photoresist can be used in many ways. When we etch away compounds we usually have some *undercut* which can be a structural problem.

Clean wafer

We first remove the particle with some rinsing in isopropanol, ultrasonic and megasonic baths. To remove the organic particle we can use some Piranha solution. To remove the metal traces that could diffuse into the wafer, we can do some classic RCA clean, this step is needed before high-temperature steps. RCA also removes ions that may be in the substrate.

RCA-clean

1. Removal of the organic contaminants (organic + particle clean)
2. Removal of thin oxide layer (oxide strip, optional)
3. Removal of ionic contamination (ionic clean)

IMEC clean The RCA-clean is quite an aggressive process and requires lot of chemical products. The IMEC clean is a bit more nature friendly and uses drying to force the particules to stay in the bath and not on the wafer.

Anti-reflective coating and adhesion promoter

We use some Hexamethyldisilazane that will remove OH groups from the surface making the wafer hydrophobic and thus photoresist-philic (since photoresists are apolar).

1. TARC: Top-side Anti Reflective Coating.

- Spin coated on top of photoresist
- Easier process
- Inferior performance

2. BARC: Bottom side Anti-Reflective Coating.

- Deposited below photoresist layer
- Better performance
- Longer processing (plasma-etched)

Coat with photoresist

We can have positive or negative photoresist where:

- Positive: exposed area gets softer and easier to etch
- Negative: exposed area gets harder and harder to etch

Spin coating is a process where we deposit some droplets and spin the wafer. Spinning it at a slow speed will spread the compound equally and then we finish it off by spinning faster. It is a pretty good and convenient way to coat a wafer's surface. But we can have some bumps around the side of the wafer (edge bead) and the way steps are coated is not always perfect.

Resist spinning We have some empirical equations for the thickness, and we spin with a force of around 5 NM.

$$T = \frac{K \cdot C^\beta \cdot \eta^\gamma}{\omega^\alpha}$$

Where K is the calibration constant, C polymer concentration in gram per 100 mL, η intrinsic viscosity, ω rotation per minute. The exponents are empirically determined.

We can also remove those edge bead in the process. But this doesn't solve the issue of uneven coating around steps of the wafer.

Spray coating We have two nozzles where one will be used as the developer and the other one is to rinse the wafer. It provides a smoother step coverage and is widely used in MEMS devices.

Other methods We can also think about dip coating, laminating dry films of photoresist, ...

Soft Bake

It is used to remove the solvents in the resist. It is non-sticky, improves resolution, improves the strength of resist. But we shouldn't bake too high too long or we would cause the embrittlement and make the removal harder.

Exposure

There exists 5 exposure methods:

Lithography We expose the resist to UV light through a mask. We have to align the mask precisely, it can be done manually for older technology. The smaller we go the more expensive a mask is and we have more and more layers.

Limits The main issue is the diffraction effects. Indeed, we have effects where we could have some destructive or constructive waves that can be unforeseen. That's why some mask can have special patterns that will result in the desired effect.

Those special patterns are Phase Shifting Mask where we will have some special pattern to change the phase.

The process of making the wafer reflective can sometimes lead to create some standing waves. Those standing waves can lead to uneven development and rippled sidewalls. A solution for this is to use arc or post exposure bake. This can also lead to linewidth variations due to reflection.

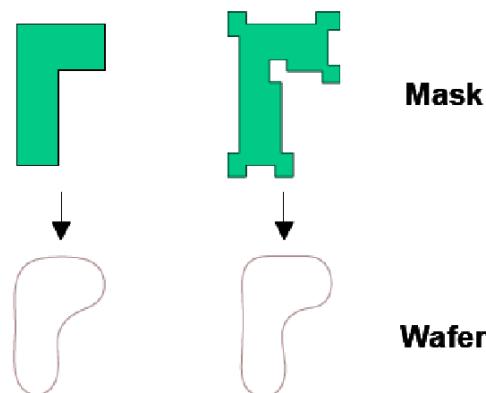


Figure 6: Optical Proximity Correction

Different printing techniques

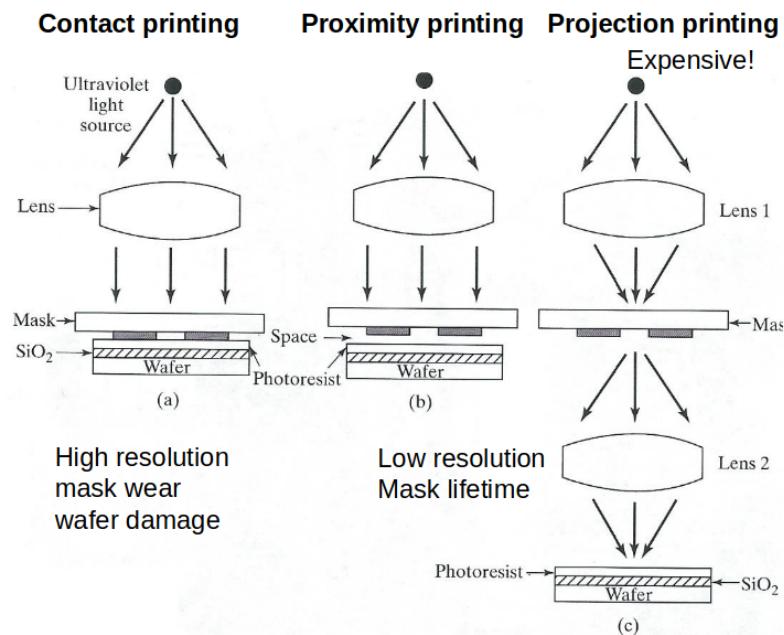


Figure 7: Printing techniques

Usually we use stepper to print successively a pattern on the wafer.

Projection printing We concentrate and project on the wafer, There is a few key metrics such as:

- Numerical Aperture: $NA = n \sin(\theta)$
- Critical Dimension: $CD = k l \frac{\lambda}{NA}$
- Depth of Focus: $DOF = k_2 < 1$

The depth of focus is an indicator to know when it is no longer good for focus.

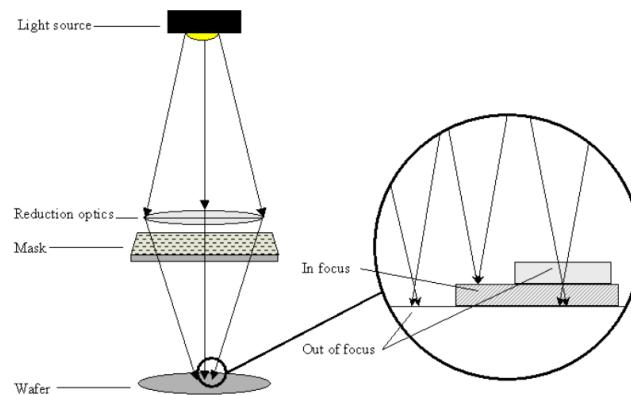


Figure 8: DOF effects

Light source

Another important parameter we can play is the light source. Back then, we used mercury bulbs for most lithographic work. It was a good enough and pretty cheap UV source. But it would produce various line of UV. So we had to use some filter to get only a specific wavelength.

Table 2: Wavelengths of light sources used in photolithography

Source	Wavelength (nm)	Name
Hg arc lamp	436 (blue)	g-line
	405 (violet)	h-line
	365 (UV)	i-line
	248	DUV
KrF excimer laser	248	DUV
ArF excimer laser	193	DUV
F ₂ excimer laser	157	DUV (vacuum UV)
plasma	13	EUV (long x-ray)

The main attract to use lower wavelength light source is to be able to draw better and smaller features. A good way to circumvent this rat race is to use multiple mask to produce one result. So we can use multiple ask with more spaced out features which simplifies and relax constraints of the problem.

1. Double patterning: Litho-Etch-Litho-Etch (LELE)

- First technique introduced, reduces k_1
- More costly as it doubles the amount of mask, need a hard mask, possible overlay issues

2. Double patterning: Self-Aligned Double Patterning (SADP)

- Solution to the overlay issue of LELE's masks self aligning
- Single lithography step, need to use an additional block or cut mask to remove unwanted material
- Complicated to design masks, process intensive

3. Double patterning: Litho-Freeze-Litho-Etch (LFLE)

- Less complicated process than LELE, increased throughput, no need for hard mask.
- Dependent on development of freezing process, freezing cam cause issues in the lines.

4. Double patterning: self-aligned quadruple patterning (SAQP)

EUV

This is the hot new trend in the industry (ASML has the technology but maybe huawei who knows). There has been prototypes since 2017 that can do 13.5 nm and NA 0.33. It doesn't have lenses but only mirrors as we can't focus EUV light like this.

Issues We need to use some Bragg reflector that have an alternating thickness of 2 nm of Mo and Si. It can only reflects 70% per mirror, so we need a quite intense light source or we won't have anything coming to the wafer.

Photo vs E-beam lithography With E-beam lithography, we can be really accurate and not use any mask, it comes at the disadvantage to slower processes. So we use E-beam to create the mask for photo-lithography.

An issue is the scattering of the electron inside the wafer, it can also go further than expected and in a random pattern.

Post exposure bake

It can help with wrinkles in the side wall. Baking can smooth things out and is quite standard for positive resist. Can also enhance crosslinking in negative resist.

Develop - wet process

Development is a wet chemical process as the wafer is immersed in developer and rinsed and dried afterwards. We can also spray the developer on the wafer as it spins but can be used and then dried. We can use the spraying nozzle techniques.

Hard bake

Sometimes used to improve etch resistance of resist. But it can causes the softer resists to reflow.

Etching, metal deposition, ion implantation, ...

See next chapters

Remove photoresist

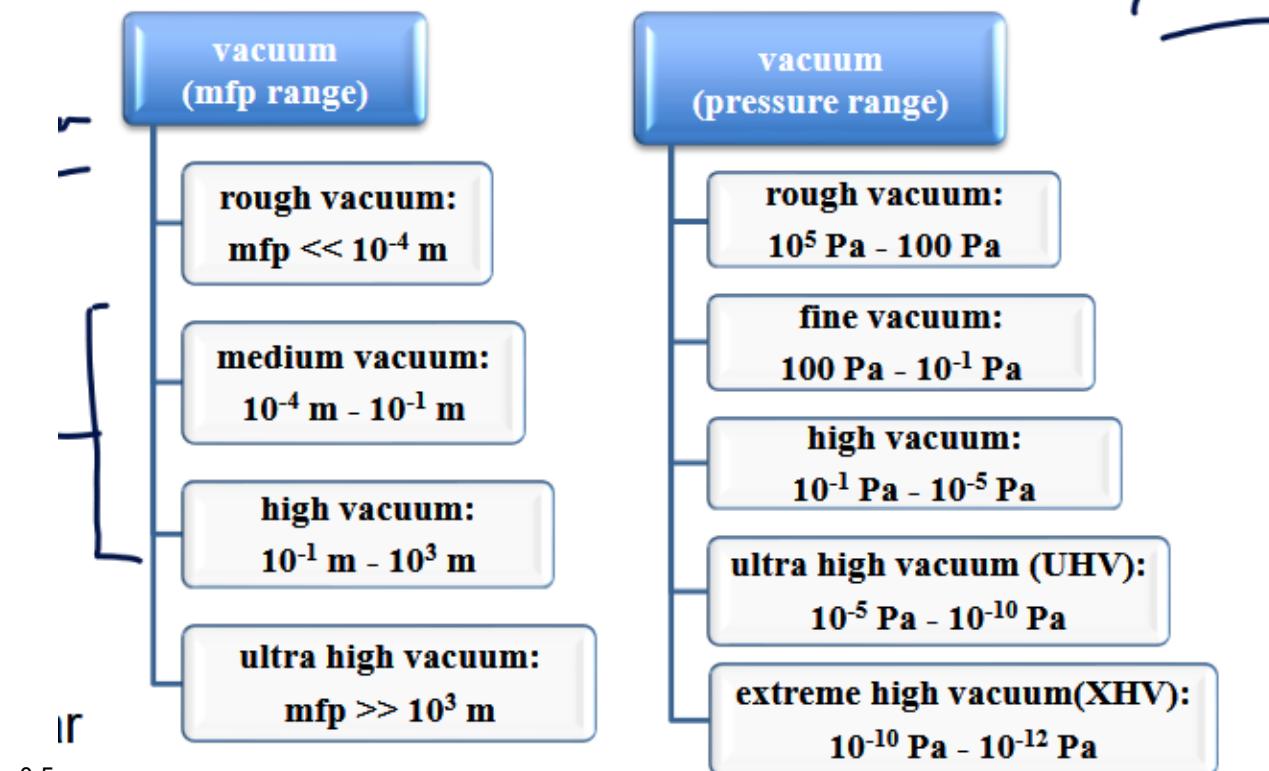
To remove the photoresist, we can either go for wet etching with some specialized solutions or acetone, NaOH, ...

We can also opt for O₂ plasma etching.

Deposition: [pvd]{acronym-label="pvd" acronym-form="singular+short": [cvd]{acronym-label="cvd" acronym-form="singular+short": Epitaxial growth, ald}

To deposit a thin film layer we can use some pvd with evaporation or sputtering. Another method is cvd that uses thermal, low pressure and plasma enhanced (electrons stripped away from atoms).

With evaporation (heat + vacuum) we can reach a growth rate of 0.1 – 1 nm/s. With sputtering (vacuum + plasma) we have a rate of 1 – 10 nm/s.

pvd**Vacuum**

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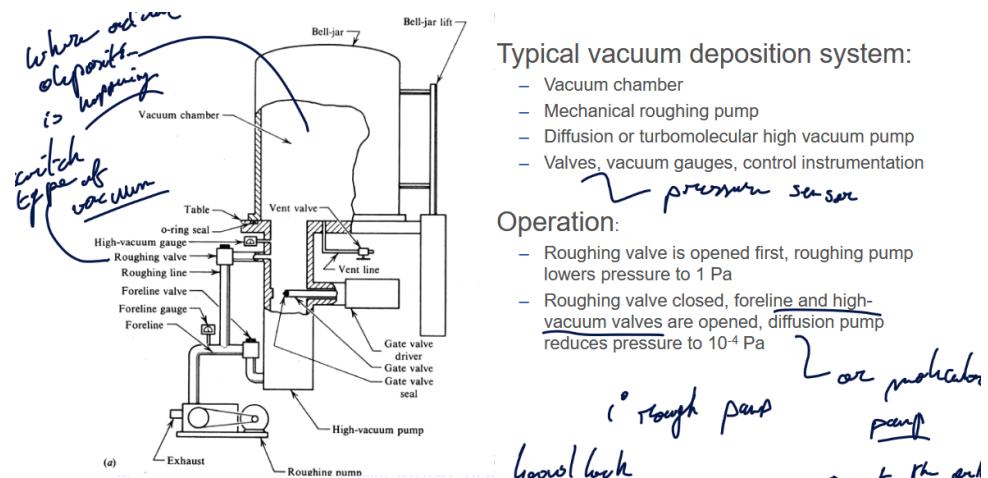
To realize deposition we need certain grade of vacuum. They are graded based on their mfp. It indicates how far can a molecule travel before hitting another one. There is an equivalency between mfp and the pressure in the environment.

The roughing pumps are simple a valve that rotates and will take out the air. But it is not the purest form of vacuum.

High vacuum diffusion pump use some oil. The oil is heated up and will vaporize, then when it gets cooled down it will take with them molecules. The pressure at the bottom is higher and so we can simply use a pump to take those extra molecules the oil vapor captured.

In a turbomolecular pump we are using some stator and rotor blades that are inclined in such way that when a molecules strike the turbine blade it will bounce and slowly travel to the bottom of the pump.

There is also cryogenic pump that is a mix of previously introduced vacuum pumps.



Operation:

- Roughing valve is opened first, roughing pump lowers pressure to 1 Pa
- Roughing valve closed, foreline and high-vacuum valves are opened, diffusion pump reduces pressure to 10^{-4} Pa

Figure 9: Typical system for pvd

Pirani Gauge ($> 10^{-3}$ mbar) It is based on a *weathstone bridge*. We will use a platinum wire that is pretty linear and will get heat up, the way this heat transfer occur depends on the pressure and is lower at lower pressure. So there is a direct link with pressure, heat and finally resistor which is easy to measure with such bridge.

Ion gauge ($< 10^{-2}$ mbar) The filaments will create a *space-charge* of free electrons. The electrons are attached by the positive grid and the collisions with the gas atoms will create ion which can be measured.

Evaporation

Now, we want to actually vaporize and create thin film on our wafer to grow all sorts of oxide, metals, polysilicon, ... There is two ways to do it :

1. Resistance heating evaporation :

- We have the crucible (holder of the compound) and the target (wafer) that gets heated
- Only low melting temperature point metals (or it gets too hard)

2. Electron beam evaporation :

- We use some electron beam to strike the material that will get *sublimate* (not a melting)
- We cool the crucible down and it doesn't need to be as pure as with heated method
- Good for high melting point metals



Figure 10: Evaporation techniques

Coverage issues Due to the radiating pattern from the crucible to the target, we will have discontinuity on the wafer which is not acceptable for traces or oxide. So we will gently spin the target to slightly change the momentum and so atoms will strike the sidewall. We also heat up the substrate to further help the step coverage.

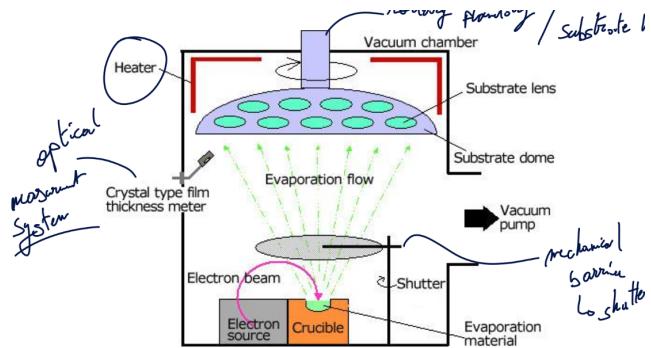
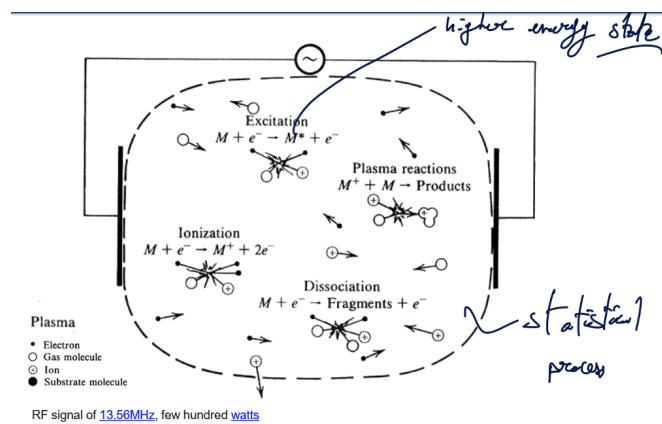


Figure 11: Configuration for pvd

Plasma

Plasma is a low pressure gas where a high energy field is used for ionization creating a large number of ions and free electrons. So we rip electrons off the nuclei and this happens in a vacuum. Plasma contains an equal concentrations of ions and electrons. Electric potential is approximately constant inside the plasma. We are using weak plasma so mostly neutral atoms/molecules.

**Figure 12:** Plasma using sputtering

So the ions of the plasma will strike the target releasing them and letting them go onto the wafer. We talk about a **sputtering yield** which indicates $S = \# \text{ of ejected target atoms/incoming ions}$ and it is usually $0.1 < S < 30$.

For example we can use a plasma of N_2 and a Ti target that will create a thin film layer of the substrate of TiN .

Using sputtering can be quite beneficial especially for multi-components thin-films. It is also better for lateral thickness uniformity. We have a superposition of multiple point sources.

cvd

The idea here is to use some chemical reaction to go from a gas phase to a solid phase. Typically we will use a sort of boundary layer which will trigger a reaction and deposit on the wafer. We need to remember that *natural* chemical reaction are trigger when we mix different molecules that will reach a higher state of energy and will tend to a lower state of energy. If we want to reverse this reaction we need to give the same amount of lost energy.

Table 3: Deposition methods, source gases, temperature, and stability.

Material/method	Source gases	Temperature	Stability
Ito	$SiH_4 + O_2$	$425^\circ C$	Densifies
hto	$SiCl_2H_2 + N_2O$	$900^\circ C$	Loses Cl
teos	teos + O_2	$700^\circ C$	Stable
pecvd OX	$SiH_4 + N_2O$	$300^\circ C$	Loses H
lpcvd poly	SiH_4	$620^\circ C$	Grain growth
lpcvd a-Si	SiH_4	$570^\circ C$	Crystallizes
lpcvd Si_3N_4	$SiH_2Cl_2 + NH_3$	$800^\circ C$	Stable
pecvd SiN_x	$SiH_4 + NH_3$	$300^\circ C$	Loses H
CVD-W	$WF_6 + SiH_4$	$400^\circ C$	Grain growth

There are many chemical reactions shown in the course so check out page 40-45. When we grow an oxide or anything, we can either be **mass transport limited** (velocity of the molecules saturate) or **surface reaction limited** (the surface isn't heated enough and the reaction isn't going well).

Reactor

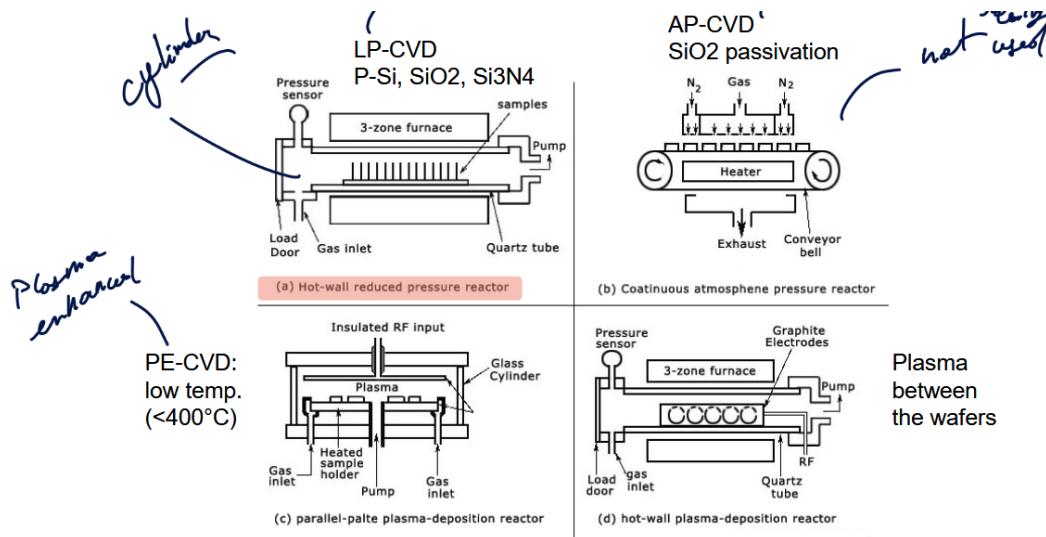


Figure 13: CVD Reactors

1. APCVD - Atmospheric Pressure It is pretty simple, we put the wafer on a conveyor belt that heats up the wafer. We use some ozone and teos gas.

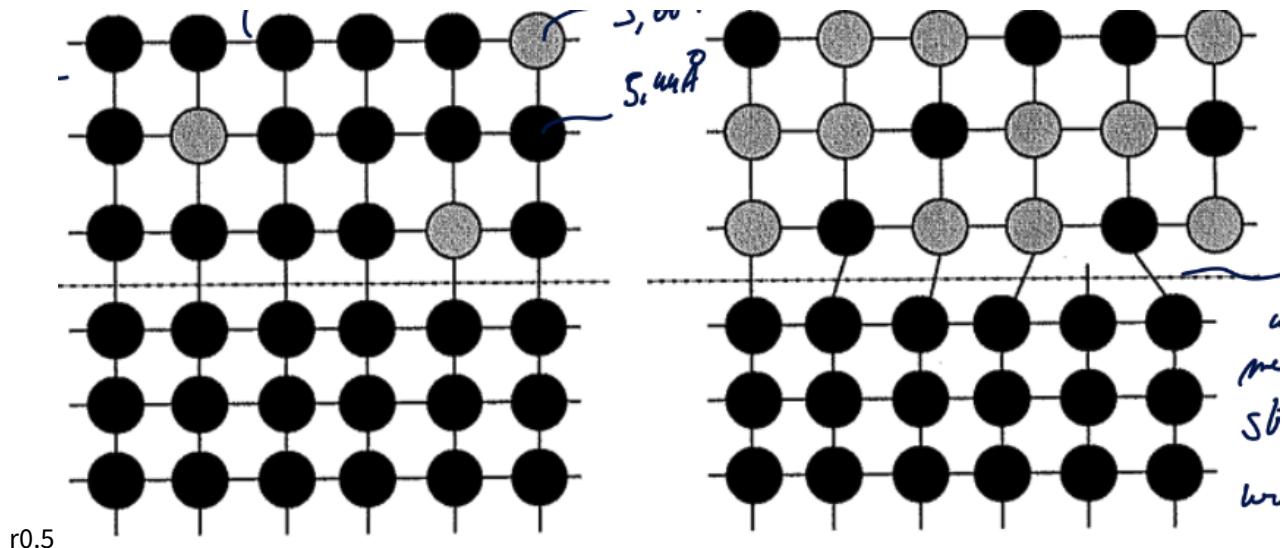
2. Lpcvd - Low Pressure We can stack the wafer vertically so keep them in the boat as we insert them in the furnace. It needs a pressure of 0.1 – 2 Torr and it needs high temperature and has a slow growth rate. It is ideal for batch processing.

3. pecvd - Plasma Enhanced We induce plasma in the gas by using some RF. We need some inert and process gas and the wafer needs to spin and be heated. This results in better step coverage and needs relatively lower temperature while having a high deposition rate.

PECVD diagram

At higher temperature the deposition pattern will create bigger "blobs" compared to lower temperature deposition.

Epitaxial growth



We can grow some layer with the epitaxial technique. We can have :

- Homo-epitaxy : independent doping on a high-conductive substrate
- Hetero-epitaxy : the difference in a size could create some mechanical stress

Some more advanced and recent epitaxy technique have been developed such as mbe. With this new method we can deposit some complex stack of material on our wafer. It is still in development and so there is not yet a wide industry adoption of industrial workstation.

ald

With this method we can literally deposit **1 layer of molecules** at a time ! We use some cycle consisting of a sequential precursor gas pulses. It will produce a monolayer of gas on the substrate. Then a second precursor gas is introduced which reacts with the monolayer and will result into another monolayer on top.

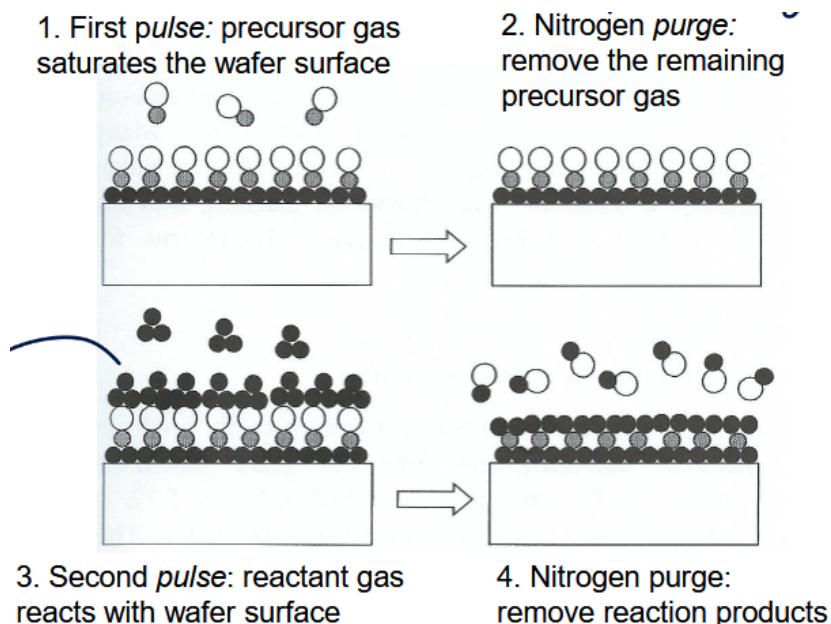


Figure 14: ald process of pulsed mode

ald is a *self-limiting* process so only one layer will be deposited at a time. It is similar to cvd but we have 2 major steps to diffuse the precursor gas not at the same time. We usually use Nitrogen or Argon as a *purge gas* which will "clean" unwanted atoms. This 2 cycles will help to avoid some *parasitic* deposition like in cvd.

It is also pretty good at making *trenches* which is usually a FoM. We usually compare width opening/depth. This value ranges from 20 to 100.

Deposition from the liquid phase

Electroplating or galvanic deposition Thick conductor layers, high aspect ratio metallization. For this method, we will use an anode and a cathode. We will use the reduction of *Cu,Ni* or *Au* typically onto the wafer (used as a cathode). We have a pretty fast growth rate of $0.1 - 10\mu\text{m}/\text{min}$.

It is a good solution to create *through-silicon vias* and do some IC interconnects which is gaining more and more popularity lately.

Electroless deposition Selective metallization. We can have a growth rate of $100\text{nm}/\text{min}$. For interconnect between IC we can use the *damascene technique* :

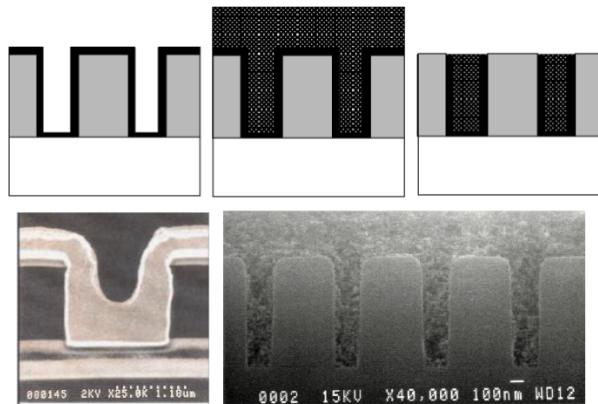


Figure 15: Damascene technique

Spin coating Photoresists, thick polymer layers, spin-on glasses. Usually we start at a slower speed to have the right amount of photoresist everywhere on the glass then we finally spin it around 5000rpm which will cause *partial drying via evaporation*.

Sol-gel Porous dielectrics, thick and complex materials.

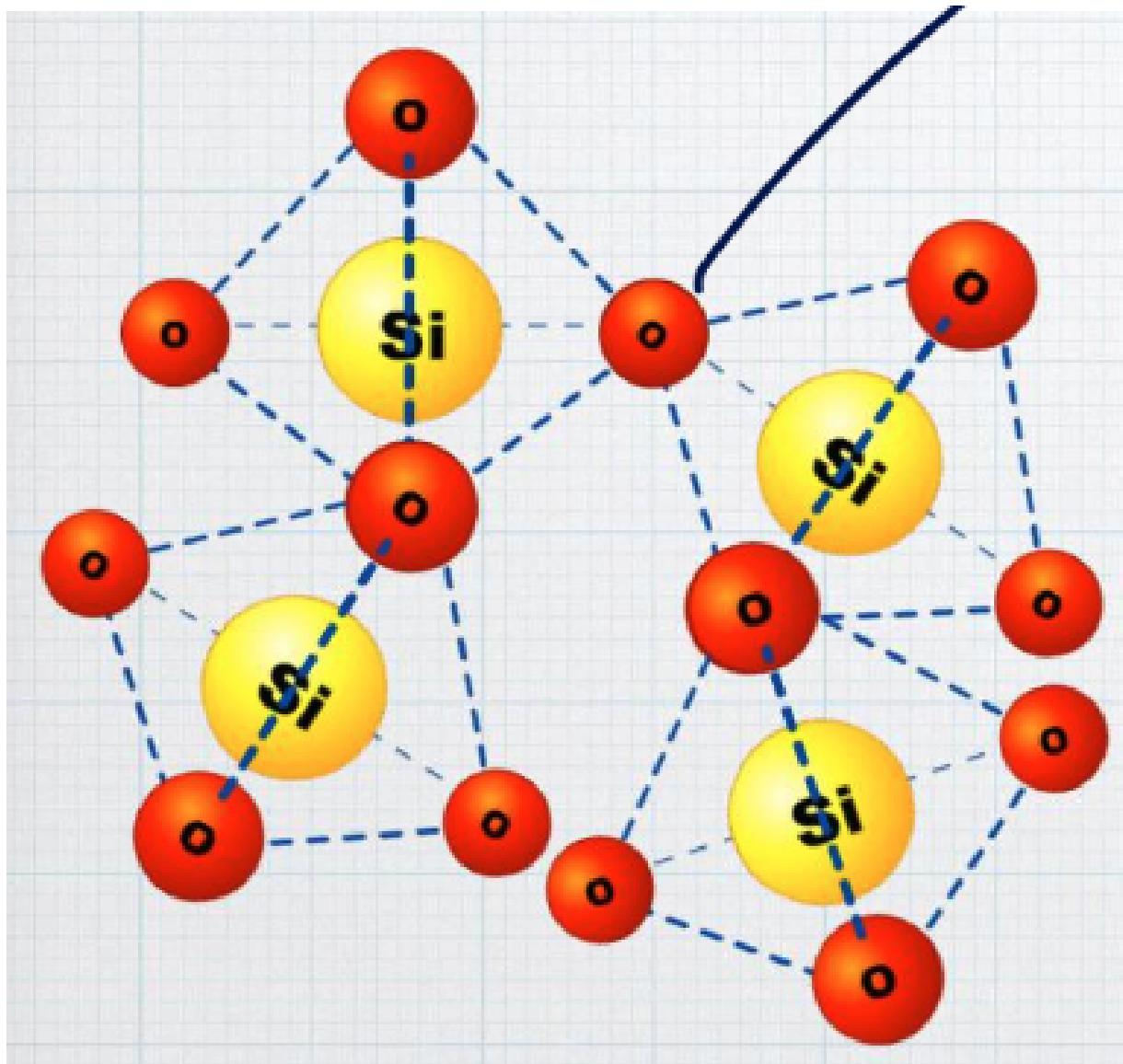
Measuring the thickness

To measure the thickness of the layer we can :

- Mechanical method : we use a needle that will check the thickness. It is not the most precise method.
- Optical method :

- Reflectometry : we need the layer to not be totally opaque and we will measure the various wave that comes out of the wafer. We need to use small die and we can measure from 10nm to $50\mu\text{m}$.
- Elipsometry : it works with the polarization of light and can measure up to $100\mu\text{m}$.

Oxidation, wet, dry



Sand is an abundant material that contains SiO_2 or Silicon dioxide. It is the main component of glass, optical fibers and we can find a crystalline structure of SiO_2 in quartz.

It has a *tetrahedral arrangement* with one silicon bonded to four oxygen atoms. We can see how most of oxygen atoms will be bonded with Si atoms making the terahedra shape joined at corner. We call those atoms the *bridging atoms*. Not all oxygen atoms will be bonded to two Si , we call them the *non-bridging atoms*. The density of those non-bridging atoms determine the quality of the oxide.

They are not always aligned in such regular manner, it can be random making some *amorphous structure*. If there is no non-bridging atoms, then

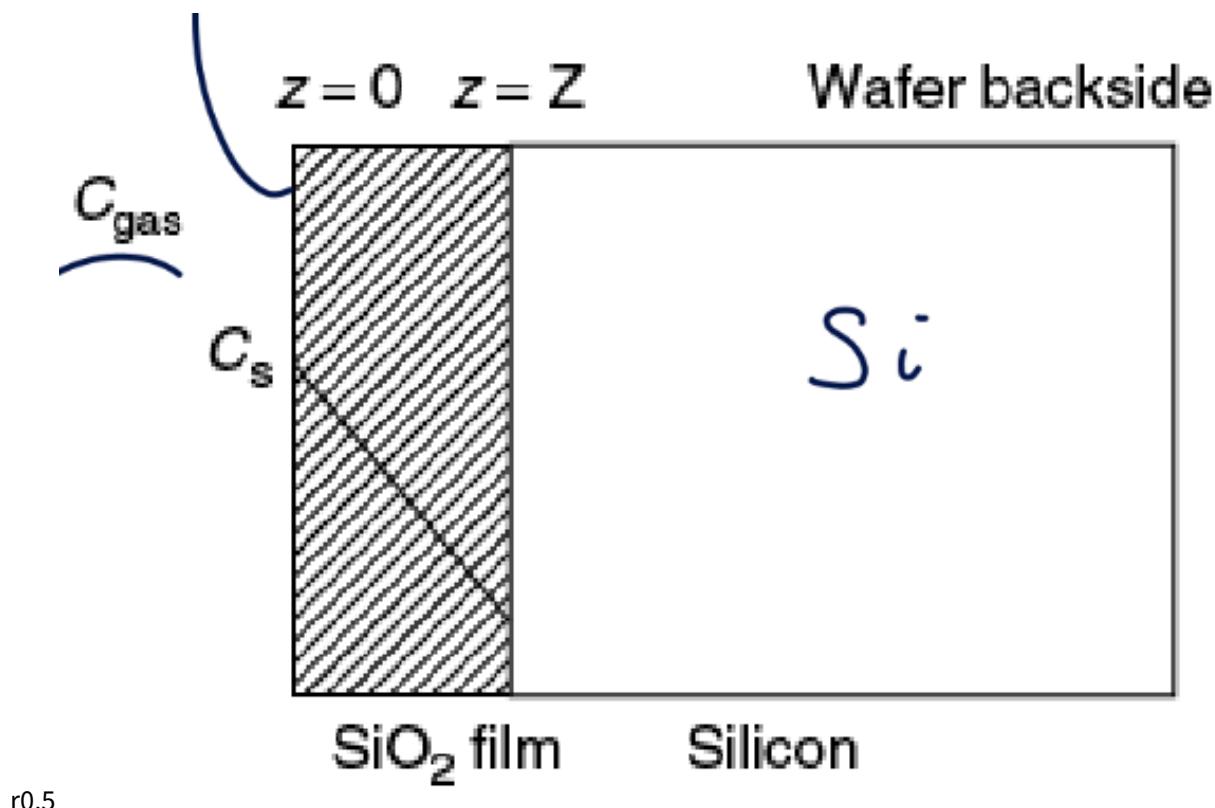
In microelectronic, we use thin layers of pure SiO_2 and they are amorphous. The density is about 2 –

2.3 gm/cm^3 , $\epsilon_r = 3.9$ (frequency dependent), $n = 1.5$ optical index. The breakdown voltage is $> 10^7 \text{ V/cm}$ which is the main reason why we need to lower V_{DD} as the thickness of the gate is getting smaller.

But we will always have some traps at the interface which causes some negative charges. The density of those defects is 10^{11} cm^{-2} , we can even lower this value using some annealing process using hydrogen. If we had more defects, this would result in a constant channel making the material no longer semi-conducting.

We love silicon due to its abundance, good electrical property, excellent insulating of its oxide, low defect at the interface.

Thermal oxidation



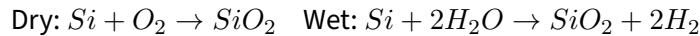
Silicon will naturally form an oxide and will grow a thin layer of it. This process is only for *Si* and not present in other type of semi-conductor such a *GaAs*, *Ge*, ... This oxide can be used as :

- Implant, diffusion mask
- Surface passivation
- Isolation between transistors
- Key component of MOS structures
- Dielectric for multilevel interconnect
- Cleaning

As shown on the figure, the concentration of oxygen will reduce the further we go towards the right which explains the slowing down of the process. This will create a **consumption** effect where the oxide will grow upwards and backwards. 1 mole of *SiO₂* is taking up more volume than 1 mole of *Si*. If we grow d thickness of oxide, we will have $0.46d$ of Si consumed.

- $Si : 2 \cdot 10^{-23} cm^3$
- $SiO_2 : 4.4 \cdot 10^{-23} cm^3$ so about 2.2 times bigger than Si . Expansion will go both ways.

Wet and dry



In **dry and wet** oxide growth, a higher temperature will lead to thicker oxide growth. This growth will decrease as times grows since the concentration of oxygen diminish. The growth rate is faster in *wet oxide* but it has lower quality which makes it easier to etch.

Since temperature plays a major role, we will have **oxidation furnace** where our wafers loaded on quartz boat will slowly roll into the furnace which has multiple temperature zone for better control.

- Dry: slower growth rate, better quality, better breakdown voltage ($5 - 10 MV/cm$) better suited for gate using ald.
- Wet: faster growth rate, lower quality, good for masking and interconnect dielectric.

For a growth of $0.5 \mu m$ of oxide at $1200C^\circ$ it takes around 6 hours for dry and around 1 hour for wet oxidation.

locos

It is a process used for *isolation between transistor*. We can simply use *patterned oxide* as the steps (the transistor) are too high and we can't do spin coating or metallisation. Reduction of topography by about 56%.

To do some masking of oxide we can use Si_3N_4 which grows slower than Si . But this technique will introduce some stress due to the thermal expansion of nitrite being much higher than of Si . We will add between the substrate and the nitrite a small oxide called *pad-oxide* (SiO_2) as a stress release layer.

1. We first add the pad-oxide of $20 - 30 nm$ and then finally the Si_3N_4 of around $100 - 200 nm$.
2. Wet oxidation to grow the oxide, mechanical stress will cause a *bird's beak* to form.
3. Remove the nitride with HF-dip to remove the *oxynitrate* and then H_3PO_3 (phosphorous acid) to etch nitrite.
4. Etching of pad-oxide with HF

sti and dti

sti With this method we can avoid the *bird's beak* phenomena. We can do from about $0.25 \mu m$ nodes without much stress. The process flow is as follow :

1. Anisotropic etching of Si
2. Thermal oxidation
3. Oxidation growth with cvd (using teos process)
4. cmp of oxide

sti vs. locos

- sti: The drawn width is almost the effective width. Can place transistor closer increasing the *packing density*. We have a larger drive current for devices with same drawn width. Less topography.
- locos: The drawn width is bigger than the effective width due to *bird's beak*. To have the same drive current, we need wider transistor which diminish the packing density. Hard to do this process for sub $0.5\mu m$.

Doping

There are two main processes for doping, either Thermal diffusion or Ion implantation. The later one is more modern and we usually go for a mix of those techniques.

Doping relies on the idea to put some foreign atoms in the lattice, either group V to negatively charge it (with an extra electron that is free to roam) or with a group III atoms that will create a hole. It will *locally* create a charge difference. Watch out, we can have some *hole recombination* and so have useless mix of group V and III that will just cancel each other.

For doping we can have:

1. Diffusion, using some *diffusion/doping mask*:
 - Gas that will bombard the wafer, not straight path so can have border effect
 - Coating will use a thin film and will also have border effect
2. Ion implantation, also uses a *diffusion/doping mask* but will be quite different.

Diffusion

It is a common mechanic phenomena where we will have a material that will search for stability and diffuse to reach a stable state.

Thermal diffusion This process happens at high temperature 1000° and when the wafer gets exposed to dopant material vapor. The *upper limit* is related to the **solid solubility**. The lower limit is of 10^{13} .

One of the advantages of using silicon, is the fact that the doping level will impact the resistance per square making it an easy material to modulate the resistance of.

Diffusion Theory We have a diffusion *flux* of *impurities* in one dimension. (We are always using x as the vertical direction of diffusion).

$$F = -D \frac{\partial C(x, t)}{\partial x} \quad D = D_0 \exp\left(\frac{-E_\alpha}{kT}\right)$$

We have D that is the *diffusion coefficient* in cm^2/s . C is the dopant concentration per unit volume. We have D_0 that is the diffusion coefficient in cm^2/s at infinite temperature and E_α is the activation energy in eV.

At low concentrations of dopant in silicon ($10^{12} - 10^{16} \text{ cm}^3$) can be seen as constant. With this simplification, we can easily solve the equation, we also see that gold, copper, ... have high diffusion coefficient which is why we tend to avoid such metal in the clean room.

If we do not have a source or sink of the impurity, we know that the *change in impurity concentration with time must equal the local decrease of diffusion flux*:

$$\frac{\partial C}{\partial t} = -\frac{\partial F}{\partial x} = \frac{\partial}{\partial x} \left(D \frac{\partial C(x, t)}{\partial x} \right) \quad \frac{\partial C}{\partial t} = D \frac{\partial^2 C(x, t)}{\partial x^2} \text{ if } D \text{ cst}$$

There are 2 methods of diffusion:

1. Constant-surface-concentration: using vapor, we have a constant concentration of dopants at the surface.
2. Constant-total-dopant: thin layer, we have constant amount of impurity at the surface.

Constant-surface-concentration

$$\text{Init: } C(x, 0) = 0 \quad C(0, t) = C_s \quad C(\infty, t) = 0$$

$$C(x, t) = C_s \operatorname{erfc} \left(\frac{x}{2\sqrt{Dt}} \right) \quad \operatorname{erfc}(z) = 1 - \operatorname{erf}(z) \quad \operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2} dy$$

We have \sqrt{Dt} that is called the *diffusion length* in *cm*. The total number of dopant atoms per unit area that has diffused into the semiconductor is given by:

$$Q(t) = \int_0^\infty C(x, t) dx = \frac{2}{\sqrt{\pi}} C_s \sqrt{Dt} \approx 1.13 C_s \sqrt{Dt}$$

Constant-total-dopant

$$C(x, 0) = 0 \quad \int_0^\infty C(x, t) dx = \phi \quad C(\infty, t) = 0$$

$$C(x, t) = \frac{\phi}{\sqrt{\pi Dt}} \exp \left(-\frac{x^2}{4Dt} \right)$$

Where ϕ is the *total amount of dopant* per unit area. So the surface concentration ($x = 0$) is $\phi / \sqrt{\pi Dt}$.

We usually use those two methods and we call this a *two step diffusion process*. a pre-deposition diffused layer is first formed using constant-surface-concentration condition. Then a drive-in (or redistribution) diffusion is used using constant-total-dopant condition.

For most practical cases the diffusion length for the pre-deposition stage is much smaller than the diffusion length of the drive-in diffusion. This allows to make deep junctions, e.g. for wells for CMOS.

Advanced Diffusion Theory We are oversimplifying the problem which will give us incorrect values when compared with reality. Moreover, the atoms vibrate and there is a non-zero chance that a silicon atom moves from its lattice site which will leave a vacancy.

Dopants diffuse in combination with silicon interstitial or vacancies and the diffusion coefficient is therefore strongly influenced by the concentration of interstitials or vacancies.

High Doping Concentration Diffusion Here, our simple theory doesn't hold anymore. The diffusion profile is different. Moreover, the diffusion of phosphorous at high concentration is *anomalous*. We often notice a *kink* on the doping profile. Then we have a deep tail region that extends further in the doping region.

The anomalous diffusion behavior has been explained by the dissociation of the phosphorus-vacancy pair ($P+V_2^-$) into P^+ , V^- and an electron. The singly charged acceptor vacancies (V^-) enhance the diffusivity in the tail region (by a factor of 100 at 1000°). So it is good for creating deep n-type junction. Arsenic is preferred over phosphorous.

Table 4: Doping levels, designations, concentrations, and resistivity.

Dopant level	Designation	Dopant concentration (cm^{-3})	Resistivity n/p (ohm-cm)
Very lightly doped	n^{--}, p^{--}	$<10^{14}$	$>100/>30$
Lightly doped	n^-, p^-	$10^{14}-10^{16}$	$1-100/0.3-30$
Moderately doped	n, p	$10^{16}-10^{18}$	$0.03-1/0.02-0.3$
Highly doped	n^+, p^+	$10^{18}-10^{19}$	$0.01-0.03/0.005-0.02$
Very highly doped	n^{++}, p^{++}	10^{19}	$0.001<0.01/0.005$

Here, we are always talking in Ω/cm resistance that relates to the sheet resistance.

For diffusion we can either have diffusion through substitutional or interstitial diffusion.

Using SiO_2 for masking The diffusion of B, P, As in SiO_2 is at least one order of magnitude lower than in Si . There exists some table that indicates the thickness of the oxide for the diffusion of a given material at a given temperature during a definite amount of time.

By mixing impurities, we can slowly diffuse some up to a deep depth and then diffuse another type. They will cancel each other out which will create some junction and deeper junction.

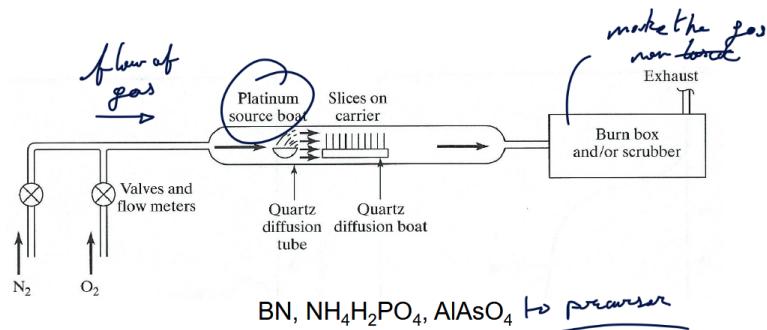


Figure 16: Solid Dopant Sources

The boat we are using has some Boron nitride wafers between 2 substrate wafers to diffuse it.

There is also a version that uses liquid dopant sources which is similar to the solid dopant one except the N_2 will be bubbling in the bubbler. We can also have the same with gas using some dopant gas. We have to add some scrubber system to trap all of the gases.

Ion implantation: deposition, drive-in and RTA

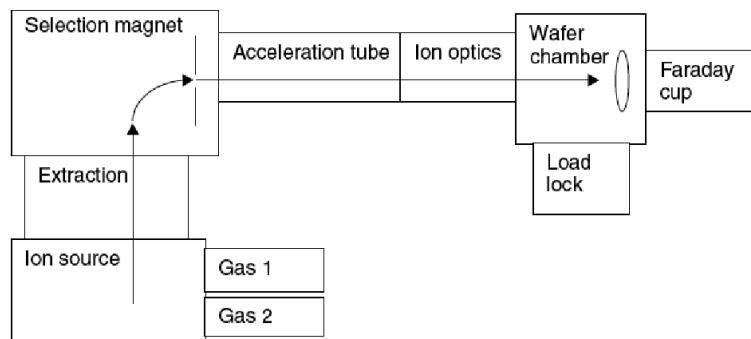


Figure 17: Basic elements of an ion-implanter

1. **Ion source:** it works at high voltage $25kV$ and creates a plasma with the desired impurity.
2. **Mass spectrometer:** it will selects which ion we want in this right angle bend.
3. **High voltage accelerator column:** to make it faster we accelerate it with a field of over $5MeV$.
4. **Scanning system:** to deposit the right amount, we also make it slightly bend so the neutral particles will go straight and not hit the wafer.
5. **Target chamber:** operated in vacuum conditions and is where the wafer is located in.

Something important to note is the fact that the ions will hit the wafer pretty straight but it will go through a random path in the wafer. This will lead to a Gaussian distribution of the particles around a certain depth.

$$N(x) = N_p \exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right) \quad N_p = \frac{\phi}{\sqrt{2\pi}\Delta R_p}$$

Ion implantation

So the main idea is "simply" accelerating ions pretty quickly so that they will penetrate inside the wafer up to a few tenths of microns. Of course, masking is used so we can create the desired pattern and not simply bombard the full wafer. We can either use some silicon dioxide or photoresist.

In [eq:ion]{reference-type="ref" reference="eq:ion":} ϕ is the *ion dose per unit area* and R_p is the distance to the peak from the surface and is called the *projected range*. ΔR_p is the *projected straggle* is the distance from the peak where the concentration is reduced by 40% and is usually empirical.

One major advantage and use case of ion implantation is to put some ions below a gate oxide for example. But we damage the lattice by bombarding like this and we require some **annealing** at 900° to repair the damage. If we go even hotter we can do some *drive-in* to diffuse even further the dopant into the silicon.

Masking

Now, how thick should a mask be so all the ions will be trapped inside the mask ? But it is important to note that since it is a Gaussian distribution we will always have a probability that the ions will go inside the substrate.

Something that is even more annoying is the fact that we will have some ions around a slit that will go under the mask.

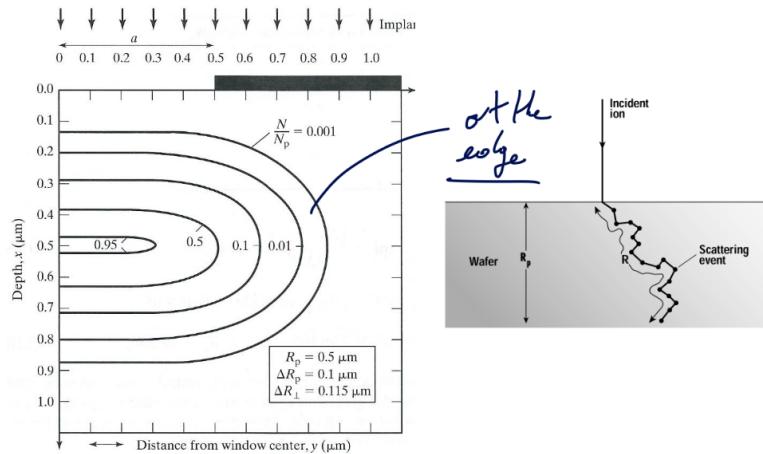


Figure 18: Ion Implantation

We have to realize some empirical experiments to see under which condition a given ions will dope or not the silicon or stop at the silicon dioxide.

Annealing

It is a crucial step after doing some ion implantation where we have to restore the lattice from any damages. But it also allows the dopants to take the correct spot inside the lattice.

As hinted previously, doing this sort of baking at high temperature will lead to some *drive-in* by diffusion and we will have more spread.

rta To avoid this diffusion to happen to fast, we can use some lighting bulb to produce a quick and rapid heating of the substrate.

Channeling

One thing that can happen if we have a perfect lattice is the fact that an ion may not bounce and will went through the lattice directly. So instead of having a nice Gaussian we will see some odd shapes and multiple peaks.

Solutions We can add a layer of oxide so it will force the ions to bounce around. Or we can tilt the wafer or even grow some *amorphous Poly-Si*.

Profile Verification

After applying a layer, we would like to measure the thickness of an oxide or other things:

- sims
- srp: destructive process since we bombard the surface and measure the amount of ions and neutral particules.

There is also electrical measurement where we use two probes and measure the resistivity by applying a current. This will leave some *damage craters* due to the probing. There is another version that uses 4 probes that measures the current and the voltage.

Etching, wet, dry, plasma, DRIE

In etching, we distinguish two types:

- Isotropic: the etching goes in every direction and etches pretty equally
 - Plasma, Wet (mostly), rie
- Anisotropic: the etching prefers one orientation of the lattice
 - Plasma, [rie]{acronym-label="rie" acronym-form="singular+short": Ion milling, [drie]{acronym-label="drie" acronym-form="singular+short": KOH wet}

Wet Etching

Isotropic

To keep a constant gradient locally, we have to replace all the time the solution that's why we overflow the bath by adding continuously new etchant and uses a stirrer.

Because of the way wet etching works, we will have **undercut area** that we also call *etch bias* and can be an issue for features that are too close to each other. Below $3\mu m$ we will prefer dry etching.

To stop precisely and quickly the reaction, we use a trap at the bottom of the bath to quickly dump the etchant and we spray the wafer with solution to stop quickly and precisely the process.

Table 5: Etchants for various materials

Material	Etchant
SiO_2	$\text{NH}_4\text{F} : \text{HF} (7 : 1)$ BHF, 35°C
SiO_2	$\text{NH}_4\text{F} : \text{CH}_3\text{COOH} : \text{C}_2\text{H}_6\text{O}_2 : \text{H}_2\text{O} (14 : 32 : 4 : 50)$
poly-Si	$\text{HF} : \text{HNO}_3 : \text{H}_2\text{O} (6 : 10 : 40)$
Al	$\text{H}_3\text{PO}_4 : \text{HNO}_3 : \text{H}_2\text{O} (80 : 4 : 16)$,

Material Etchant

	water can be changed to acetic acid
Mo	$H_3PO_4 : HNO_3 : H_2O$ (80 : 4 : 16)
W, TiW	$H_2O_2 : H_2O$ (1 : 1)
Cr	$Ce(NH_4)NO_3 : HNO_3 : H_2O$ (1 : 1 : 1)
Cu	$HNO_3 : H_2O$ (1 : 1)
Ni	$HNO_3 : CH_3COOH : H_2SO_4$ (5 : 5 : 2)
Ti	$HF : H_2O_2$
Au	$KI : I_2 : H_2O ; KCN : H_2O$

We can also use other etchant or use some HF that is often used for SiO_2 . But HF is pretty dangerous to handle as a spill on your skin doesn't burn or causes pain immediately, it will slowly penetrate the body until it attacks the bone.

Anisotropic

We also have some anisotropic wet etchant where we will have various effect depending on the lattice orientation (using the notation as seen previously):

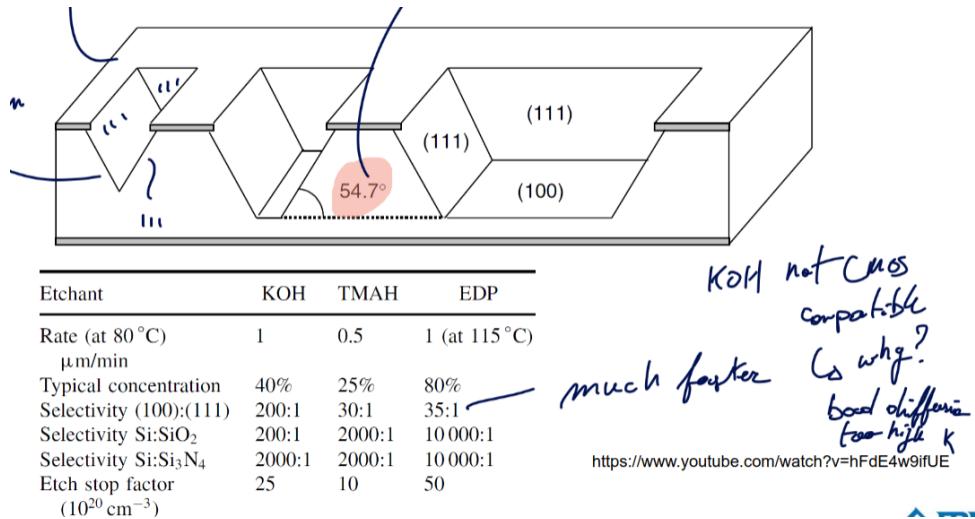


Figure 19: Anisotropic wet etching

Dry Etching

This process comes in many flavors but they are all a combination of some excitation energy and pressure where we either have high energy-low pressure or low energy-high pressure. We use mechanical and chemical as well to better control the process.

- Physical: we bombard the wafer with some *positive ions* and we strike the substrate with high kinetic energy.

- Chemical: we can either use neutral or ionized species to react with the surface to create some *volatile product*. This process is often *isotropic*.

Plasma Etching

Plasma is a *fully or partially* ionized gas containing an equal amount of positives and negatives charges but has different number of unionized molecules. We then need a strong enough electrical field to ionize the gas.

The goal of plasma etching is to produce some chemically reactive species from a relative inert gas. Then we make this gas react with the specific material we want to etch and the product should be pretty volatile to be easily removed. We need high speed and high chemical reactions between neutrals and the substrate materials. We use a *carrier* gas producing some ions and reactive neutrals. This reactive neutrals attack the sidewall and the normal surface. BUT, the positive ions will **only** attack the normal surface. So we will first go in the vertical direction.

We have around 10^{15} cm^{-3} and $10^8 - 10^{12} \text{ cm}^{-3}$. After hitting the surface, we may have the volatile particles to react against the wall of the chamber which is really problematic. But washing is not always the solution as it can disrupt the precise setting for the reaction to happen at an optimal point.

To have some idea about the type of gases we can use look at the various tables chapter 5 page 30-32.

Ion milling - drie

Ion milling is a sort of *sputter etching* where the wafer is coupled to a voltage source. It also uses some plasma gas but the added voltage to the wafer add some acceleration to the positive ions.

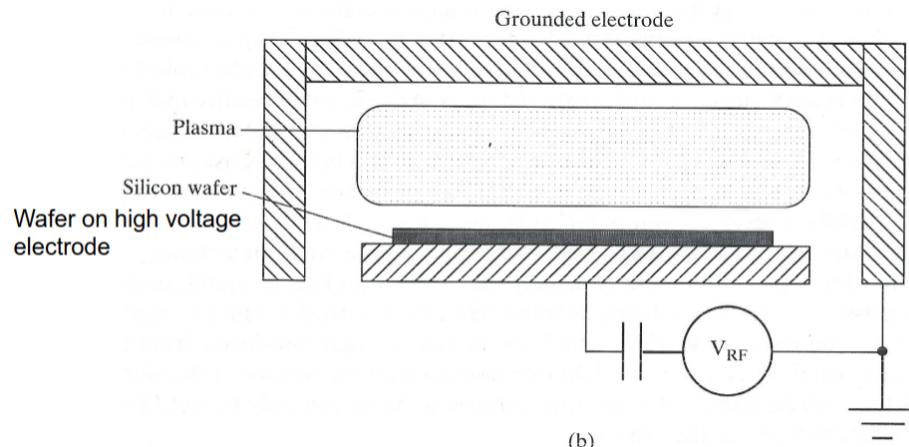


Figure 20: rie setup

rie

It is a combination of plasma etching and sputter etching/ion milling since we use some plasma and accelerate it towards the susbstrate. Again we use a chemical and mechanical process.

The setup is pretty similar as depicted in 5.2{reference-type="ref" reference="fig:rie-setup-label": we use the asymmetry between electrodes to create a self-bias to accelerate the ions towards the substrate. We can also add additional electrodes to create a DC electric field.

It is a combination of chemical and sputtering:

1. Chemical:

- Thermalized neutral radicals that will form volatile products.
- Isotropic
- little electrical damage

2. Sputtering:

- Ion energy will mechanically ejects substrate material
- Anisotropic
- Purely physical and pretty directional, low pressure so longgg mfp
- Low etch rate

	Plasma Etching		Reactive Etching		Physical Etching	
	Barrel Reactor	Planar Reactor	Ion	Ion Beam	Sputtering	Ion Beam Milling
Substrate Location	Surrounded by plasma	On grounded electrode in Plasma	On powered electrode in plasma	In beam, remote from plasma	On powered electrode in plasma	In beam, remote from plasma
Pressure (torr)	$10^{-1} \sim 1$	$10^{-1} \sim 1$	$10^{-2} \sim 10^{-1}$	$10^{-4} \sim 10^{-3}$	$10^{-5} \sim 10^{-3}$	10^{-4}
Ion energy(eV)	0	$1 \sim 100$	$100 \sim 1000$	$100 \sim 1000$	$100 \sim 1000$	$100 \sim 1000$
Active Species	Atoms, Radicals	Atoms, radicals, reactive ions	Radicals, reactive ions	Reactive ions	Ar^+ ions	Ar^+ ions
Products	Volatile	Volatile	Volatile	Volatile	Nonvolatile	Nonvolatile
Mechanism	Chemical	Chemical/Chemical-Physical	Chemical/Physical	Chemical/Physical	Physical	Physical
Etch Profile	Isotropic	Isotropic/Anisotropic	Isotropic/Anisotropic	Anisotropic	Anisotropic	Anisotropic
Selectivity	$30 : 1 - 10 : 1$	$10 : 1 - 5 : 1$	$30 : 1 - 5 : 1$	$10 : 1 - 3 : 1$	$1 : 1$	$1 : 1$
Resist Compatibility	Excellent	Excellent	Good	Good	Poor	Poor
Device Damage	Little	Little	Some possible	Some possible	Very possible	Very possible
Etch Rate (um/min)	$0.1 \sim 0.5$	$0.1 \sim 0.5$	$0.05 \sim 0.1$	$0.05 \sim 0.1$	$0.02 \sim 0.05$	$0.02 \sim 0.05$
Resolution (um/min)	3	2	$1 \sim 2$	$1 \sim 2$	$0.5 \sim 1$	$0.5 \sim 1$

Figure 21: rie etching possibilities

There is two categories of rie etching:

1. Ion-Induced rie: reaction controlled etching with typically Cl_2/Si

- When substrate is not spontaneously etched away
- Ions modify the surface reactions in one way or another. Make the radicals to react with the substrate.

2. Ion-Inhibitor rie: desorption-controlled etching with typically $\text{F}/\text{Si}, \text{Cl}_2/\text{Al}$.

- Substrate is etched spontaneously so we need an inhibiting layers to achieve directionality.
- The bottom of the trench is exposed to ion bombardment.

Fluorine-Based Plasma - Anisotropic Si etching Due to the isotropic nature of the chemical reaction, we have to use some inhibitor layer composed of Silicium, Fluor and oxygen. This is some ion-inhibitor process and the oxygen covers the silicon surface with silicon oxide. The issue is that the SF₅⁺ will etch the layer making it possible for the F* radicals to etch the silicon substrate.

Chlorine-Based Plasma - Thin-film Al Dry etching Aluminum is spontaneously etched by Cl₂ but there is a native aluminum oxide layer. We have to use some ion bombardment because it is essential for aluminum.

Chlorine-Based Plasma - Poly-Si Dry etching We use some ion-induced rie with gases like Cl₂, HBr, O₂.

Ion Milling Etching: thin film platinum etching We use some Ar gas and the platinum has been *physically* etched by argon plasma. We can witness some sort of fence because the platinum may redeposit on the sidewall creating some fences.

Inductively coupled Plasma rie Here we use some CCP to etch the silicon and other material slowly. ICP rie generates the plasma through a RF powered magnetic field which allows us to create some very high plasma density.

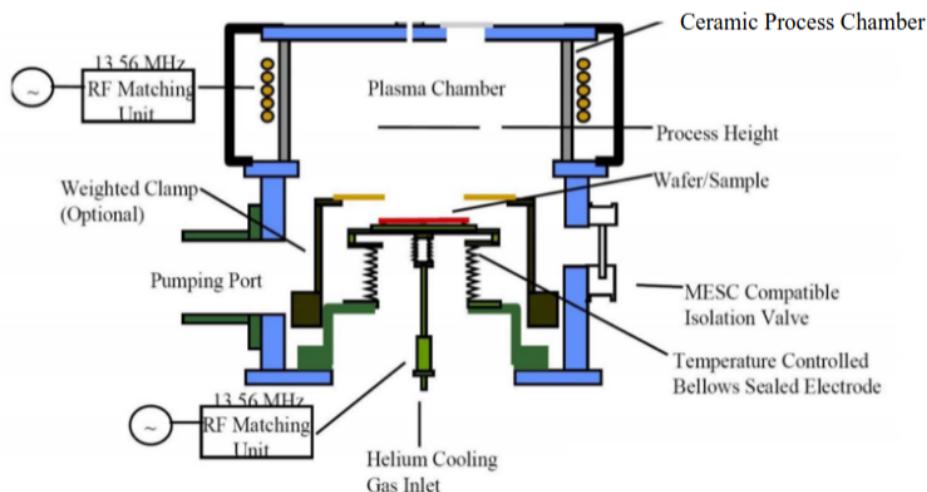


Figure 22: Plasma coupled rie

drie

We also use some DRIE or Bosch process that allows us to draw some pretty precise features with a high-aspect ratio (20-50), it is a cyclic process where we alternate between etching and depositing. We etch using some SF₆ and deposit some polymer layer of C₄F₈. We can etch over 10 μm/min and go through the whole wafer. We pulse but it will still eat a bit of the sidewall. It is pretty good for MEMS devices.

Etch Lag A bigger opening will etch more vertically compared to a shallower one with the same amount of cycles.

Comparing Dry etching

Table 6: Etching Pressure Ranges

Etching Mode	Pressure (Torr)
Ion Milling	$10^{-4} - 10^{-3}$
Reactive Ion Etching/Ion Milling	$10^{-3} - 10^{-1}$
Plasma Etching	$10^{-1} - 5$

Interconnects, Al, Cu, CMP

Interconnect is a crucial part of any IC's as they connect the various transistors among each other and to connect the IC with other components.

We first considered Aluminum for interconnect as it is cheap, compatible with Si technology, it adheres well to SiO₂. One major flaw is the low melting point of 577 c. Copper was for a long time avoided as it diffuses really fast in Si and SiO₂ and adheres not really well to SiO₂.

Aluminum as interconnect

Spiking and pitting

Silicon will naturally diffuse non-uniformly into Aluminum creating **spiking**, this Silicon that diffuses will leave some space that the Aluminum will "fall" into it due to those pits.

Those pits could break some junction inside of a transistor.

Solution Add some Silicon to the Aluminum or during the PVD step. We can also add some barrier metal as Titanium-Tungsten.

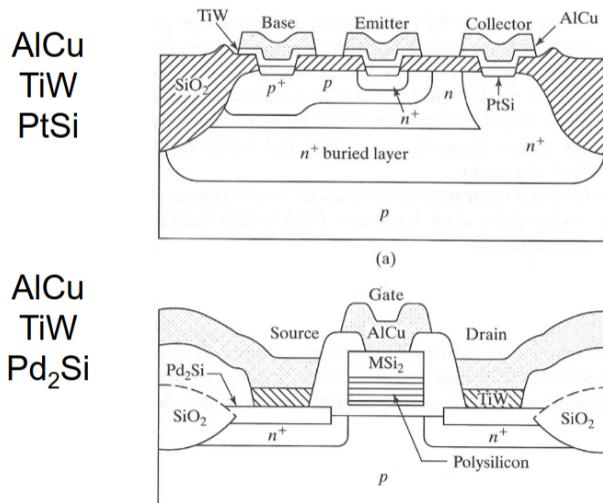


Figure 23: Barrier solution to TiW

Silicides Silicium can react with various metal which have various resistivity and can appear at different conditions. Those properties can be used to make some metal to react with the wafer, the rest of the metal that didn't react with the silicium.

Electromigration

If we make the interconnect too thin we can witness electrons carrying away some chunk of metal. Also good to remember that the flow of current is opposite to the flow of electrons.

Solution We can add Cu to Al, 95 % Aluminum, 4% copper and 1% Silicon. Or the simple solution is to use some Cu.

Multilevel Metal Problem

We will have non planar structure in our wafer with all those layers and structures we form. We will have some **via-depth** problem.

Solution This is why we usually make the contact wider and wider contacts as the stack increase. We can also slightly shift the stacking to avoid alignment issues.

We also have developed techniques to make the structure more planar by filling up via with tungsten through cvd and we also deposit some Aluminum using pvd. The filling of tungsten is a *selective deposition* as seen with the reaction:



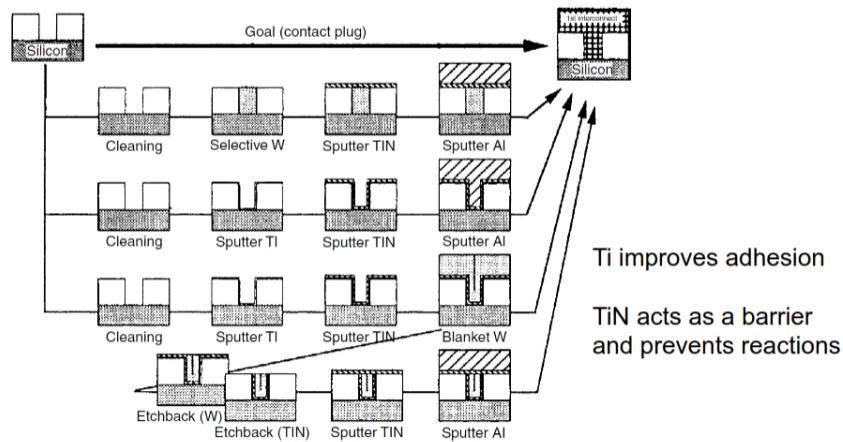


Figure 24: Several ways to create interlayer contacts

cmp

Planarize the surface A common used techniques is to use oxide-cmp to planarize the surface after applying some contacts. Then we can build on top of a flat and clean surface.

Another way is to use some cmp that uses a **chemo-mechanical polish**. It can be used to:

1. Smoothing
2. Planarization: ideal after applying some interconnect
3. Damascene: a commonly used techniques in Cu interconnet and allows to draw some precise features

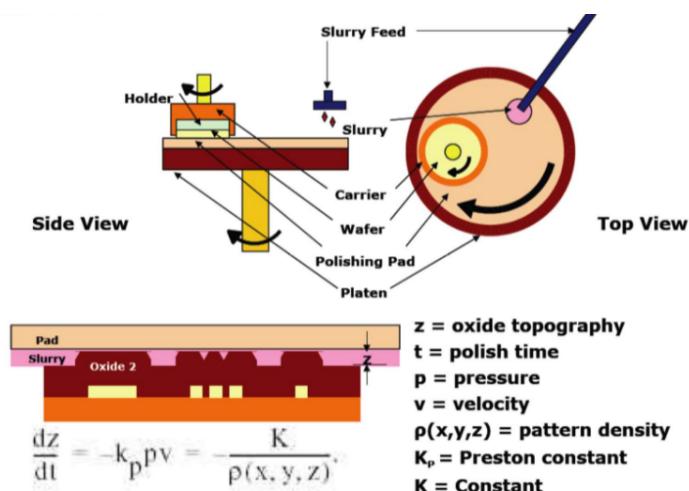


Figure 25: cmp principle

cmp principle It is a pretty straight-forward process, we can also have some *multiwafer* machinery that allows us to process multiple wafer in parallel.

This process is not perfect and can smooth out *local* planarity but it will distribute it *globally* resulting to global non-planarity which is not really the desired effect.

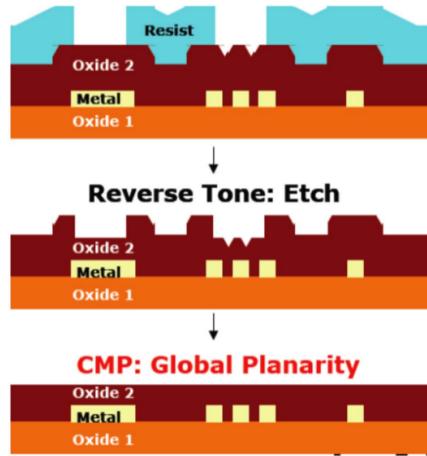


Figure 26: Global planarity

Solution to reach global planarity Another solution would be to add dummy oxide which will make the cmp smoother. This dummy oxide can sometimes be seen in finished products.

Copper IC

The main reason to push for copper interconnect, is to further reduce the delay time as we scale down.

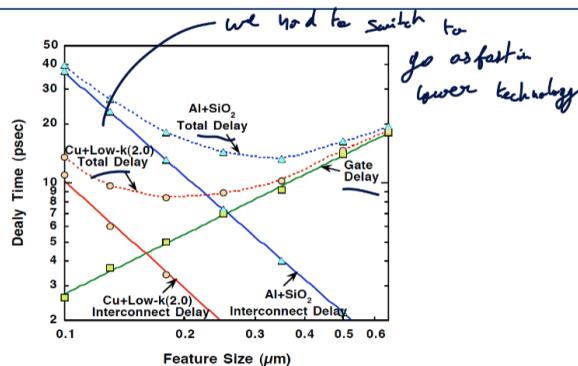


Figure 27: Copper interconnect

It also has some better resistance against failure but it doesn't adhere well to dielectric, it diffuses with the dielectric. It is compatible with tungsten plug (good point) but the copper just contaminate the chip and the equipment, ...

So to avoid this, we will use some *seed layer* that behaves as a sort of protective layer. The damascene process is extensively used to produce some pretty flat result.

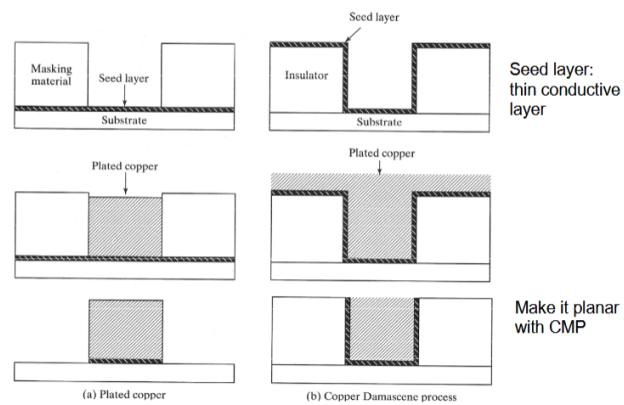
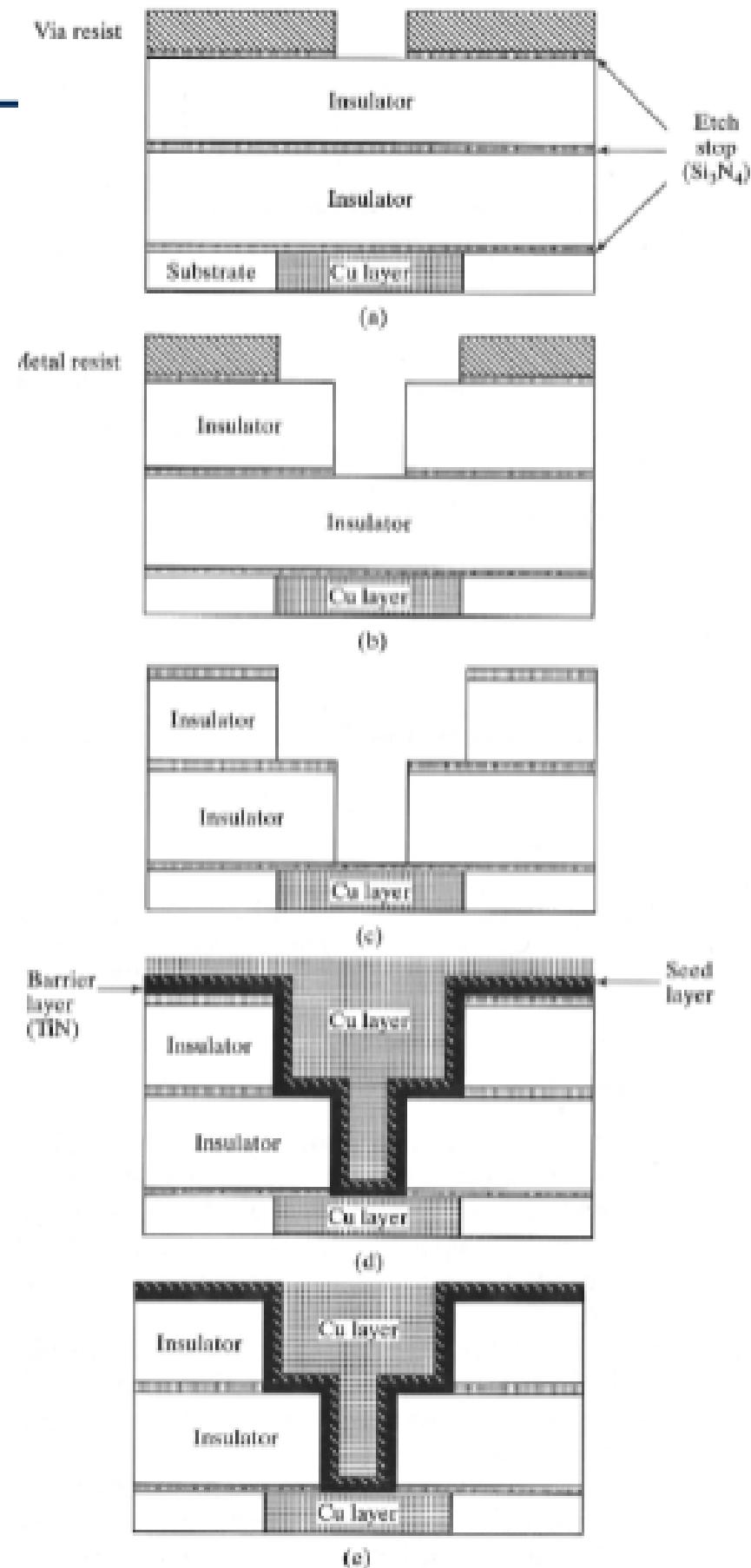


Figure 28: Copper, electroplating



Damascene process r0.24

The idea behind this process, is to simply add this protective layer (through ald), deposit the copper and polish using cmp.

The dual damascene process is extensively used in vias and interconnect traces as it can make some thicker top traces

It is the de facto standard in CMOS processing. This allows to create complex stack with many many layers.

If we are using the simple plating of copper, we can use some lift-off process which makes removing the excedant of copper quite easy. Employed especially for and .

IC Processing overview

CMOS

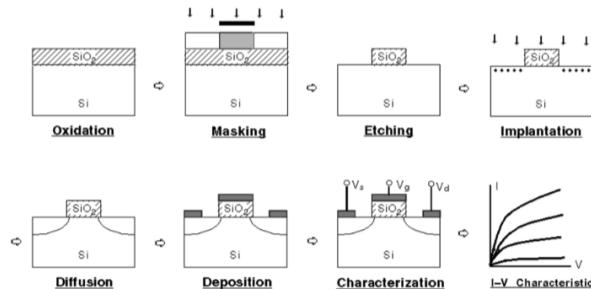


Figure 29: The simplified CMOS processing

In the beginning, we used a lot of gate to control the gate which was a sensible choice given the easy of connection and we just have some thermal diffusion. But the biggest issue and limitation was the fact that it was not a **self-aligned process**. Meaning that engineer had to take margin when doing the gate creating some unnecessary overlap which amplified the junction capacitance further reducing the speed. On top of this, after applying we couldn't do a lot of other processes that works at higher temperature !

In Aluminium process, we first dope through some high temperature step then we need to align the gate on top of the source and drain.

But now, in poly-gate, we can withstand higher temperature and here we use the poly gate as the mask for the source and drain region. **The gate comes first, forcing the source and drain to be at the right place.**

Self-alignment

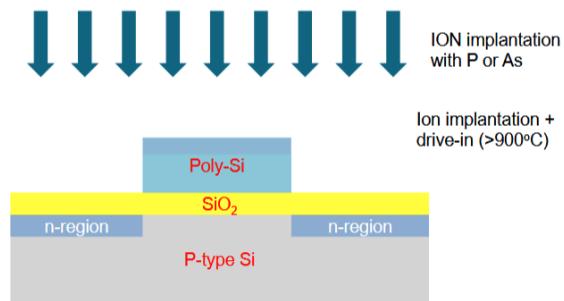


Figure 30: Self-alignment polygate

Basic flow

We first start "drawing" the poly-silicon gate using a mask. We do for the NMOS and PMOS at the same time. Once it is done, we remove the photoresist, do some Boron implantation for NMOS. We implant some Arsenic with low-energy (so we don't put too many) which acts like a channel stop, to avoid any charges during operation to flow from a NMOS to PMOS.

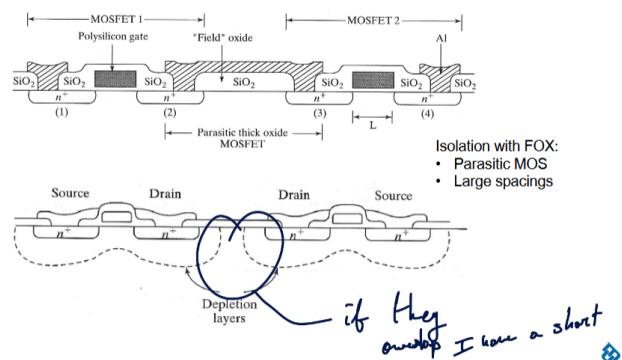


Figure 31: Parasitic NMOS thick

In this process step, we can find back the locos process and see the appearance of those bird's beak. Then we apply remove the Nitride to implant some Boron for the PMOS.

Once we have the desired region for the channel, we can add the polysilicon and **then** the actual doping with some high dose boron for PMOS and high dose phosphorus for NMOS. We just have to invert the mask from the previous step. It is self-aligning since the implantation will slightly bend around the gate which will create a controlled channel capacitance.

Finally, we can do some cvd deposition of the contact holes and finish it with some nice metallization and etching. And voilà ! we have a CMOS. Ofc, it is not flat and nice as depicted in schematics. It is quite chaotic and uneven.

Latch-up One big enemy: Latch-up ! Typically there is some undesired bipolar junction that forms a *thyristor*. So for this we usually use some epi and sti to ensure no such behavior can occur.

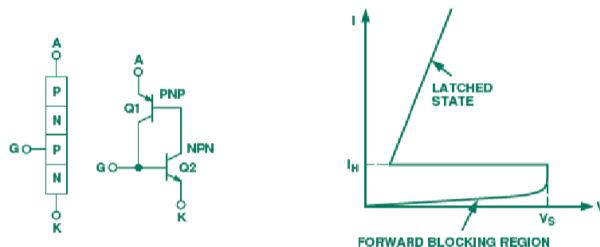


Figure 32: Thyristor and its operation

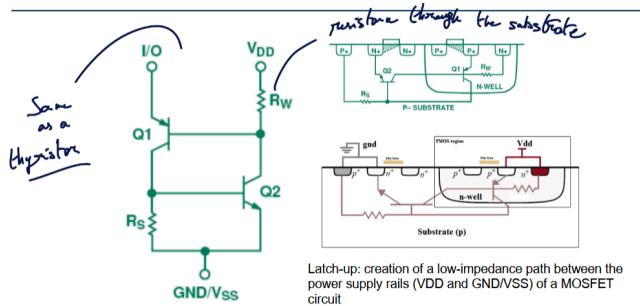


Figure 33: Latch-up

So this is why we love sti in this case !

Advanced CMOS process

We use a base substrate p where we grow some epi on top, we then deposite some with a buffer layer made of nitride. We use some plasma etching to create trenches using the inverse of the active area mask.

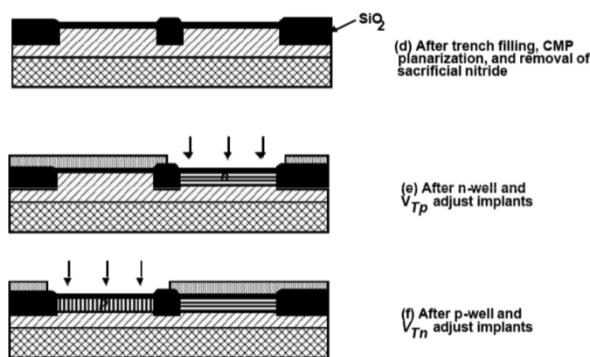


Figure 34: Advanced CMOS process

But this isn't always enough and sometimes, we need to do some ldd to avoid *hot electron effect*. This effect can sometimes change the actual doping which can then destroy the junction and make MOS not work at all !

Hot carrier effect It happens when a strong EM field is applied and when an electron has enough *kinetic energy* to break lattice bonds and hence create another electron-hole pair. They have an energy over kT .

This will increase the current in the channel but the holes will be absorbed by the substrate creating a little current that can be monitored. This creates a sort of BJT.

This is why we often add some spacer to help with this effect.

Salicide

It allows a better current flow synonym of more freedom in the layout !

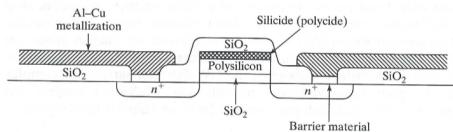


Figure 35: Polycide - Salicide

Salicides are **Self Aligned Silicides** hence the name. it consists of:

1. metal deposition;
2. annealing forms silicide on polysilicon gate and single-crystal silicon source/drain areas
3. Unreacted metal is selectively etched away.

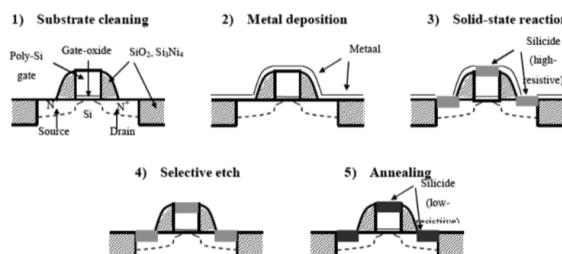


Figure 36: Salicide

As we get lower and lower, we need to use ald to realize this technique.

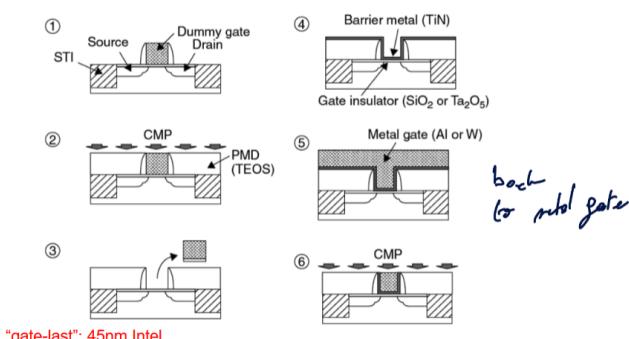


Figure 37: Gate MOSFET

Guest Lecture

Extra notes: Important numbers and figures

Glossary

- Mean Free Path (MFP):
 - The average distance a particle (such as an electron, atom, or molecule) travels between collisions.
In semiconductors and thin films, it influences transport phenomena.
- Chemical Vapor Deposition (CVD):
 - A process where gaseous precursors chemically react or decompose on a substrate surface to form a solid material, often used for thin-film fabrication in semiconductor manufacturing.
- Physical Vapor Deposition (PVD):
 - A vacuum-based process in which material is physically vaporized and deposited onto a substrate to form thin films.
- Molecular Beam Epitaxy (MBE):
 - An ultra-high vacuum technique where atomic or molecular beams are directed at a heated substrate to grow highly controlled epitaxial layers.
- Atomic Layer Deposition (ALD):
 - A vapor-phase technique for depositing thin films one atomic layer at a time using sequential, self-limiting reactions. Offers excellent conformality.
- Shallow Trench Isolation (STI):
 - A process used to isolate CMOS transistors on a silicon wafer by etching shallow trenches and filling them with dielectric material.
- Deep Trench Isolation (DTI):
 - An isolation method using deep etched trenches filled with insulators, used in 3D integration and high-voltage devices.
- LOCal Oxidation of Silicon (LOCOS):
 - A technique for selectively growing oxide on silicon for isolation by locally exposing regions to thermal oxidation.
- TEtraethylorthOSilicate (TEOS):
 - A silicon precursor used in CVD to deposit silicon dioxide films. TEOS provides good conformality and uniformity.
- Chemical-Mechanical Polishing (CMP):
 - A planarization process combining chemical slurry and mechanical abrasion to produce flat surfaces in semiconductor fabrication.

- Low-temperature Oxidation (LTO):
 - A thermal oxidation process performed at lower temperatures to form silicon dioxide, used when high-temperature processing is not feasible.
- High-temperature Oxidation (HTO):
 - An oxidation process performed at high temperatures to produce high-quality oxide films on silicon.
- Plasma Enhanced CVD (PECVD):
 - A variant of CVD where plasma is used to enhance chemical reactions, enabling deposition at lower temperatures.
- Low Pressure CVD (LPCVD):
 - A CVD process carried out under reduced pressure, leading to better uniformity and fewer contaminants.
- Anti Reflective Coating (ARC):
 - A thin film applied to reduce reflections and improve pattern fidelity in photolithography.
- Rapid Thermal Annealing (RTA):
 - A process of quickly heating wafers to activate dopants or repair damage without significantly affecting the rest of the structure.
- Secondary Ion eMission Spectroscopy (SIMS):
 - An analytical technique that sputters a sample surface and detects secondary ions to determine composition and depth profiles.
- Spreading Resistance Profilometry (SRP):
 - A technique for measuring the resistivity and doping profile of semiconductors by placing probes along a beveled surface.
- Reactive Ion Etching (RIE):
 - A plasma-based etching technique using reactive gases to anisotropically etch materials with fine resolution.
- Deep Reactive Ion Etching (DRIE):
 - An advanced RIE process capable of etching deep, high-aspect-ratio features, especially in MEMS and silicon micromachining.
- Capacitively Coupled Plasma (CCP):
 - A plasma generation method used in etching where power is capacitively coupled through electrodes. Often used in RIE.
- Inductively Coupled Plasma (ICP):
 - A high-density plasma source where power is inductively coupled through coils, providing high etch rates and better control.

- Epitaxy (EPI):

- The process of epitaxy allows the growth of a higher purity layer on a substrate of the same material. The goal of the epitaxy process is to make electron transmission more effective through the device.