Bio - Microelectromechanical Systems
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Module No. # 01
Lecture No. # 36

Hello and welcome back to 36 lecture of Bio-Microelectromechanical system. Let us quickly review what has been done last time. We talked about float zone methods of silicon production, we discussed on the wafer specifications and the preparation of the silicon wafer in industries keeping the standards in mind.

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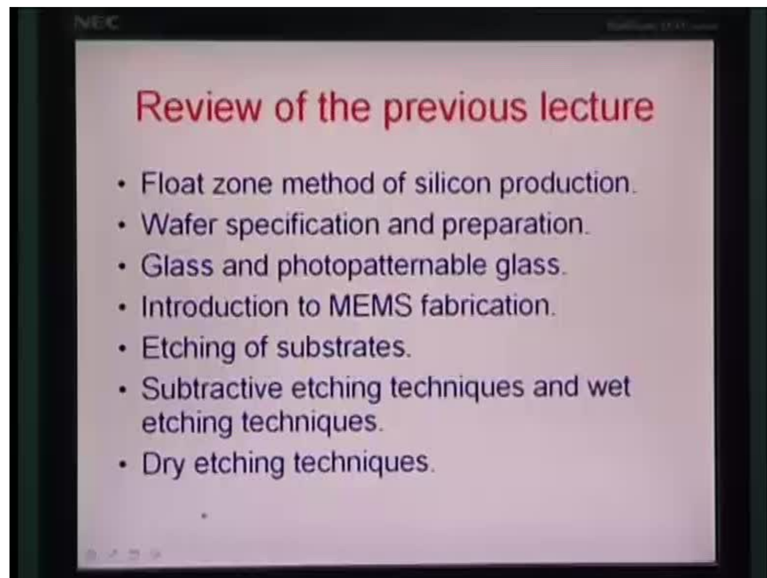

We also talked about some of the glasses like borosilicate or soda lime or quartz. Essentially, the glasses are nothing but combinations of some metal oxide ions along with basic silica matrix. We talked about some photopatternable glasses like forturn, which can be directly written with the optics. Then, we came to this introduction to mems fabrication area, where we talked about silicon mems in details, how bulk and how micro machining can be categorized into bulk and surface based micro machining.

We also discussed the detailed schematics of etching processes of substrates wherein you do a photolithography based masking layer and use that as a protective shield for etching through silicon wafer. Then, we talked about various other techniques like subtractive

etching techniques and wet etching techniques and also some dry etching techniques etcetera.

We move ahead and do some other silicon processing techniques like photolithography. As you know photolithography is really one of the most important techniques for fabrication of microstructures. If you look into just the lithography domain, you can divide this whole lithography business into several subtypes.

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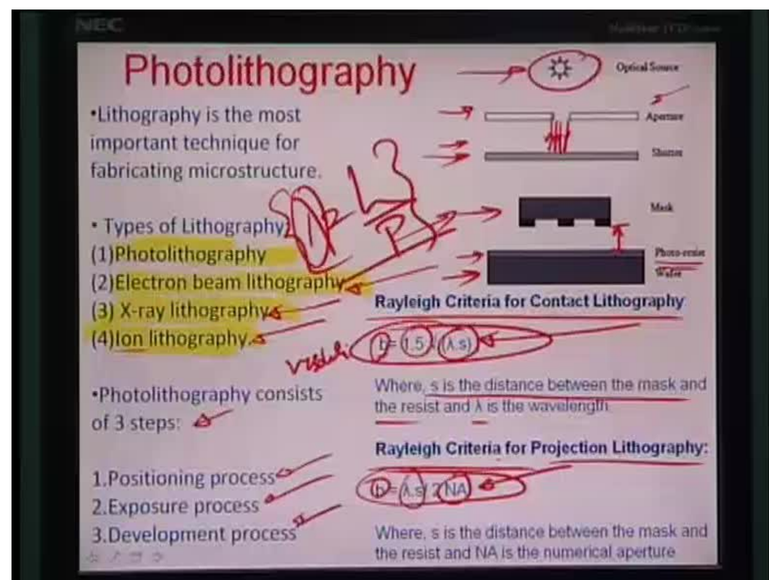

You can have photon driven lithography which is also as Photolithography, you can have electron beam driven lithography, x-ray lithography, ion lithography so on so forth. The only difference in this case is the resolution goes up because the ion energy is much more than simple photons. If you just look at the famous De Broglie relationship between lambda and the momentum, the ionic momentum increases also the function of ion mass. Therefore, you can have a lower wavelength or a higher energy or higher frequency by just increasing on the lambda. So, that is why electron beam lithography is probably a high energy beam than photon beams; x-rays even further higher ion lithography, because the mass of the ion also increases so rapidly.

Therefore, there is a tendency of trying to accelerate ions through large particle accelerating systems using electric fields. The whole idea is to generate some energy

levels, where the momentum is so large that you could write really at a very small resolution directly.

The photolithography process essentially is based on optics, it consists of three steps; there is a positioning process, there is an exposure process and there is further a development process. If you see here, we have this wafer here which is covered by a photo resist and there is a layer and then, there is a mask which is kind of black and white feature, where you have some areas - well, I can go through and some where they cannot or it cannot. Then, we have a shutter basically to the photolithographic system and there is an aperture which directs the light and makes it parallel directly to the mask and here is the light source.

We have so many things in the path of light before it falls onto this resist and changes the property of the resist by other cross bonding it or debonding it, depending on what kind of resist it has. Some of the important aspects about Photolithography especially for contact lithography are what you call the Rayleigh criteria.

Here, you get this relationship wherein the resolution distance between two features is also proportional to the root of lambda times s, lambda is the operating wavelength and s is really the distance between the mask and the resist. Essentially, this particular distance in contact lithography, you have to assume the mass to be placed in consonance or facing the resist.

Therefore, if you are writing a feature which is already inside the resist by some distance, you have effectively some distance between the mask and the feature which makes the resolution little different. So, b the resolution essentially is dependent on root of lambda into s, 1.5 is the quotient attached to root lambda s. For projection lithography, again the Rayleigh Criteria is little different b here, the distance of resolution between two particles is directly proportional to lambda times s, where s is the distance between the mask and photo resist and lambda is the wavelength and is inversely proportional to the numerical aperture - NA - between the optical paths.

These are the two different criterions, let me just describe lithography to be categorized into three different modes. Contact, where the mask comes and sits over the wafer; projection, where the mask is far away from the wafer and proximity, where there is a

small layer of nitrogen purging between the mask and the wafer. There are different aspects of these different processes.

Industrial applications require more approximate lithography or projection lithography, because of a single issue of resist damage while multiple processing steps are incorporated on a laboratory scale. However, contact lithography is preferable because you do not need to develop that costly instrumentation, the number of times you are exposing a wafer may be smaller relative to the high production industrial process. Therefore, in industry - specially in silicon industries - there is a huge demand of optically well aligned projection lithographic systems and they are very expensive because essentially, the optical engineering which goes in for avoiding the diffraction at very small levels is really a matter of precision. That is what cells and it is very expensive.

Contact lithography however, is the most favored process with the research scale and the laboratory scale. This coupled with proximity lithography make of, almost 99 percent of the research level work that can be done using Photolithography.

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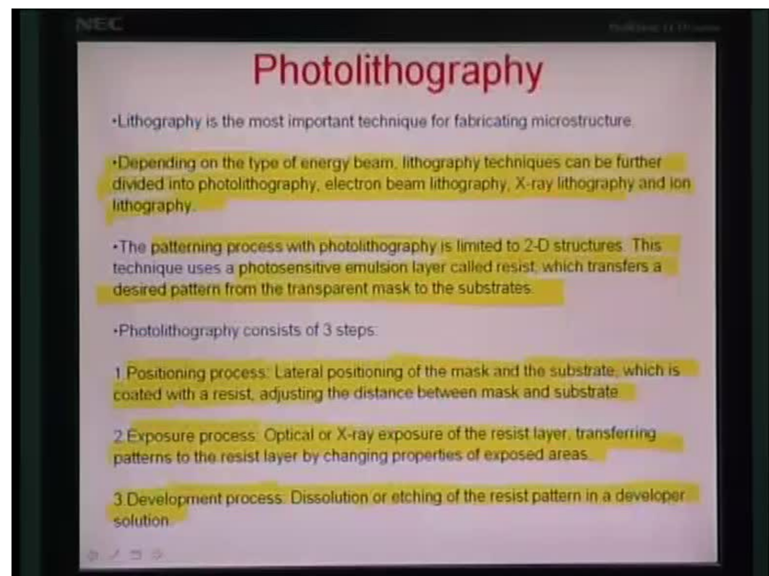

Let us actually look into some of the techniques - these are the take homes. So, depending on the type of energy beam, the lithography techniques can be further divided into photo based, electron based, x-ray based and ion based. The patterning process with

photolithography is limited only 2-D structures - two dimensional structures. It does not go over a certain level on the z direction of the thickness because that is definable by the spin speeds and the viscosity of the solution that you are spinning. So, the layer thickness of the resist which comes up is essentially the maximum thickness up to which these structures can go on the z direction.

It sometimes actually called two and a half d process and the half essentially signifies that you do not have much control on the third dimension. Except, what you have with controlling the speeds at which you are spinning and the viscosity of the material on what you are spinning on the top of the substrate. The technique uses photosensitive emulsion layer called resist which transfers a desired pattern from a transparent mask on to the substrate and consist of three stages. Positioning processes essentially, lateral positioning of the mask and substrate which is coded with the resist, adjusting the distance between the mask and substrate.

Exposure process is a step where optical or x-ray exposure is done to the resist layer and it immediately transfers the pattern to the resist layer by changing properties of the exposed areas, the exposed areas are being sealed and directed through the mask. Then, you have the development process whatever has been exposed is now dissolved and etching of the resist pattern is made in a developer solution.

In one case, where the pattern is the negative tone and cross bonds on exposure the other areas get typically removed away in the other case, where the pattern is on a positive resist the portions which are exposed are cross bond and debonded and they get removed away as vias and trenches essentially, so that is what this is about.

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Let us also look at what is the difference between contact proximity and projection lithography. Essentially, it is a distance at which the mask is placed from the substrate and contact in proximately; they are very close by projection where it is at a high distance for reasons mentioned earlier.

Let us do a numerical example to see what a variation is. Let us say you have a resist layer at the bottom of a 5 micrometer deep channel which has been etched in earlier step using a masking layer, 20 micrometer deep channel is to be patterned on this layer 5 micro meters of resist. The photo resist is exposed to UV light and a 400 nanometer wavelength. So, you have to compare the resolutions at the bottom of the two channels; one, where the depth is 20, another depth is 5 microns.

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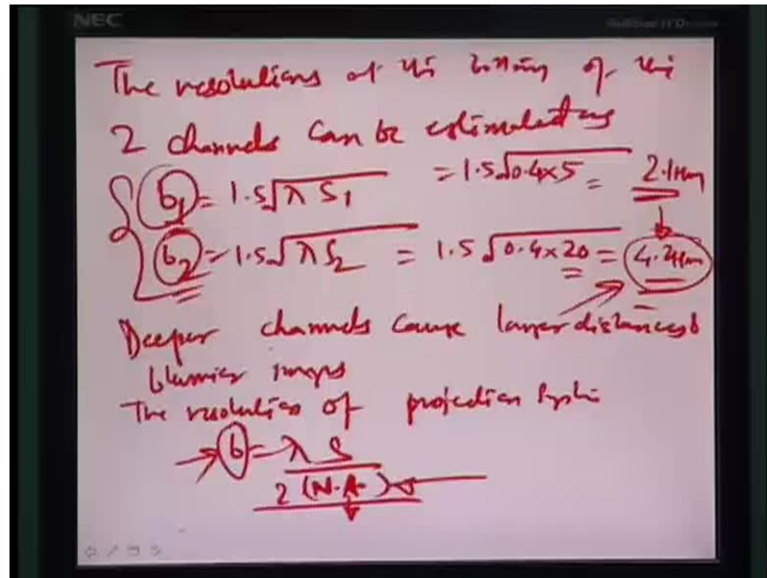

Essentially, what were left with is the following; the resolutions at the bottom of the two channels can be estimated as b 1 and b 2, so b 1 is a relationship mentioned earlier as 1.5 lambda s 1, as 1.5 lambda s 2, so this is 1.5 times of - you have it as 400 nanometers which makes it - 0.4 microns times of 5 microns in one case, another is 0.4 times of 20 microns.

This is 2.1 micrometers, another is 4.2 micrometers and these are the two different resolutions that can be achieved. Just by going about four times more on the depth, you have already lost the resolution by almost 50 percent and you have to only realize a higher minimum feature size by going deep down inside the channel, so this is a potential problem. In Photolithography and in contact lithography, if you go on higher channel depths and try to do resist processing you will always end up with a lower resolution.

This has to be somehow controlled by guiding light in a manner that diffraction does not happen in the whole process of exposure. In a nutshell, deeper channels cause larger distances and effectively they also cause blurrier images means, your resolution is lost because of going deep down. The resolution of a projection system is actually dependent on the lambda as well as s - the distance of mask from the surface - but is also closely dependent on the numerical aperture.

If you control there is another control aspect here, if you have a lower aperture value of course, you need a higher intensity light because lower aperture has lot of energy loss, but then you could actually ensure if this numerical aperture of value is higher, I am sorry, you could ensure that the b reduces because of that. So, there is some control is there in this particular case.

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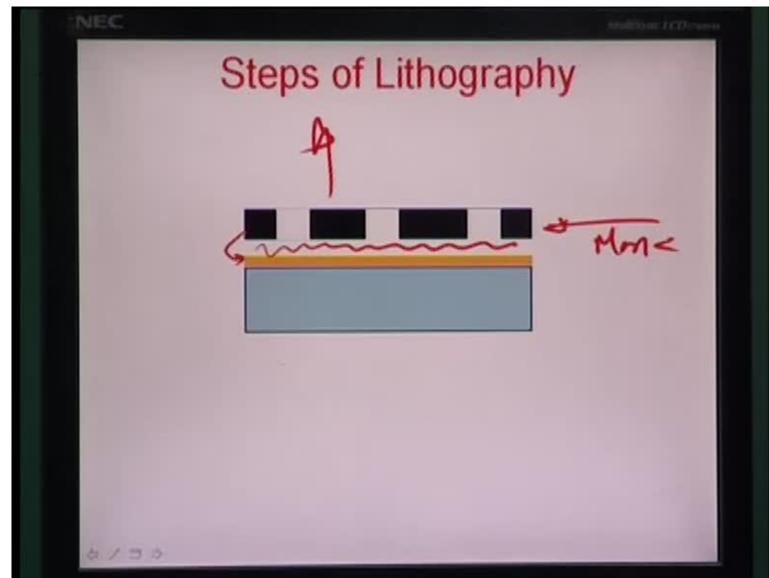

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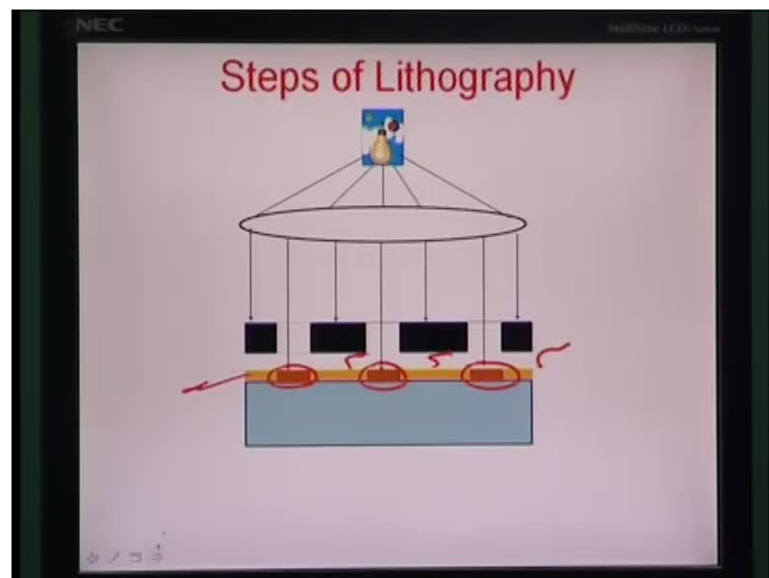

Let us see, what the different steps of lithography are, you have starting with a silicon wafer as you are seeing here (Refer Slide Time: 13:11). This spin code layer of resist,

this is the layer of resist. Then, you basically set to the black and white transparency mask over the resist. In contact mode, you actually contact these two surfaces; proximity you still have a small gap in between and in projection, this would be far away from the normal resist layer.

Then, basically with the lensing and a focusing arrangement, you draw parallel beams of light to fall through this mask onto the wafer and as you are seeing here the light passing through these transparent domains or transparent regions hit onto to the surface. Whereas, once which actually are blocked here due to the black or the opaque portion of the transparency do not travel; effectively, the areas exposed are just below the transparent features and thus the feature on this top of this mask is translated on the top of this resist layer.

In next go naturally because the exposure is selective, you have these zones of different chemical compositions developing in case of negative resists. They are cross bonded; in case of positive resist they are kind of debonded.

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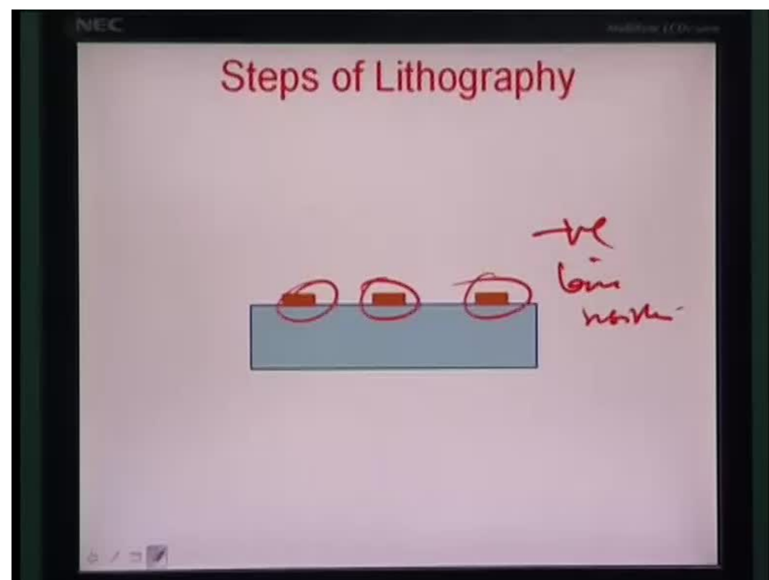

Therefore, if suppose it were a negative resist you could etch off the remaining material away, because they are still debonded with the developer solution and you get these features which were cross bonded and stayed back. So, this is only in case of negative tone resist. The positive resist would behave just in the.

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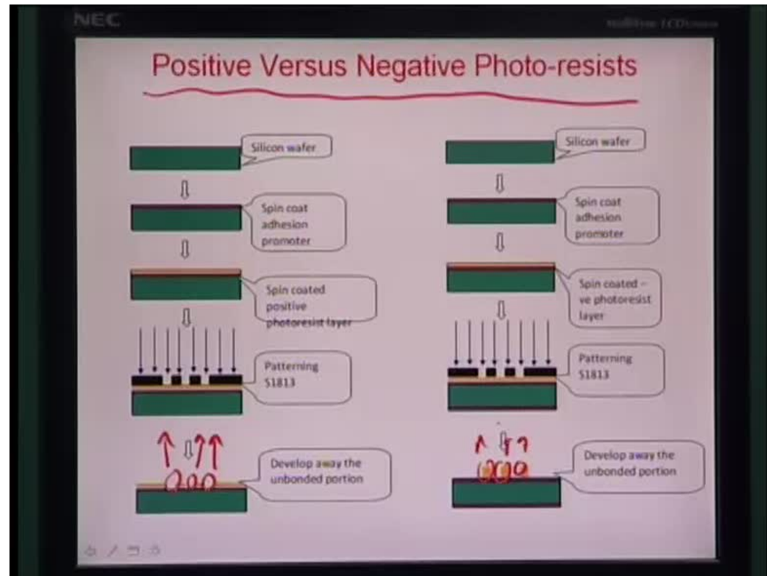

In case of positive verses negative photo-resist the only difference is that in one case, positive resist there is always a taking off of the areas which are exposed because of debonding action. In case of negative resist, they stay back as you can see here because of cross bonding action, that is the only difference between the two different kinds of resists.

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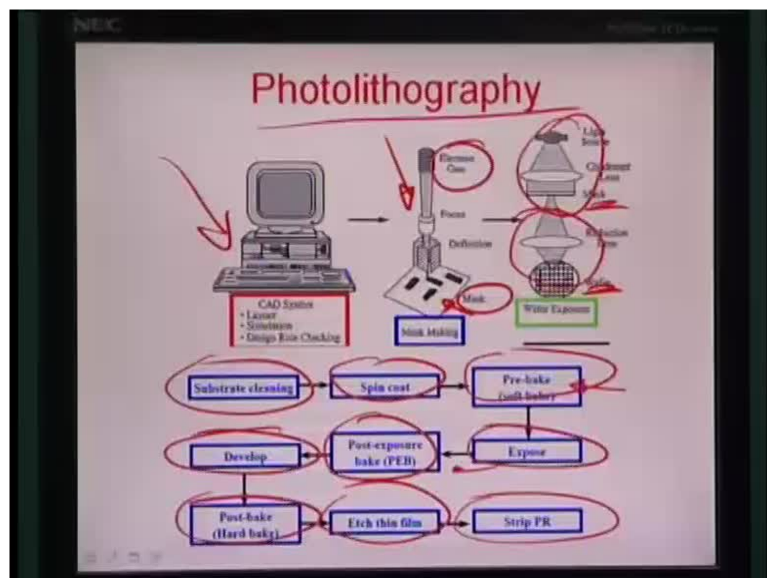

If you look at the process schematic, the photolithography is a process where you need to start with cleaning the substrates thoroughly for better addition of the resist layer, spin

coat a layer of photoresist and emulsion. Essentially, the resist contains solvent phase some of the chemicals which can cross bond or debond on exposure to light by means of something called a photoesic generation.

I am going to look into that aspect little bit later. Once you are spin coding it, the solvent has to be evaporated, so that the resist has a mechanically good strength and you prebake - also call it as soft bake. Then, you expose the prebaked resist to light using masking step.

The post exposure bake is carried out at this stage, so that it catalyzes the way that the resist can set on a surface. Otherwise, if suppose you have just prebaked and exposed, it would take some while for the photoresist to get diffusively to different parts of the resist, where it would create cross bonding action. Exposure however, can be pronounced and catalyzed further by application of heat, because heat actually enhances the diffusion process the way that the photoresist generator would go through.

Therefore, the post exposure bake is highly needed for this kind of situation. Once this is done you actually develop that wherever the photoresist generator has gone which would expose they cross bond or debond and then, you actually post back after the first develop. So, that whatever features are remaining are firmly held onto the surface by again heating - catalyzing process. Then, you can actually do etch, whatever three thin film you want to etch and strip the photoresist, if the photoresist were a chemically sacrificial material that you are using.

Some of these equipments here are used, typically for the lithography you have a CAD based layout planning simulation and designing center, which actually using a laser beam or an electron beam actually writes on the masking material which typically is harder or softer. Soft masks are made using transparencies black and white of a certain resolution but, hard masks which are also used for a better feature sizes or high resolution feature sizes and used in most of the industries are made by a coating of chrome over a glass surface, which is actually laser etched or electron beam etched. Very accurately, precise features of machine onto that small thin layer of chrome and then, the idea is wherever the features go away is used as a transparent part and wherever the chrome remains is used as an opaque part.

Therefore, whatever features are thus realized in this chrome and no chrome region combination is totally translated onto the resist surface. You can use projection systems like one shown here, which has complicated optics to make a streamlined behavior of light, mask here is much away from the photo-resist coated wafer as you could see here.

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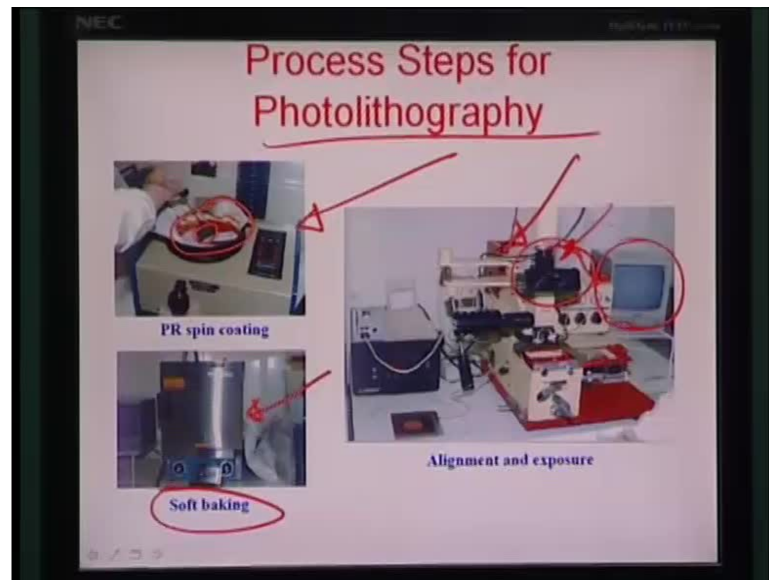

The steps for lithography occur in the following manner. First, two photo-resist pin coding this here shows such a spinner where you are dispensing the photo-resist, this is a small wafer here, which is on the spin table it spins at a very high rate and then, there is a thin layer of photoresist which is created.

Then, do the soft baking process using a laboratory oven which is gravity driven convection oven. You could also use a hot plate at times and it gives more uniformity, specially while doing thick resist processing like photoresist like SU-8, you prefer using a hot plate than a convection oven, for better uniformity of temperature. This is what a mask liner physically looks like, you have an alignment system where there is a mask which is loaded at the top here and the wafer which comes through this folder at the bottom and then you could actually align them using this microscope which is at the top here. This can be used as a video display for whatever the microscope is seeing, there is a CCD camera through which input can go to this video display. Therefore, you could actually do resist processing in this particular manner, where these particular equipments can be used.

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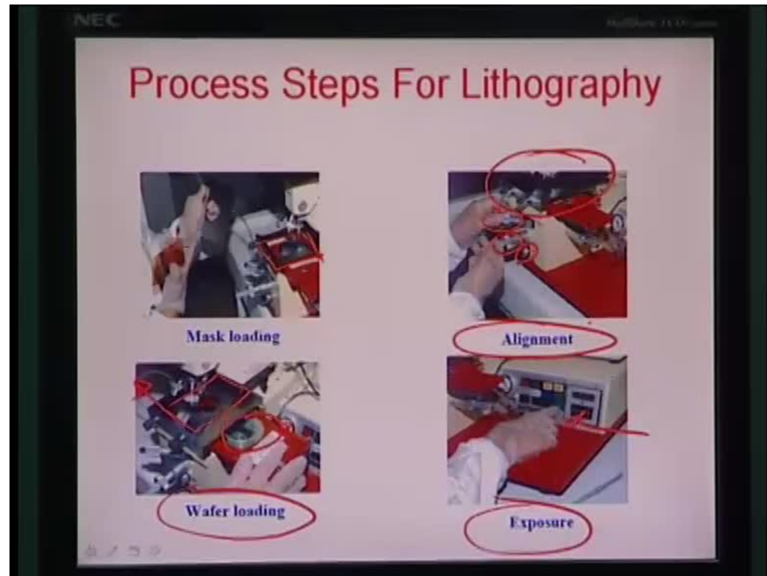

Here, it shows how you are loading the mask, so you essentially load the mask in the first layer of the aligner here. Then, you do alignment and then you do the wafer loading here, as you can see on the lower layer. The mask is here on the top, as you can see here and the wafer comes from the bottom layer. This is the slidable rack which slides in between this particular area where the wafer can come directly in line with the mask process, then you have the alignment done using this microscope aperture.

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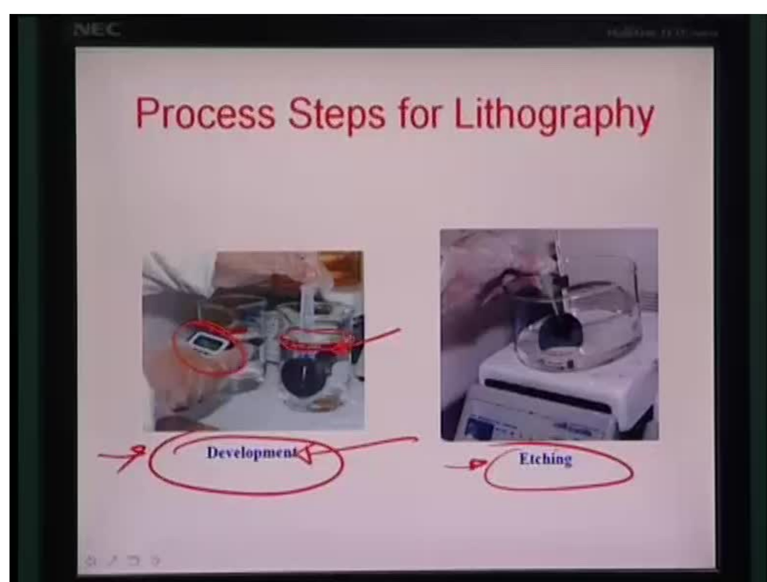

Then, by closely using this x, y, z and rotation table aligning the mask with respect to the wafer and then, you do the flood exposure wherein the shutter opens somewhere at a distant area where there is a light. So, this whole thing is transported further right towards the exposure area. There is certain time and intensity which is preset, density can be calibrated from time to time within laboratory.

Hence, the exposure makes the necessary changes written on to the photoresist surface which after the post exposure bake can be developed essentially using like a tweezer to hold it. Then, continuously circulating this through a photoresist, as you can see in this particular beaker, while time is maintained, you cannot over do on the time part. So, the resist starts coming off and you may have inaccurate feature sizes because of under etching or over etching. Therefore, you have to critically examine the development process and find out the optimum best in any Photolithography. Then, you can use that layer as a masking layer to etch of silicon and then, take off a strip of the photoresist later on.

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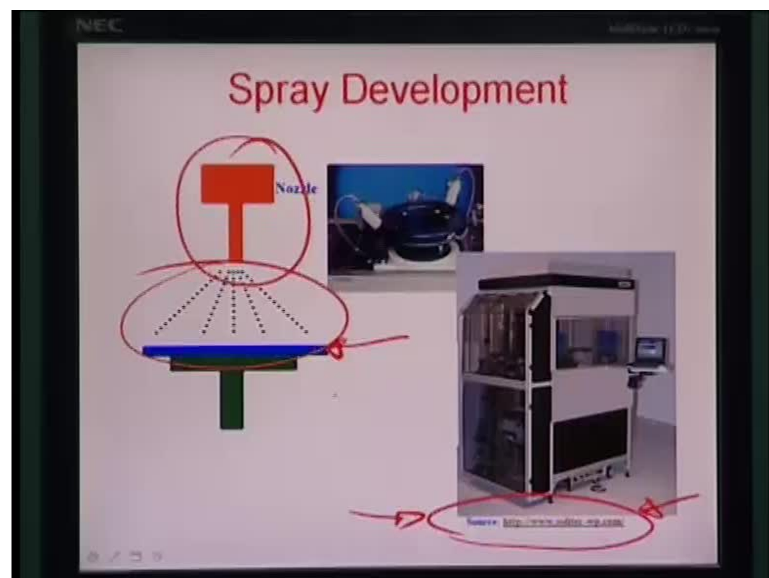

The way that the photoresist is normally applied in industry and this is essentially, something which is a huge automated system for silicon process industries, microelectronic industries - this was borrowed from website on solid tech. Essentially, such a technique would involve nozzle spraying where on a continuous basis as the wafer is automatically handled and mounted over this spin table. The nozzle

automatically sprays the photoresist all round this wafer at a high pressure, so that we could actually spin the wafer simultaneously and control the thickness.

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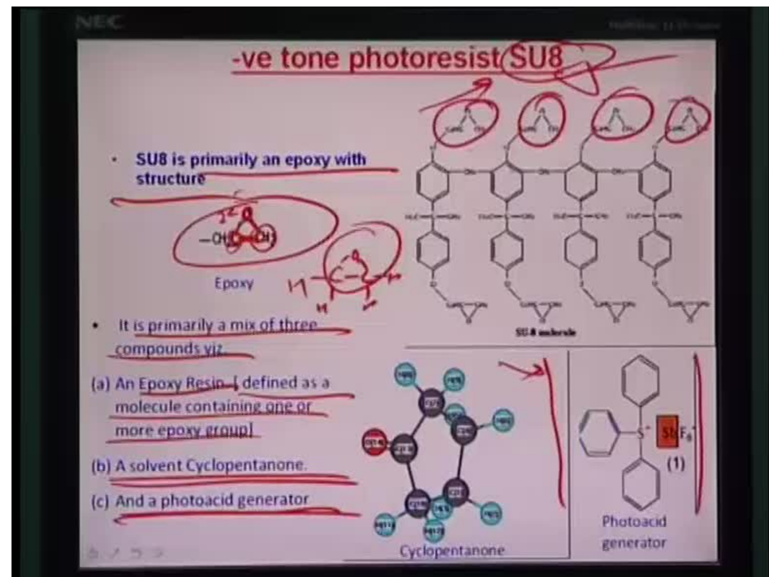

There are some of the illustrations and schematics of how a negative photon photoresist would work. You may also be wondering by now that what is it that causes that the area which is exposed to light to be suddenly becoming sensitive and changing the chemistry or chemical nature. So, I would like to give an example of this particular kind SU8 which is the negative tone resisters you can see here.

It is primarily an epoxy, so the way that the epoxy made is like a C O C bond as you can see here (Refer Slide Time: 22:02). It is a triangular bond with C or carbon sharing two electrons on both sides with the oxygen atom and sharing one electron - its own electron with itself. Basically, you have a case where oxygen which has two electrons here, is sharing one electron with each carbon and there is a bond between the two carbons that is how an epoxy would typically look like, there is a single bond. Then, there is also hydrogen at the other end which satisfies the valency of this particular system.

Now, two hydrogen essentially, you can represent the epoxy more like the following, so you have C H H and C H H on both sides interconnecting O bond. The SU8 primarily is a mix of three such compounds, you have an epoxy resin defined as a molecule containing one or more epoxy groups like you can see here. These are the epoxy resin

materials that are containing more than one molecular group which are like in epoxy C O C kind of bond. You have a solvent cyclopentanone because you have to make it fluid like, so that it can flow and coat over the whole wafer and then, you have a photoacid generator which I am going to explain just about a minute what happens.

This itself is like a photoacid generator, it is a weak acid; it is a lewis acid and it actually protonates on exposure to light, so wherever there is a light exposed to this kind of material, it is certainly formulate into a proton H plus and the remaining compound would becomes negatively charged.

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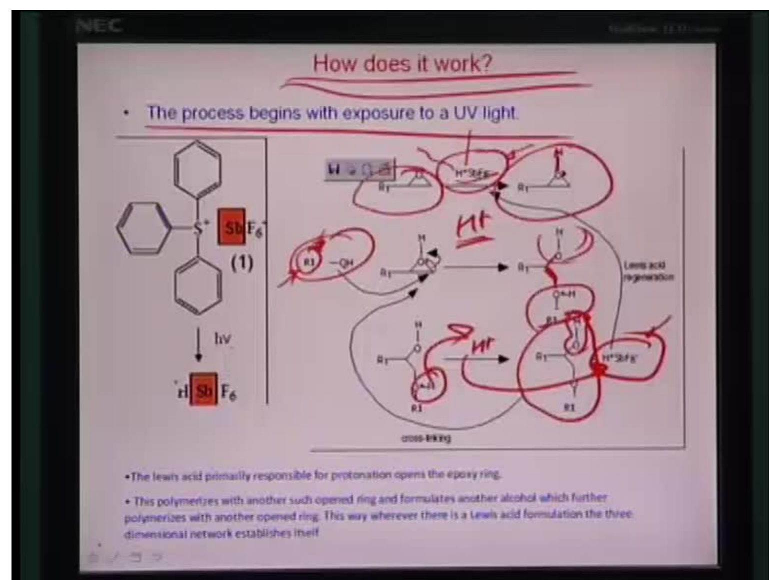

Let us look at what happens to this protein, how does the photo-resist work? If you look at this particular figure here, you can find out the process really begins with an exposure to UV light in certain selective areas. This here is an illustration of the photoacid generator H plus Sb F 6 minus is a demo photo acid generator, on exposure to light it would immediately release the proton and so proton goes and opens up the epoxy chain in the following manner. The first step is carried out by a positive charge on to the oxygen and the hydrogen formulating a bond with the oxygen.

The second stage is maneuvered by the very fact that there are a lot of hydroxides like with R 1 or an alkyl group along with it. So, they are ready to donate the hydroxide and bond this R 1 OH the alcohol which is their along with this particular configuration is a

high energy bond with a positive charge, so this bond opens up. You have R 1 OH with a plus charge on one side and R 1 OH here with no charge. Therefore, this is how the lewis acid giving a proton plus has already formulated or opened up the epoxy ring from a triangular orientation into some kind of double alcohol compound which is formulated here.

In the third step essentially, what happens is that this H plus comes out as a proton and again mixes up with this photo acid generator S plus H plus Sb F 6 minus. So, H plus here or this whole compound here is nothing but a catalyser, it does not participate itself in the reaction, but let the reaction carry forward, opening up the epoxy state which is a very essential intermediate step in this particular reaction.

Once this happens then you are left with a bonded structure like this. Now, you can assume that you have other epoxy rings which are closed by will bond to this kind of a structure because it has an OH group. Therefore, slowly this whole structure is cross bonded and formulated by bonding to each other.

Therefore, wherever light falls and photoacids generate the H plus becomes a lewis acid, it automatically starts the bond on the different epoxies. There is a growth cycle of these bonds happening in all the three dimensions but confined only to the area where the light is tailoring, the photoacid generated to give the hydrogen ion or the H plus but, because it is different division driven process there are problems.

One of the problems is that because you do not have a control on the distribution of this photoacid generator all though it is premixed in a very fine manner, but spinning sometimes lets the photoacid generator moves away from time to time. Therefore, you have to really optimize the exposure time, you have to optimize the exposure intensity, so that whole thickness of the resist is having all these photoacids initiated and generated. The whole thickness is basically having the cross bonded structure available.

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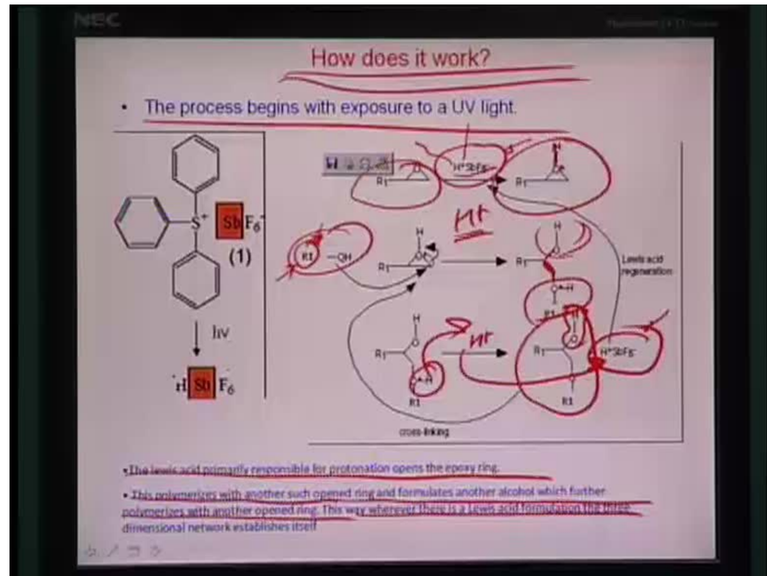

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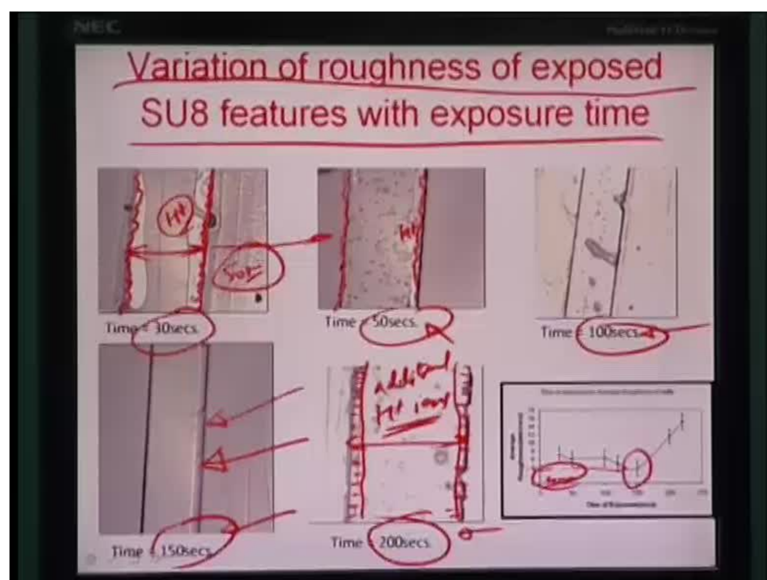

The lewis acid primarily is responsible for protonation, it opens the epoxy ring, polymerizes with another such opened ring and formulates another alcohol it further polymerizes with another open ring. This way wherever there is a lewis acid formulation the three dimensional network establishes itself. Now, I would like to bring your notice to several of these experimental results, which I have personally done during different parts of my research experience.

As you see, this is the time optimization technique that we are having. Basically, we are trying to optimize an exposure time, so we wanted to build up a feature which is about 50 microns thick like this - let us say - this depth here or this width here across is about 50 microns. So, really if you look at different exposure times like 30 seconds, 50 seconds, 100 seconds, 150 seconds and 200 seconds, you see that the edges are slowly turning from curvy to flatter and with the best resolution which is available at 150 seconds.

Now, what happens before is this is definitely the exposure is inadequate to send enough number of hydrogen ions to cross bond. Therefore, this structure here the roughness really eats away into the 50 microns structure, as you can see.

Now, this gets a little better here, because probably the time of exposure was little more, so a little more number of H plus was generated and it could correctly - although not totally correctly - formulate the edge. So, the edge keeps on increasing its straightness as the exposure time is increased, more and more amount of hydrogen ions gets generated. This is the optimum best after which suddenly the reverse effect happens. This in fact is much bigger than it is 200 seconds, it is much bigger than 150 second which is actually equal to about 50 microns. This may be bigger on account of the fact that additional H plus ions are generated here, because you are over exposed the resist material.

The additional ions would diffuse and create a very rough edge in the positive direction that means, this feature size effectively broadens out because of that. Maybe, 150 was just near about this and this is broadened out by several more microns because of additional hydrogen ions which diffusively sneak past the edges of this particular configuration. If you look on the average scale, there is an optimum best of the average roughness which is about as less as about 4 microns or so, beyond it photolithography is not sometimes able to do its job properly even if you are using a hard mask.

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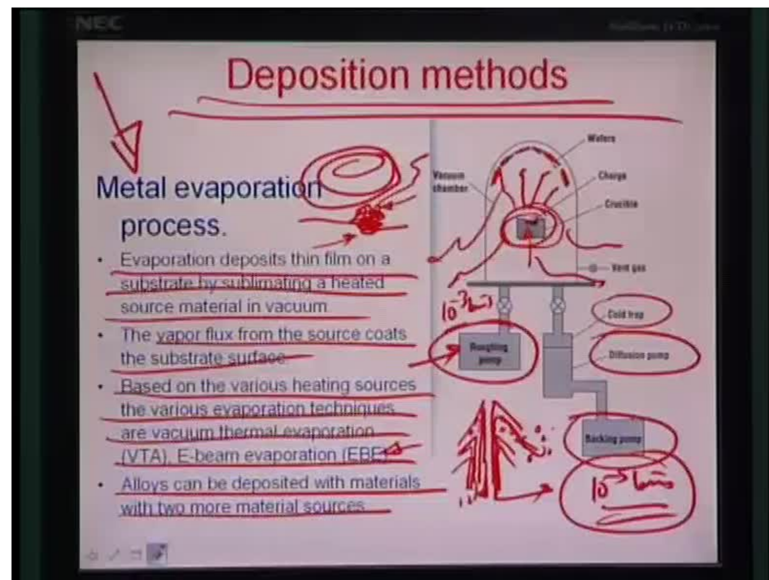

After doing Photolithography in great details, let us actually look at some of the deposition methods and the surface micro machining methods. The first technique which comes to mind is Metal Evaporation Process.

Now, this is a very conventional, a very old age technique where you are actually creating a crucible where you have some metal wires like may be, platinum wires or gold wires or titanium wires or chromium wires. Then you are suddenly evacuating this chamber sending the gases outside this chamber and heating. So, this is actually a wafer holder or a wafer boat, it is made of tungsten and something like this (Refer Slide Time: 30:08). If you look at the overall feature it is something like a small boat like this on both sides, where your tungsten material is kept inside. The wire is kept inside all folded and jumbled, sorry, the material which you are trying to deposit is kept inside.

The tungsten is a very highly resistive or has substantial resistivity and substantially lower on the temperature based resistance variation scale. Also, it can withstand high set temperature values because of its high melting point which is about 3400 degree Celsius. Assuming some of this data, if you have a wire which is of a lower melting point, you can of course, red heat this tungsten wire, so that it is just about a lower to the melting point and still in formulation of a solid structure.

In that case, the heat which is delivered is good enough to evaporate all this material out from the crucible into the atmosphere and this is the high vacuum therefore, there is no chance of contamination. The high vacuum is created essentially by two mechanisms, one is roughing pump which would actually go up to about 10 to the power of minus 3 torrs or so. The remaining would be taken care by this diffusion based pump which has roughly a backing pump and a cold trap.

Essentially, the way the diffusion pump, if it is a oil diffusion pump would work in the following manner. You have this fins at different levels basically both sides of the wafer and you have oil vapours which actually go into this particular area and absorb whatever is there is a high vacuum pull on this direction. The oil vapours which are left here in this area absorbs whatever little bit molecules are leftover in the chamber after the roughing vacuum has been achieved. Takes the absorbed molecules along with it back to the roughing pump, that is the way the oil diffusion pump really works.

Therefore, it can attain a final vacuum level of about 10 to the power minus 5 torrs or so. In this vacuum it is sufficient to create a clean process where there is no oxygen or nitrogen intrusion within the silicon.

The substrates are mounted on the top as you can see, there are series of substrates here which are rounded off, just over the target in the vacuum chamber. These wafers are deposited with the metal on the top and you can do a sacrificial layer in photolithography, so that the deposition gets in a normal way. The evaporation deposits a thin film on the substrate by sublimating a heated source material in vacuum. The vapour flux from the source coats the substrate surface, based on the various heating sources various evaporation techniques are vacuum thermal evaporation. You have another technique called E-beam evaporation, where the same process is done by heating this with an electron beam. So, you have a high voltage electron beam which is pumped at a high energy onto this target material.

It sputters off the target, vacuum or vapours are created within the vacuum in which all this process happens and it goes and fizzes off on the surface of the wafer. Then, there can be other techniques or other means of heating for depositing the vapour of the metal on the top of a silicon substrate. You can also deposit alloys using this or using two or more materials conveniently in a certain ratio. In this case, it may be a wire made up of

alloy or may be just by percentage weight you could do the two metals as globules and put it inside the crucible and then evaporate them together. But then, it will also be a function of the relative melting points of the two metals which one floats earlier and which one melts earlier and vaporizes earlier, which one vaporizes later.

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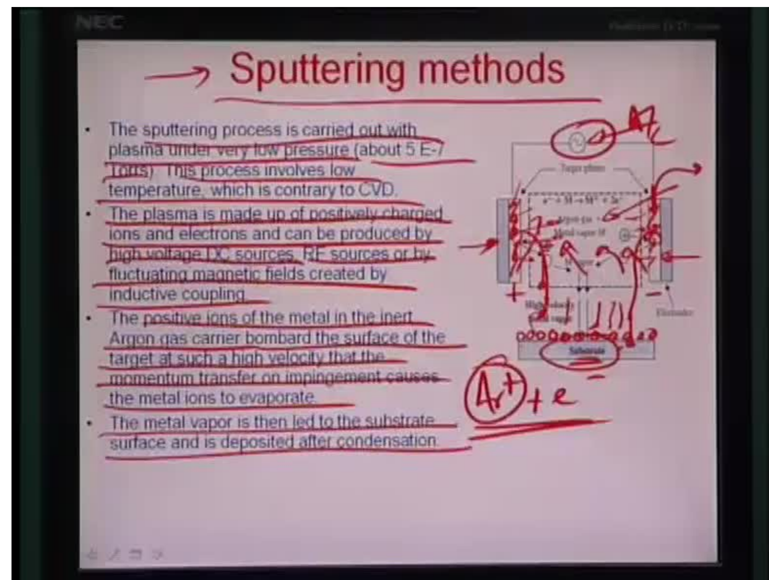

The idea is to quickly go to a temperature in that case, where both the phases are vaporized. One is more vaporized based on the fact that you have a lower amount of melting points that ratio would be maintained. Another very popular deposition technique is sputtering based deposition technique which is actually a plasma driven process. Here, in this particular illustration as for example, the sputtering process is carried out with the plasma under low pressure of as low as about 5, 10 to the power minus 7 torrs.

This process involves low temperature which is contrary to CVD, plasma really is the state of ions and electrons. Here, what happens is you having these two electrodes which are also responsible for generating the plasma, you pump in argon in this type of space here which is at a certain pressure. The argon generates argon ions and electrons as you can see here and then, you actually drive the argon ions to the substrate as you can see here. Both the target plates are kept on both sides as in this particular case. Then, this particular electrons and argon ions which are generated are slowly, if you to put a bias on to the system such that this plate is made positive and this is made negative (Refer Slide

Time: 34:50). The positive ions would hit this target and the negative electrons would hit this target; let us suppose, we drained electrons away, so the positive ion as you can see the bias is outside here - the AC bias.

So that the positive plate changes between both time to time in when if it is an AC bias. If it is a DC bias it will only be positive over one and negative over another but, whatever happens brings a substantial amount of ionic momentum on both the plates. Thus, physically up-plating the material off, so if this target is platinum or gold it will update the platinum or gold materials or atoms off the surface and then the carrier gas would essentially drive this more towards the substrate, which can be given a slight bias, so that you can hit with the carrier gas the material onto the substrate of the electrodes.

The gas is too evanescent to escape but, the material once deposited would be embedded onto the substrate surface and it has high energy impact based on what this bias voltage can be really made. Therefore, this is another way of transporting material from these substrates on both ends, onto the surface of this substrate material. In a nutshell the plasma is made up of positively charged ions and electrons can be produced by high voltage DC sources.

RF sources or a fluctuating magnetic field is created by inductive coupling. The positive ions of the metals and in the inert gas or in argon gas carrier bombard the surface of the target at such a high velocity that the momentum transfer of on impingement causes the metal ions to evaporate. The metal vapor is then led to the substrate surface and is deposited after condensation.

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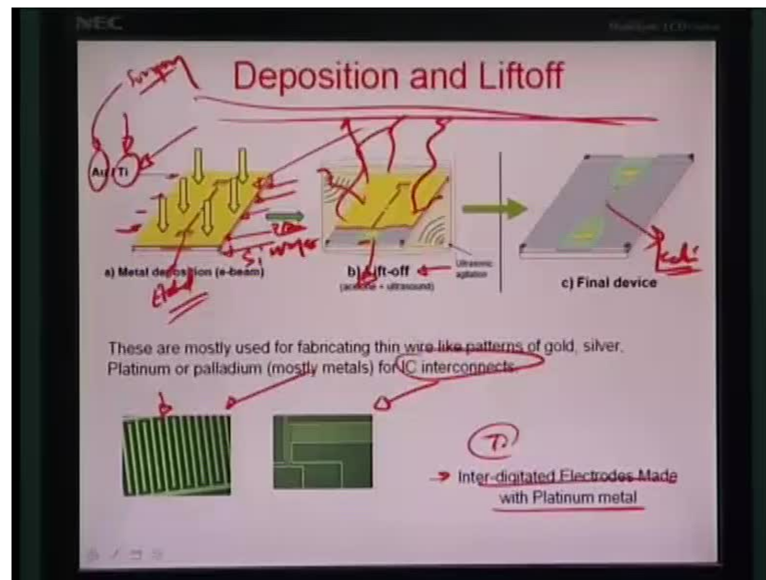

After doing these sputtering methods, let us briefly discuss what these can be - the E-beam evaporation or the vacuum evaporation of sputtering can be used for. So, the best way of using them in micro electronics or mems is deposition are left off. Basically, metal circuits or metal conduits are fitted within or over a sacrificial mask made up of positive tone resists.

Here, for instance one example, you have a silicon wafer at the bottom which is coated with a layer of photoresist which is this layer here - which is slightly red. So, this is the positive term photoresist on, a selective feature is etched by photolithography and developing process. Now, you are exposing this first to a vapors of titanium and then, followed by vapors of gold.

You have to really be careful in this about the interlayer adhesion. If you are depositing something like gold you may have to use either titanium or chromium layer for building an intermediate, which can bond effectively to the silicon dioxide on one side and the gold or the parent metal that you want to deposit finely on the other side. So, it creates a ligand kind of system or framework to retain a good adhesion between the deposited film and the surface. You have something like an intermediate layer and this layer does not go really above a few 10's of nano meters about 10 to 20 nano meters and then, this layer can go as high as about 500 nano meters or so.

Of course, it is very thick beyond that you need to use electro plating methods, because the rate of deposition is very small and you should not cross a limit where the photoresist surface can be damaged. Once, both these are evaporated and this can be found out from this yellow line here (Refer Slide Time: 39:15). The areas which have trenches or vias have these deposit on them and then, you can remove the resist layer and you can expose this metal deposition on the top of this etched surface of silicon and this method is known as lift off.

So, whatever photoresist here can be literally etched using some kind of solution like acetone etcetera. However, the portions which are adhered more firmly onto the silicon substrate remains and the other layers of the photoresist go off, because of the development, this process is known as lift off. Finally, you are left with a feature or a conduit made up of a metal on the silicon wafer.

You have an etching process followed by a deposition and lift off process here. Let me show you some of the examples like for example, this essentially is except from my previous work where we are showing a set of inter-digitated electrodes made with platinum metal with a titanium interlayer in between, so this can be mostly used for IC interconnects. In this case, it is used for bio-mems devices as I will be discussing later in the part, where I will be doing a discussion of the research area essentially.

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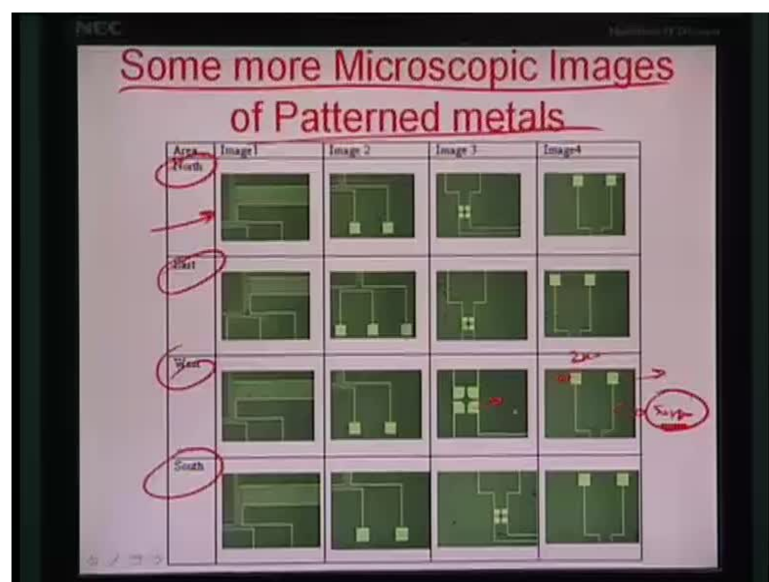

These are some more microscopic images of patterned metals, as you can see and this has been characterized under a microscope. The terms here north, east, west, south is really indicative of what portion of the wafer we have taken these photographs and they have been photographed or imaged in different areas. You can see that the quality of the deposition process essentially is just replicating what feature was there on the masking surface. Essentially, this finest line here is of size about close to 50 microns or so.

That is how small this feature is and this is close to about 2mm by 2mm essentially. This is how you can use successful deposition and lift off to realize any kind of patterns or features onto the surface.

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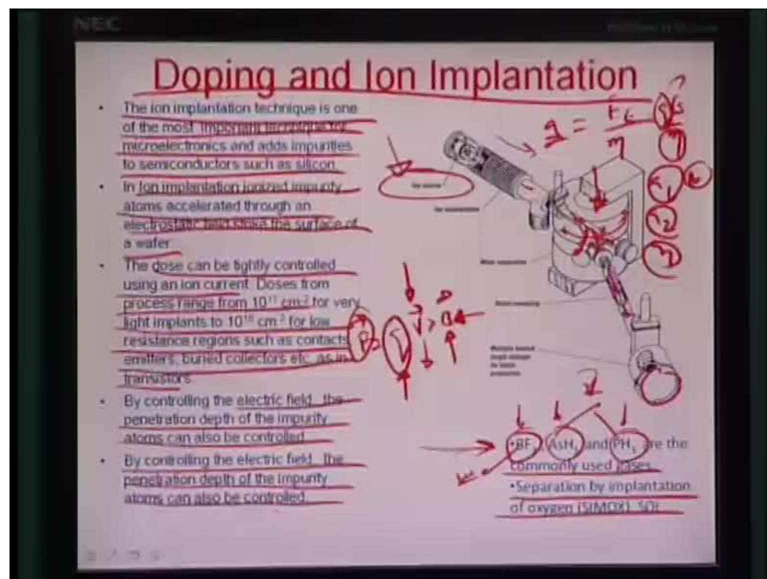

Let us talk about another new area which is related to how you can introduce defects which can be group 3 or group 4 insight silicon materials, this is also known as doping and ion implantation. Why is it needed is because as you know, the semiconductor can be P or N type based on whether the metal belongs or the dopant belongs to the group 5.

You have an excess electron that it can share with silicon apart from its regular 4. If it is to group 3 you have an excess hole which is a divide of electron which is a vacancy. Essentially, the electron hops between the first to the second atom the vacancy shifts in the opposite direction that is how you look at it. So, one is the P type, one is the N type;

N type being the group 5 doped matrix and group p type being the other way that is group 3 doped matrices.

How you do the deep doping is essentially through using something called an ion implanter. Here, essentially there is an ion source which can generate from a gas phase a beam of positive ions typically and then they are accelerated through an electric field. It reaches this coil here which is magnetic coil and it can actually - based on Lawrence forces - deviates this into different tracks. If you are essentially looking at may be several ions coming together, they have different forces that they feel on each other based on q times of V cross B - this is the Lawrence force (Refer Slide Time: 42:47).

Essentially, q is the charge on the ion, V is the velocity of the ion, B is the direction of the magnetic field. Assuming the velocity, the B remains constant and the magnetic field remains constant and velocities are different. Essentially, when you are accelerating an ion of a heavier atom or a small or a lighter atom under same electric field, the accelerations started again may be different which is essentially the electric force FE divided by the mass of the ion. So, this is essentially q times of e times of mass of the ion.

If your charges are same and the masses are different, so the accelerations could be varied a 1, a 2, a 3, so on and so forth. If the accelerations are different the velocity is that these attain at a particular instance of time will also be all different. Therefore, assuming there is an ion flux coming out of this chamber this electrical chamber here, with the high electric field and coming on to this magnetic field, you have different values of V and so, you will have different deflection forces (Refer Slide Time: 44:07).

You can actually split up ions based on that and the heavier the ion is the lesser it will deflect. The lighter the ion is the more it will deflect, but the idea is then you can actually separate ions on the basis of sizes and you can have a particular ion go passed at this tube which has the target at the very end here. This whole system is carried in vacuum and this target is kind of implanted with the particular ion which is filted off this magnetic field using Lawrence force.

Therefore, the ion implantation technique is one of most important techniques for microelectronics adds impurities, the semi-conductor in a nutshell. In ion implantation

ionize impurity or atoms are accelerated through an electro static field and strike the surface of a wafer. Dose can be tightly controlled using ion currents and doses from process ranges from 10 to the power 11 per centimeter square for very light implants to about 10 to the power 16 per centimeter square for low resistance region such as contacts, emitters, buried collectors, etcetera - as popularly done in transistors.

By controlling the electric field the penetration depth of the impurity atom can also be controlled. You can see up to what extent you want to make it into a p plus or a p double plus applicable plus or a n minus a, so on so forth. By controlling the electric field the penetration depth of the impurity atoms can be made smaller or bigger. You have also the gas phases which are used typically for these purposes like a trifluoro borain, this is arsenic hydride and this is phosphine hydride, phosphine or phosphorous hydride. These two as you know are group 5, this is group 3 (Refer Slide Time: 45:55).

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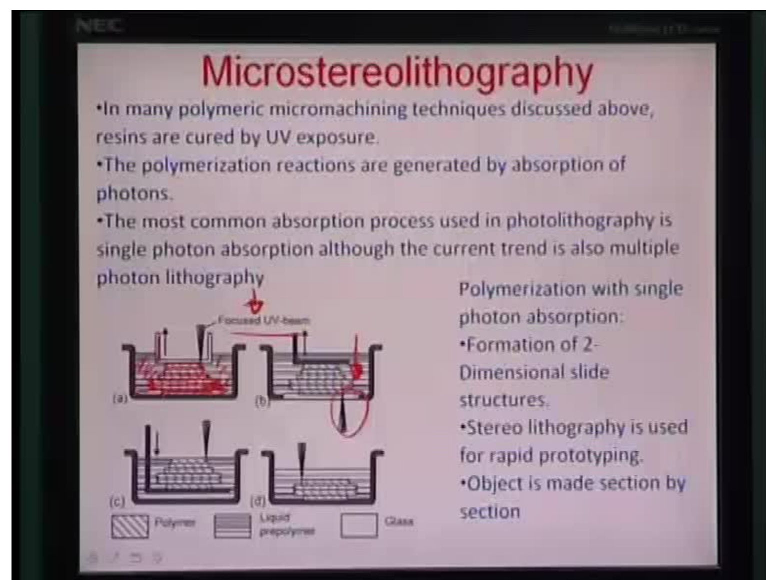

Essentially, they are commonly used gasses for both P and N type impurities separation by implantation of oxygen can also create what you call as silicon metal oxide features - simox features - or SOI silicon on insulator wafers. So, this is how the doping and the ion implantation process really goes. Let me also talk a little bit about very novel and a very interesting process called Microstereolithography which has been translated very effectively to build three dimensional microstructures especially by groups of at u c or so.

This particular technique microstereolithography is also based on section by section three dimensional writing. For those who were already aware of the process of rapid prototyping, the RP machine were developed with an intention of really making a complicated geometry.

Let us suppose, you want to make a mold for something like the femur bone of a particular animal or may be human beings. Normally, such an irregular shape is very hard to machine. What people formulated was, RP or Rapid Prototyping where this bone structure is taken on a CAD drawing. Then, it is sectioned into thin pieces or thin sections and each section is made thin to an extent, so it is a uniform cross sectional area. There is not much of depth involved in that and then a polymer melt is essentially used to write.

Therefore, this spray of polymer is done in a manner that this polymer melt is used to write over a surface in a manner that layer by layer, the whole shape can get built up. Then, there is some kind of melting where the glass transition temperature would be reached and then some fine polishing is done for the final feature to be realized. It can really generate very good three dimensional features with great accuracy and precision. If you could really traverse the nozzle head in a exact parity with the CAD drawings - section by section CAD drawings - so that is what the RP technique normally does rapid prototyping.

Stereo lithography or microstereolithography is exactly replica of that process, its only fact is the medium that in which you are actually writing it is a based on photo resist, you are exposing the photoresist and trying to simultaneously cross bond the material as you keep writing layer by layer.

Here, for instance is an example, where Photolithography this microstereolithography is done. As you see here, there are two ways of doing it. Microstereolithography can be categorized into single photon or two photon type of lithography were you have slightly different nature of these processes based on their exposure methodology.

Here, as you seeing this is a plate which is actually moving from the very bottom of this liquid resist here, this is actually all liquid resist and it is going towards the top. The UV beam which is used to write on the top of the resist is focused in a manner that it goes to

various focal depths. In one instance it is focusing on to this surface in the next instance, it will be focusing on maybe a little bit down, the next instance further down, next instance further down and so on so forth.

The beam essentially is being focused at different regions of depths within the liquid resists. As this writing process continues - let us say - this is the first section of the overall feature. So, you are actually putting this plate very close to this feature and then starting to proton write or UV write on the top of this, so that you have cross bonded this area. The plate moves a little bit further up here, so the idea is that the resist which is not bonded and around it flows because of hydrostatic pressure in this region. Once it is completely filled, you again write this other part - the second cross section - on the top of it, when you write another cross section on the top of it and so on so forth, you actually come towards the end and the whole feature is realized into several blocks of different sections of the feature.

Now, you can also use the same technique by putting the laser beam in the opposite direction and start writing more in the top down manner. You go selectively from top end to the bottom end as you can see in this particular illustration here. The idea is that you are actually writing whatever feature you want to write by sectioning into thin pieces and the writing exactly along. So, the laser head which actually focuses the light also is the CAD defined - the path is defined by the CAD package. The cross sectional area that you are defining onto the microstereolithography system by the CAD package.

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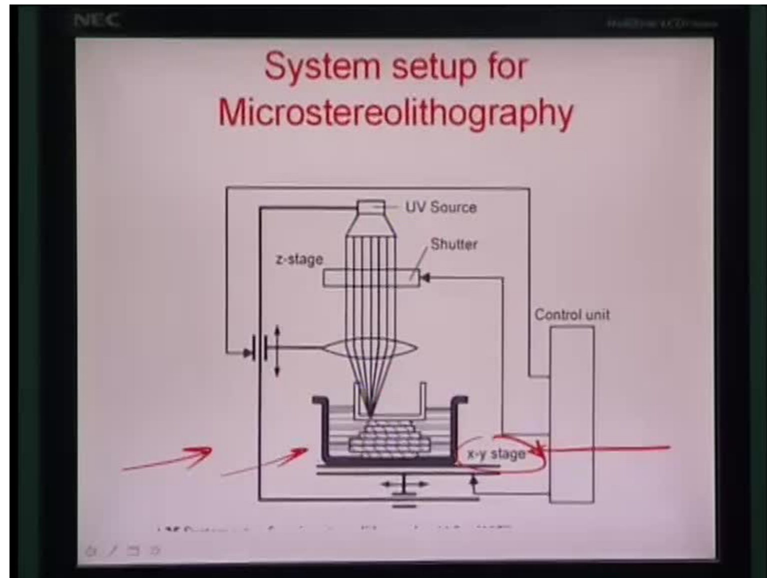

If you want to increase the throughput of the process, this is typically how it would look like. Therefore, there is also a motion of the x, y, z stage which is containing this resist which actually ensures that whatever two dimensional features you are wanting to imprint on, the surface is getting imprinted because of this x y motion. The control unit also controls the UV source and the focusing arrangement, z stage for that and the x, y, z stage parallel and this all is defined by layer programming that is made onto the CAD package to realize the complicated shape.

You can make this process high throughput; typically this mechanism is a very low throughput process because you have to generate so many different features one at a time. As you know, in the micro world the feature density is really very high, so you may have to independently write all the features in this kind of a process and it becomes extremely time consuming or very low throughput one.

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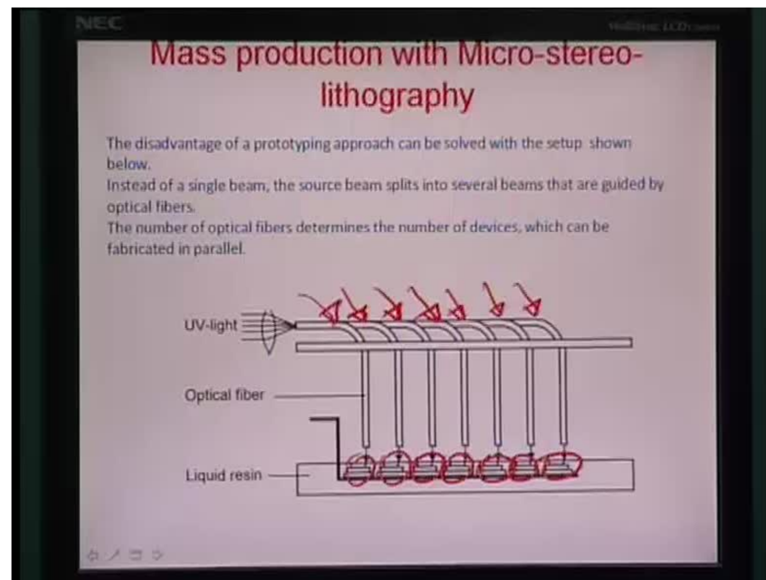

People have used other methodologies including some things like this where you have multiple fibers as you are seeing which takes the light onto different places where you can write all at a glance - all at once. You can parallel write many features instead of one. Another very interesting mechanism that a group of UA UC had actually developed is by introducing something called a Digital Micro-Mirror Device DMD or a projector to use the light or shine the light onto a microscope by defining a digital image onto the projector.

The idea is, the mirrors will turn on and off the pixels and then only a portion which would be corresponding to the whole feature would glow up together and this can be translated down to do stereo lithography and that way very fine three dimensional features can be resolved at a very fast rate, because of this Digital Micro-Mirror Device. So, various intelligent processing techniques have been used to modify the microstereolithography process, so that you can actually develop lot of interesting microscale features on the surface.

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Let us look at some other processes - some other micro fabrication techniques - for instance is thermal oxidation. It is basically used whenever you want to develop insulating oxide layers onto the top of silicon wafers, particularly for doing a proper installation bed or providing a proper insulated bed for electrode layout. Like for example, the inter-digitated electrodes that you saw in the earlier example in sputtering were made over a silicon dioxide surface which was thermally grown.

Now, thermal growth of oxide is essentially a diffusion process, so the silicon dioxide grows at the cost of pure silicon. Pure silicon essentially, the oxygen ion diffuses through the lattice or creates an oxide layer because of diffusion. You have a thinning down of the overall pure silicon and a thickening of the silicon dioxide or the wet oxide in the top. Silicon dioxide is deposited with CVD or thermal oxidation, so there are two different kinds of oxides; one is a dry oxide which is essentially done by heating the oxygen at a temperature of 800 to 1200 degree Celsius.

You can also carry the oxidation process by wet oxides where in, you have the gas or the oxygen passed through or bubbled through heated water, which moistens. The temperature required also is the same, but in this case the oxidation is much faster and the wet oxides typically grow in much lesser time in comparison to the dry oxide.

If you see here in the figure, you can actually find out that there is this set of resistance heaters on both sides. This is a quartz tube where you have a gas supply which can be wet oxygen or dry oxygen and this is going towards the vent side. So, the gas inlet is from the left end here, the gas outlet is from the vent end. This essentially is the wafer boat it is also made up of quartz and these aligned wafers on the top of this particular illustration here (Refer Slide Time: 55:18).

As you heat this wafer to certain surface there is always a thermal motion or movement of the atoms on the surface and then you flow oxygen, so there is a rapid capture of oxygen moieties over the whole surface which develops finally, the oxides.

There are different models to explain the different growth kinetics of oxygen, which I am not going to look into at this time; however, we are towards the end of this lecture. Next time onwards, we will just talk a little more about micro fabrication and some of the process which are left over today. Like how plasmas can be generated or how gas plasmas can be used to modify surfaces including etching and then, chemical modification so on so forth.

With this, I would like to close the lecture. The final lecture would on the basis of some research papers which have been done earlier, based on some of the concepts that we have illustrated throughout the length of this course, thank you.