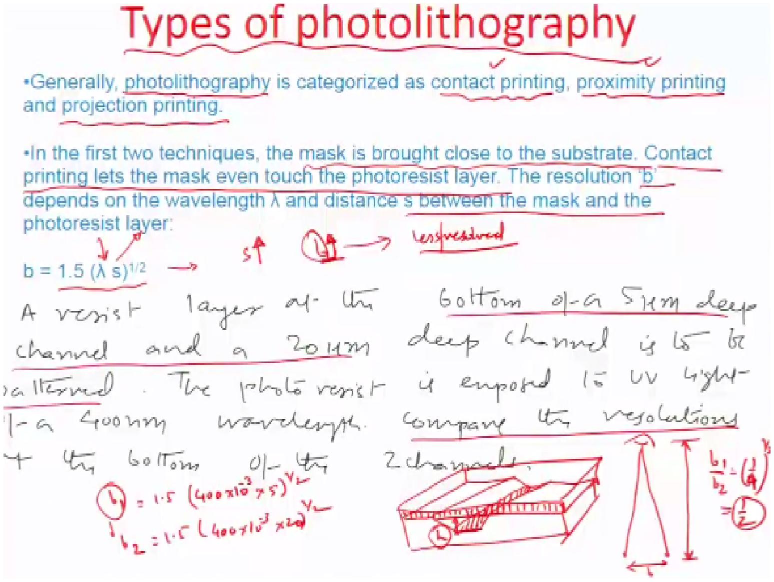
Design Practice - 2
Prof. Shantanu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology-Kanpur

Lecture - 18
Types of Photolithography

Hello and welcome to this Design Practice 2 module 18. We were discussing about photolithography and in context of that I would like to do some more analysis related to the process.

(Refer Slide Time: 00:26)



Types of photolithography

- Generally, photolithography is categorized as contact printing, proximity printing and projection printing.
- In the first two techniques, the mask is brought close to the substrate. Contact printing lets the mask even touch the photoresist layer. The resolution 'b' depends on the wavelength λ and distance s between the mask and the photoresist layer:

$b = 1.5 (\lambda s)^{1/2}$ → $s\uparrow$ $b\uparrow$ → less resolved

A resist layer at the bottom of a 5µm deep channel and a 20µm deep channel is to be patterned. The photo resist is exposed to UV light of a 400nm wavelength. Compare the resolutions at the bottom of the 2 channels.

$b_1 = 1.5\,(400\times10^{-3}\times5)^{1/2}$

$b_2 = 1.5\,(400\times10^{-3}\times20)^{1/2}$

$\frac{b_1}{b_2} = \left(\frac{1}{4}\right)^{1/2} = \frac{1}{2}$

So as we already found out that this process of lithography is categorized into 3 different you know ways of doing printing. So one is contact, another is proximity and the third one is projection printing. In the first two techniques namely the contact and the proximity printing, the mask is brought close to the substrate. In one case there is small gap between you know particularly the proximity case between the wafer and the mask and the contact printing sort of lets the mask even touch the photoresist layer which is actually detrimental sometimes for the resist layer.

So when we look at particularly the contact printing method or even the proximity printing method, the resolution of the process b would typically depend on the wavelength of the elimination source as well as the distance of the source from the particular layer of resist which needs to be exposed to. So if the resist distance is changed the resolution will definitely change. For example if s goes up in this particular expression or the distance between the mask and the resist layer goes up, there is a change of the resolution b.

So the b will also go up meaning thereby that it is lower resolution. B is typically the distance between 2 different objects paste and get visible independently. I think we just need to reiterate what resolution really means. So let us say there are 2 points in space and so the b goes up meaning thereby that let us say the distance is more the ability to resolve between these 2 points, this is b okay. The distance between 2 points which still can be visualized by an eyepiece situated at some distance from the 2 points as independent.

So as this b reduces, the points become merged into one another and they may not be able to get independently visualized. So here the whole purpose behind the experiment is to just make the b as small as possible considering a distance s from the eyepiece to the particular substrate or let us say in this case the resist layer.

So obviously when we are trying to pattern within micro channels for example in one particular instance in a particular flat silicon wafer there has been a channel which has been carved because by by etching techniques okay, something like this there is a channel and this is the remaining part of the wafer. So we want to pattern somewhere in this particular surface which is hashed on the inside surface of the channel.

And obviously the placement of mask in this particular case would happen in a manner so that the mask is present over the surface and the windows which would let the light go in are present at a certain height h from the channel surface. So in such kind of cases it is obvious the resolution would depend also on this distance h as well as the wavelength of light that what is using, s being the distance between the mask and the resist layer.

So supposing the resist layer were kept here and the mask layer is this particular layer which I show through this vertical line hatching so the etch distance between the resist layer and the mask layer is basically the height of the channel or the depth of the channel in this particular case. So let us say we have now a resist layer at a bottom of a 5 micron deep channel and another one at a 20 micron deep channel and we want to pattern and we want to find out if the resolution is going to change. Is it going to be more or less.

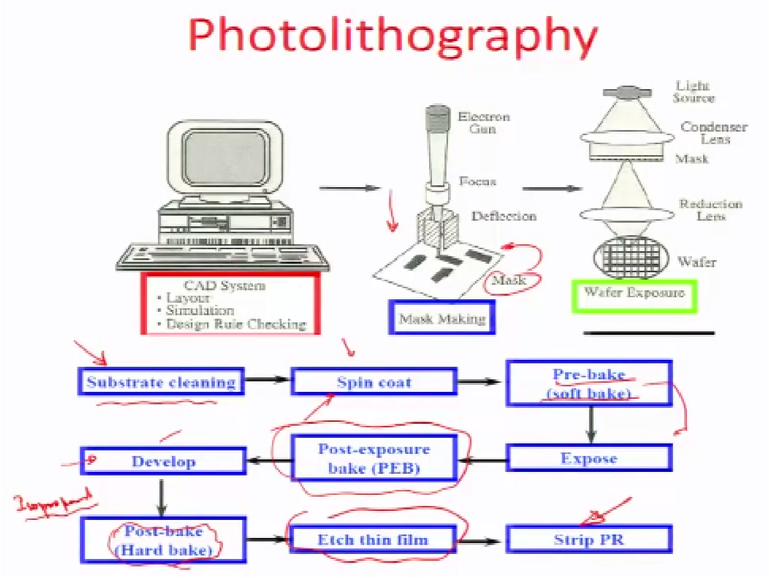
So if b is more the process is less resolved. Because obviously b lesser and being able to independently resolve means the resolution of the process is higher. Thus very clear from the terminology related to resolution. So in this particular case we have 2 different resolutions let us say b 1 and b 2. One is at the behest of 400 nanometer beam.

Let us say we resolve everything in terms of microns. So we have 1.5 times of 400 10 to the power of 3 sorry -3 microns times of s which is 5 microns in one case whole to the power of half and the other case once the distance of the channel becomes 20 microns this is into 20 to the power of half. So if you compare both the resolutions, obviously the resolution is better in the first case; b has a lower value in comparison to that of the second case.

And the resolution would be simply reduced to one half as you can see here b 1/ b2. So when we when we compute b 1/ b2 in this particular case we have one-fourth to the power of half which comes out with this half. So basically in the case of b 2 the resolution is simply reduced to 50% okay. So the minimum feature size that can be accommodated at a channel depth of 20 microns is going to be exactly twice the feature size that can be accommodated at the channel depth of 5 microns.

So these issues need to be kept into mind while developing mask designs particularly in the MEMS application. And let us move ahead now into actually how you do lithography.

(Refer Slide Time: 06:30)



So lithography can start from a cleaning step where a substrate, particularly a silicon substrate being taken and cleaned through various cleaning protocols. The idea is to get off all the organics and other contamination which is there on the surface. After the substrate cleaning step you take photoresist and spin coat this on the wafer creating a small thin layer of the photoresist film on the wafer.

You prebake or soft bake the film and remove it, remove all moisture content from the particular film and then you expose the prebaked film you know to a certain wavelength of light using a mask. This is defined, well-defined mask which is in the beam path here. This is the beam path with the beam guidance which is given by the optical alignment you know engineering of the photolithography system.

After the exposure you need to heat catalyze the bonding mechanism which would happen. Let us say if we are talking about negative tone there is going to be cross bonding. And so the cross bonding gets affirmed more because of more post exposure bake and then finally you develop what you have done on the film surface so supposing it is a negative tone resist so what the areas exposed would going to remain away.

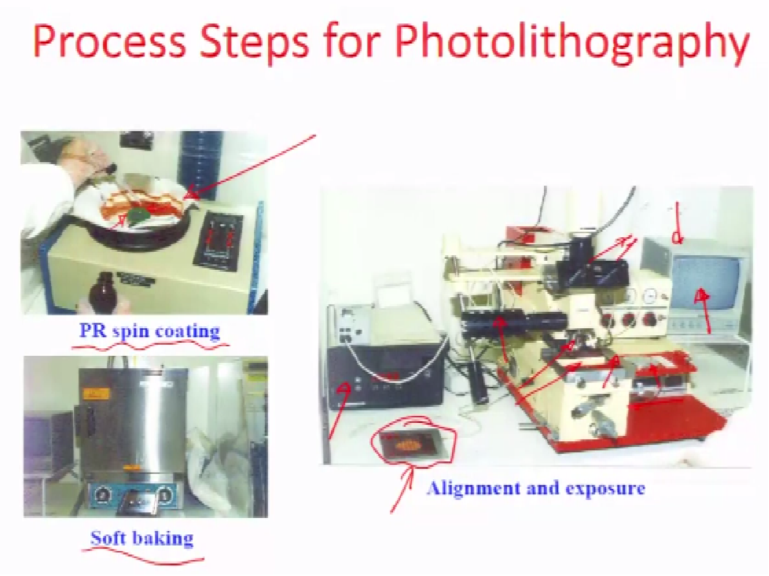
The remaining are going to etched off because of this development process. And then you post expose bake it because or post develop bake it because you want to get rid of all the liquid from the surface particularly the developer solution which is left over after all the resist is successfully removed. So isopropenyl is typically used for finding out if there is any residual resist which is unexposed.

Left on the surface it becomes whitish or cloudy and so once you have no cloudiness by spraying isopropanol you are able to figure out whether the resist is all removed. And so you do post exposure bake post development bake which also affirms the cross developed or cross bonded areas which stay on back on the wafer surface. Then you etch out the thin film which is related to whatever you are using this for a mask.

For example lithography is typically carried out because either you want to use it for a lift-off process or you want to use this for a etching process and you must keep this mind that resists are normally always used as sacrificial material unless you want to develop something with the resist like a micro cantilever or something like that. So you etch the thin films and then strip off the photoresist so that you are left with the etch pitch on the thin film that you wanted to etch for.

So resist would act as a etch top layer in those situations. So this is all about how photolithography is carried out.

(Refer Slide Time: 09:16)



Process Steps for Photolithography

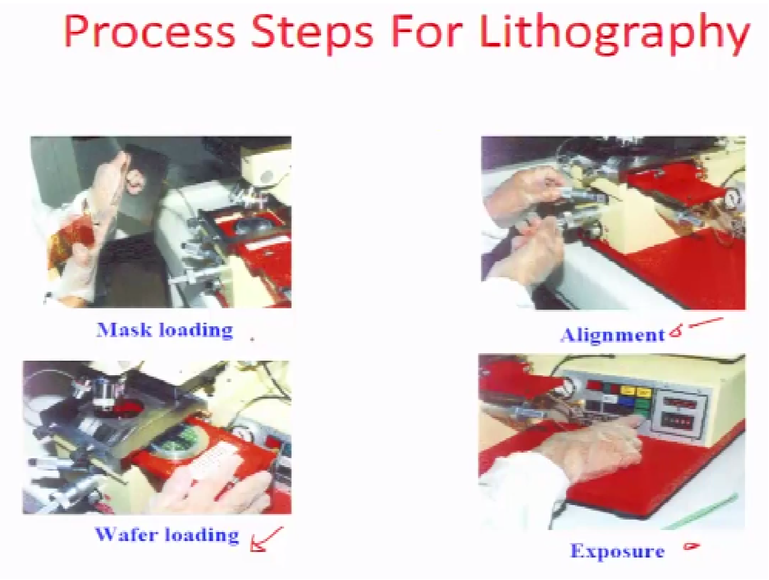
In the laboratory if you look at the various aspects of the lithography process it starts with a spin coding of resist because you want to spread the resist so there is typically 3 different components in a resist. One is a photo asset generator, another is an epoxy resin which kind of cross bonds on exposure because of the furnishing of photo ions and then there is carrier solvent. So the solvent is typically used for spreading the photoresist uniformly like a film on a surface.

This is spin coated to do this job. It drop the photoresist on the center and it spreads out as the wafer, silicon wafer as shown by the green piece right here, rotates at a certain RPM. Then you do soft baking in a gravity fit convection oven like this. You do alignment exposure step. You can see the mask here in the lithography system. So the mask attaches into a frame right here in this area and the wafer is kept down underneath.

So this is the wafer check in fact which goes inside and you know aligns the wafer with respect to the mask. This is the exposure box, the counter which also counts time as well as sets up the intensity level. There are many other visualizing tools for example a CCD a screen you know which is here. So this is for visualizing particularly the back side alignment issues using infrared camera etc.

There is also a objective and a set of IPs here and there is a microscope in place to visualize whether alignment is being carefully done okay. So and then there are various other components like a light source. You know there is a shutter which would be operating on the light source to expose or unexposed whenever whatever times are set in so on so forth.

(Refer Slide Time: 11:21)



Process Steps For Lithography

Mask loading

Alignment

Wafer loading

Exposure

So the process happens with first the mask loading. You can see mask being loaded. The wafer loading okay and then the process alignment and then the exposure. So these are the different steps carried out on lithography.

(Refer Slide Time: 11:34)

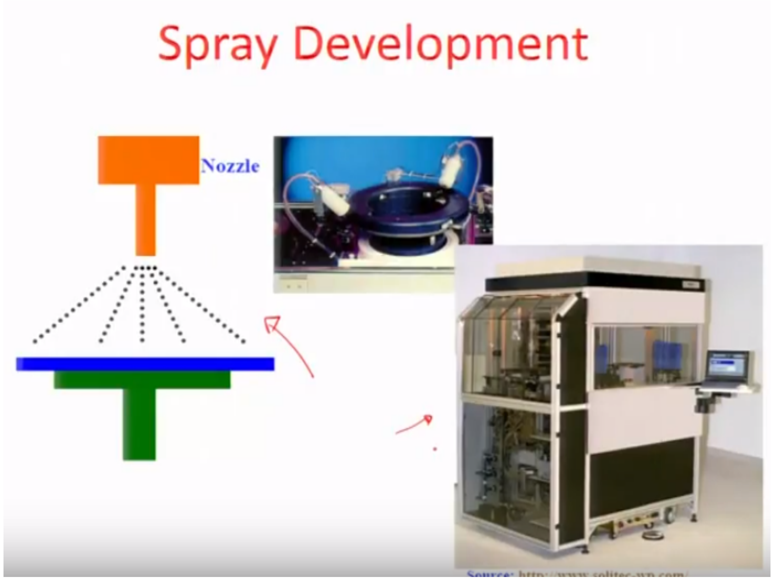
Process Steps for Lithography

Development

Etching

And then you have after the lithography is happened the time development where a solution is used, the wafer which is already exposed to light is dipped in and material is taken off. So there you have you know the sacrificial resist pattern on the wafer and you use again a etching solution to etch off the film underneath the resist so that you could make vials or crevices or craters into that particular film which you are etching so this process for which the resist is actually a etch stop. So this is how different steps of lithography are executed.

(Refer Slide Time: 12:08)

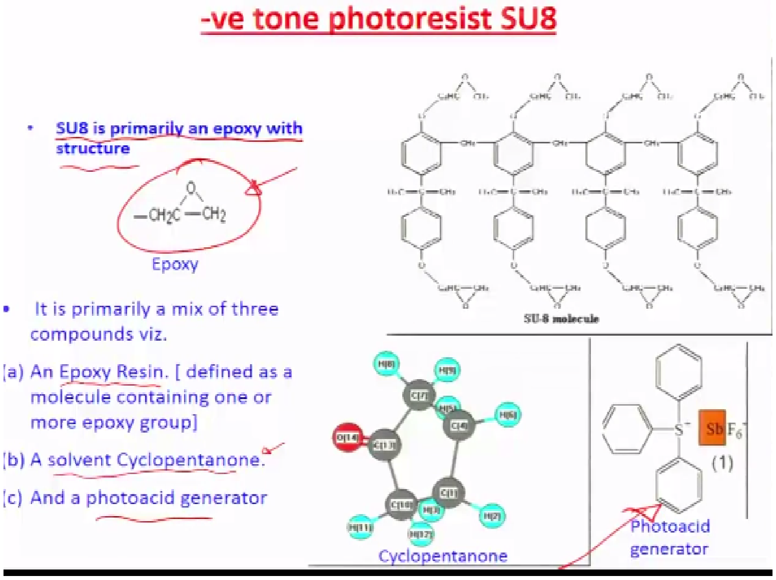


Spray Development

Source: http://www.solitec-wp.com/

Typically in high production systems this pin coated in the nozzles are eliminated and so there is spraying system which will do the job of spraying the resist at a high pressure and ensure that there is uniformity in thickness and then there are large machines called steppers which are used sometimes for the purpose of (()) (12:28) lithography. So these are how the process is carried out and these are all projection lithography based systems. The process is carried out in the industry in a very high yield through the following things.

(Refer Slide Time: 12:40)



-ve tone photoresist SU8

- SU8 is primarily an epoxy with structure

Epoxy

SU-8 molecule

- It is primarily a mix of three compounds viz.

(a) An Epoxy Resin. [defined as a molecule containing one or more epoxy group]

(b) A solvent Cyclopentanone.

(c) And a photoacid generator

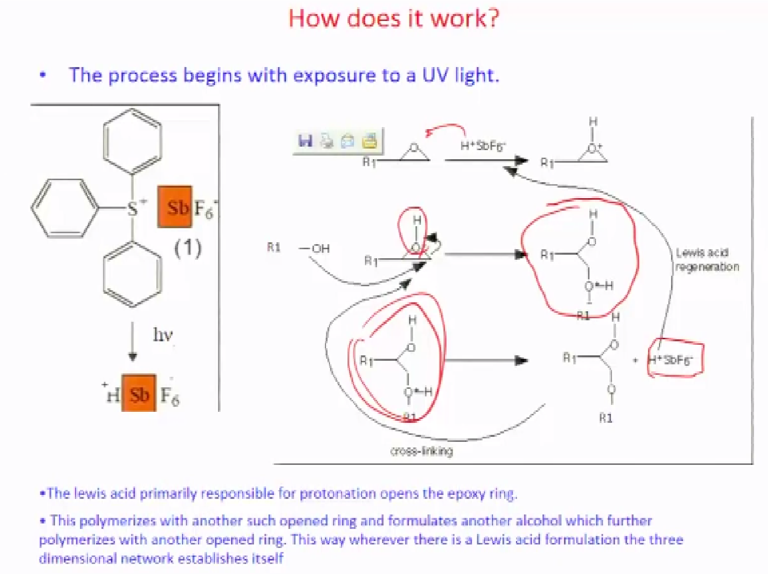
Cyclopentanone

Photoacid generator

So if you looked at the basics of what really is changing in the resist, what is the reason why the resist changes properties. Primarily SU8 has an epoxy structure. It is a carbon oxygen carbon ring as shown here and then if we looked at what all components are there you have a epoxy resin as the base matrix which would be corresponding whenever there is a exposure to light.

There is also carrier solvent which evaporates in the pre-exposure bake step which is executed and then there is a photo acid generator something like what you can look at here which is actually a loose acid and generates protons.

(Refer Slide Time: 13:28)



How does it work?

- The process begins with exposure to a UV light.

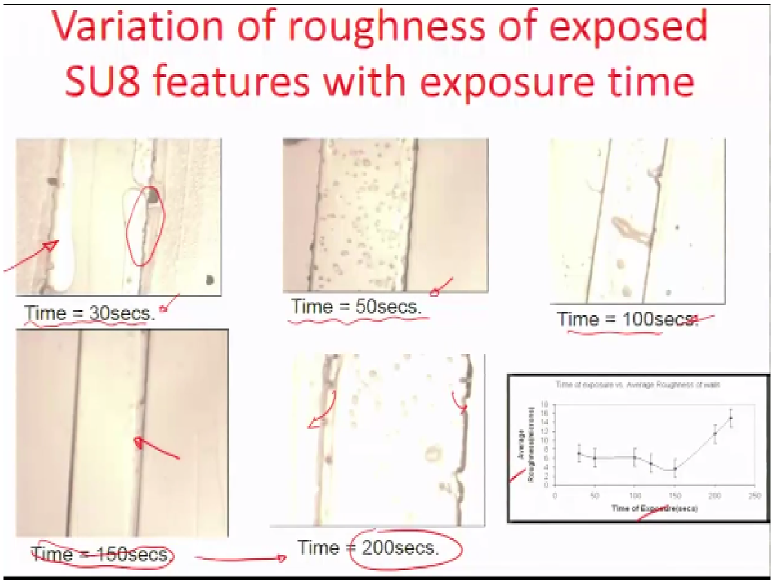
- The lewis acid primarily responsible for protonation opens the epoxy ring.
- This polymerizes with another such opened ring and formulates another alcohol which further polymerizes with another opened ring. This way wherever there is a Lewis acid formulation the three dimensional network establishes itself

And typically when such photo acid generators come in contact with radiation of a fixed wavelength they are going to generate protons which are going to then start affecting these epoxy rings. For example this proton right here has started opening the epoxy ring and 2 such rings simultaneously opened would cross bond like being shown here.

So this is like the crosslinking mechanism of the resist which goes on happening okay and so you can probably have the proton retreated back part of the same molecule, the photo acid generator molecule but what it has essentially done is to gone into the system and opened up ring so that they can crosslink and such cross linking is important for the process of lithography.

So it is a sort of a cross bonding polymerization kind of reaction where multiple organic molecules come together and crosslinking develops between them so that they can be enabled to stay on the surface without the developer solution being able to etch them away and so partially the structures which are on the surface in the negative zone resist are the ones which are cross-linked in this manner.

(Refer Slide Time: 14:41)



Variation of roughness of exposed SU8 features with exposure time

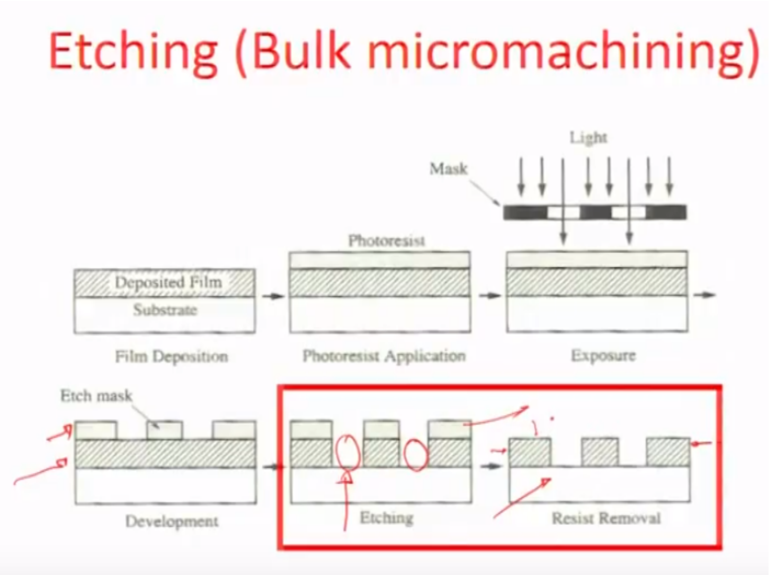
So there is a lot of associated methodology which is very carefully drafted for example the way that light source is able to expose the photo acid generator and the way that diffusion processes for the protons to start going out from the photo acid generator and affect the epoxy rings and mechanically limited would really determine the extent of finish that would come on to the structures that are enabled.

For example this shows schematics or this shows microscopic images for structures developed. These are like micro channel structure developed for different time instances of exposure. So in one case you have underexposed, actually both of these cases you have underexposed the surface and so you can see that probably the proton diffusion is not proper relating to a lot of wavy edges, under dimensions because you are not allowing enough time for the exposure and the protonation to happen.

And then once it hits the right time, it automatically changes the surface toughness of the channels or the smoothest channels here and this is a plot of average roughness with time of exposure and so if the time again increases to few more seconds then it starts over diffusing and then it starts changing the dimensions to slightly oversize which is also something which should not be allowed okay.

So it is very carefully planned and drafted if you want to have good patterning process on the system and every patterning process has to be developed ab initio by looking at the various resist parameters and then trying to balance out the times, the thickness, the spin speeds, the heating times you know the development time so on so forth.

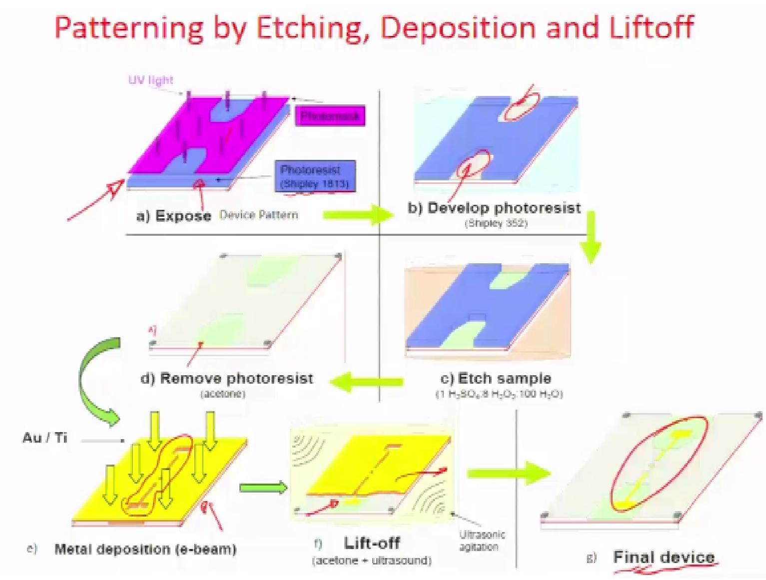
(Refer Slide Time: 16:18)



Etching (Bulk micromachining)

So typically with this kind of resist this is sort of a step which shows how resist acts as an as a sacrificial material and this is a you know let us say a etch stop film which you want to expose. So you have used resist as a sacrificial material and selectively taken off with etchants the hatched area so that it can open windows for the base material which can be further etched okay. So the resist is typically removed and then these are used, the sacrificial material here is used as a way of etching out the main material okay and then you can even remove the sacrificial layer off. So that is how bulk micromachining is typically performed with resists and with patterning on surfaces.

(Refer Slide Time: 17:09)



Patterning by Etching, Deposition and Liftoff

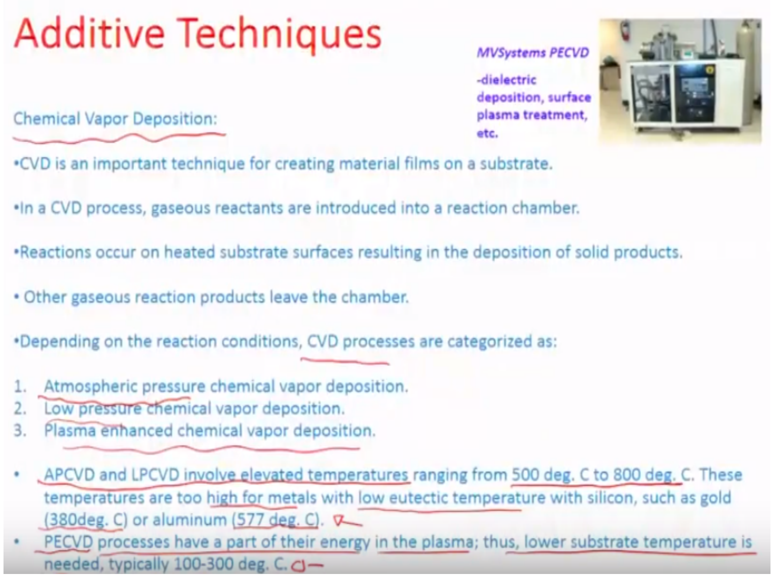
So you could do a lot of processes through such lithographic techniques. This right here shows how you can use exposure step followed by selective etching of the blue film okay the blue colored surface okay which is outlaid on the substrate surface. It also shows how you can you know remove the photoresist. So this shows how a layer of you know this blue region on the substrate is being selectively etched through lithography.

So this is the resist and it is a Shipley positive tone resist which gets debonded on exposure to light. There is a mask which has been kept. So the resist is patterned here opening vials. And the grey layer which is underneath the blue photoresist layer you know gets etched off because of the opening of the windows in these 2 regions and the resist acts as sacrificial material thus exposing the green area now which is just underneath the grey area.

And then after doing this the photoresist is removed and another layer is coated where you can actually carry out metal deposition. So this is again lithographed, a pattern like a interconnect is created. Vaporization of metal is made in the top surface and once the metal comes and sits on the surface, the green area, you can take off the resist layer so that you have interconnects on the final device as it mentioned here.

So patterning by etching deposition and lift-off all at one go is in fact represented in this particular slide which gives you an idea of what can be done with interconnects, with etching features and structures producing mechanical and electrical features and a variety of things you know as per plan on surfaces of materials like silicon.

(Refer Slide Time: 19:03)



Additive Techniques

MVSystems PECVD
-dielectric deposition, surface plasma treatment, etc.

Chemical Vapor Deposition:

•CVD is an important technique for creating material films on a substrate.

•In a CVD process, gaseous reactants are introduced into a reaction chamber.

•Reactions occur on heated substrate surfaces resulting in the deposition of solid products.

• Other gaseous reaction products leave the chamber.

•Depending on the reaction conditions, CVD processes are categorized as:

1. Atmospheric pressure chemical vapor deposition.
2. Low pressure chemical vapor deposition.
3. Plasma enhanced chemical vapor deposition.

- APCVD and LPCVD involve elevated temperatures ranging from 500 deg. C to 800 deg. C. These temperatures are too high for metals with low eutectic temperature with silicon, such as gold (380deg. C) or aluminum (577 deg. C).
- PECVD processes have a part of their energy in the plasma; thus, lower substrate temperature is needed, typically 100-300 deg. C.

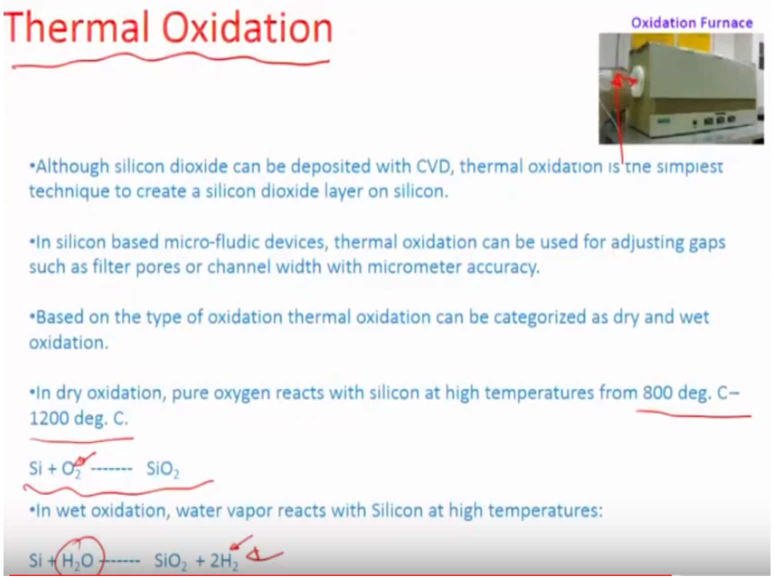
So I talked about various other MEMS processes. I want to in fact finish up this area today so that we can start doing the sensor design and actuator design after that. So there are additive techniques like chemical vapour deposition where you can create some kind of chemical reaction the byproduct of which is a solid film which can get deposited on the top of again silicon. So you can carry out, so this is called chemical vapor deposition.

CVD can be carried out under different pressure conditions. For example there can be the APCVD, the LPCVD and the PECVD the plasma enhanced chemical vapor deposition. And you know the APCVD, LPCVD involved typically elevated temperatures ranging from 500 to 800 degree Celsius. These temperatures are too high for metals particularly with low eutectic point and you can use materials like gold which has about 380 degree Celsius eutectic point.

And aluminum which is 577 degree Celsius eutectic point to some extent to make deposition possible okay. PECVD is basically plasma enhanced. So there is going to be a bunch of ions and electrons and you can have a drive energy so that the films become stable okay. So basically the PECVD processes have a part of their energy in the plasma state and so lower substrate temperature is accommodated in these kind of cases where the films are still stable at a lower temperature.

In this particular case in the APCVD or LPCVD case because of the fact that there is no such momentum transfer it is the temperature which tries to build up a kinetic energy on the surface so that there can be a diffuse layer which acts as an adhesion promoter for the metal that is deposited in the top of silicon. Okay, so this is one additive manufacturing technique responsible for doing surface micromachining.

(Refer Slide Time: 21:01)



Thermal Oxidation

Oxidation Furnace

- Although silicon dioxide can be deposited with CVD, thermal oxidation is the simplest technique to create a silicon dioxide layer on silicon.
- In silicon based micro-fludic devices, thermal oxidation can be used for adjusting gaps such as filter pores or channel width with micrometer accuracy.
- Based on the type of oxidation thermal oxidation can be categorized as dry and wet oxidation.
- In dry oxidation, pure oxygen reacts with silicon at high temperatures from 800 deg. C–1200 deg. C.

$Si + O_2$ ------- SiO_2

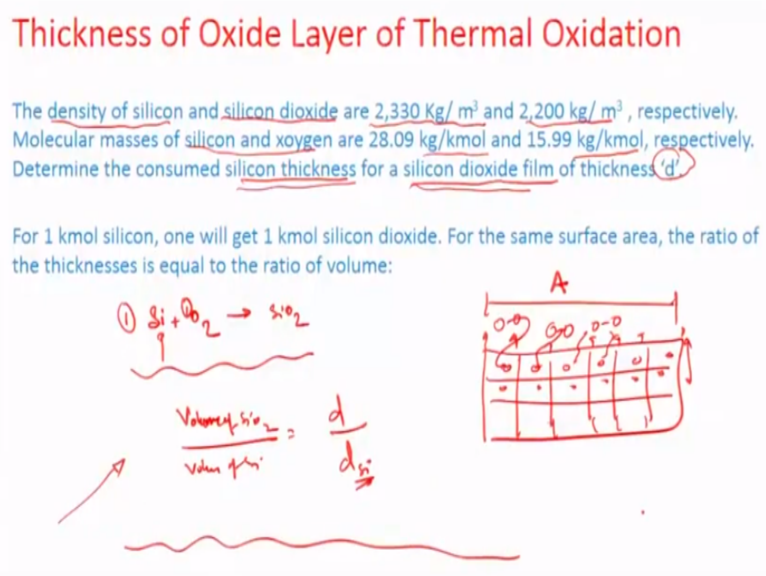
- In wet oxidation, water vapor reacts with Silicon at high temperatures:

$Si + H_2O$ ------- $SiO_2 + 2H_2$

And there is another very interesting thermal oxidation process where you are using thermal energy to excite the crystals on the top of silicon wafer and then passing oxygen molecules close by whether they are in dry or wet state. Wet state the reaction rates are very high and typically the silicon wafer for creating a condition where it can start entrapping the oxygen needs to be heated to 800 – 1200 degree Celsius in a quartz tube something like this.

And the wafers can be stacked inside this tube and the furnace can be set up at a high temperature and the oxygen flow at dry condition or passing through a bubble trap so that it has water vapour and oxygen can be passed close into the through the particular tube and through surrounding the particular wafer at a higher temperature so that there is diffusion of molecular oxygen into the substrates.

(Refer Slide Time: 21:57)



Thickness of Oxide Layer of Thermal Oxidation

The density of silicon and silicon dioxide are 2,330 Kg/ m^3 and 2,200 kg/ m^3 , respectively. Molecular masses of silicon and xoygen are 28.09 kg/kmol and 15.99 kg/kmol, respectively. Determine the consumed silicon thickness for a silicon dioxide film of thickness 'd'.

For 1 kmol silicon, one will get 1 kmol silicon dioxide. For the same surface area, the ratio of the thicknesses is equal to the ratio of volume:

So one has to realize something here that when we talk about oxide layers you know the oxide layer kind of gets built on the surface at the behest of the silicon so you have plane silicon which is now heated up and oxygen diffused into the silicon. So there is going to be some bulging and deformation of the film and let us see how. So we have a case here where we want to find out what is the thickness consumed of silicon for certain silicon dioxide film to grow on the surface.

Some parameters are given, for example the density of silicon, silicon dioxide in terms of kg per unit volume is mentioned. The molecular masses are also mentioned for silicon and oxygen as kg per kilomoles and we want to find out what is the consumed silicon thickness for a film of size d or thickness d formulated because of dioxidation process. So if you look at this stoichiometry of let us the dry process, we know that at the behest of 1 kilomole of silicon we are going to get exactly 1 kilomole of silicon dioxide okay.

So exactly there is a 1:1 molar ratio. So if we treat this case in a manner that let us say the exposure of the surface, this is a crystal lattice and you have cubic crystals and I am actually showing you side view of such a lattice and so the oxygen molecules which are there and let us say the crystal lattice is also oscillating because of thermal energy because of heating and all and the oxygen somehow gets trapped into this lattice and starts diffusing through the structure.

So there is going to be definitely the use of silicon to formulate the silicon dioxide and let us assume that the area here of the silicon and silicon dioxide are similar that is A and so if you wanted to look at the volume ratio that means the volume of silicon dioxide to the volume of silicon it is really about how much is the size of the silicon dioxide vis a vis what is the size of the silicon in terms of thickness which is consumed okay.

So we assume that the silicon and the silicon dioxide before and after the oxidation are having identical nature. So I think in the interest of time we will try to close on this module but after this understanding you will try to solve in the next lecture what is going to be the ratio of the two different thicknesses in this particular case and then this close over with one or two more illustrations of MEMS processes and start with the sensor design. So as of now thank you very much from my side.