Microsystem Fabrication with Advanced Manufacturing Techniques
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Lecture – 5

Welcome back. So, today we will be talking on this polymer processing, with some details of how polymers are fabricated. And this would be followed by again some basics of gas plasmas and how you can use gas plasmas to fabricate microsystems.

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Review of Previous Lecture

- Isotropic etching and etchants.
- Etch Selectivity.
- Physical Dry Etching, Chemical Dry Etching, Physico-chemical dry etching.
- Photolithography basic process and contact, proximity and projection lithography processes.
- +ve and –ve tone photoresists.
- Polymer MEMS
- Soft Lithography, Compression Molding and Injet printing

So, let us do quick recap of what we did in the last lecture, we talked about various etchants and isotropic homogeneous etching, technique. We mentioned about etch selectivity and selective layers, we also briefly talked about physical dry etching, chemical dry etching, physical chemical dry etching, were use of plasma as would in hands directionality on an isotropocity, of the etching process.

We also described photolithography is a basic process of mask aligning with the wafer, which is coated with the photoresist and then we described their in different types of lithography like: contact, proximity, and projection lithography processes. We discussed about positive and negative tone for photoresist. And how they would cross bound in 1 case, in the case of negative and debond, in the case of positive to basically create features and structures on the surface.

We also described polymer mems and then talked about systems like: soft lithography, compression molding, inject printing so on so forth. And then we have just about started with application and molding process, which we kind of illustrated as the mother process for all these soft lithography techniques ok.

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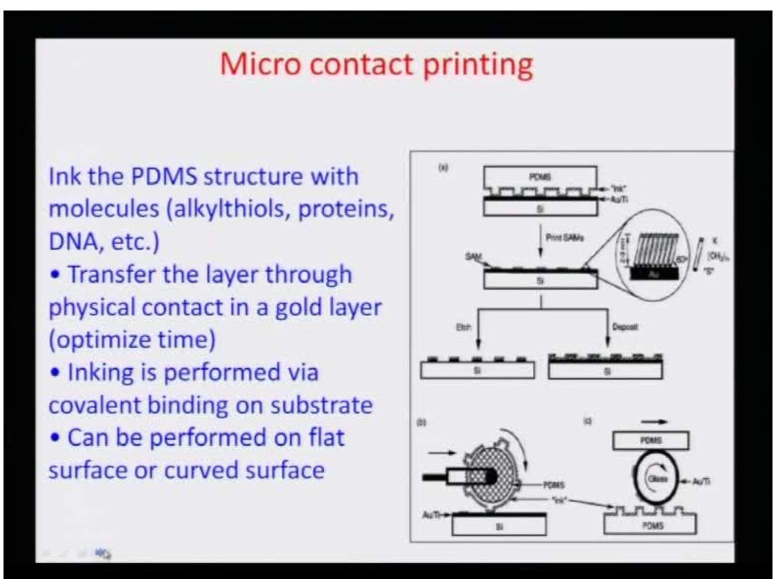

So, we will now start with some other soft lithography techniques, which we come from the same replication and molding technique and. So, first technique which is of lot of prominence is micro contact printing. Now here, the basic process is somewhat similar to inking or stamping. So, in a stamp typically what happens is that, there is sheet of paper and then you have a stamp pad and you have a rubber stamp.

So, you basically take the stamp and take the ink from the stamp pad and print it on to the surface in question. While printing what happens is that, the capillary action of the paper dries the ink from the surface of the stamp on to the paper itself. So, this is a normal stamping process, if I can actually miniaturize this whole activity on to a scale where we are talking only about a few micron by few micron.

Let us say 10 micron by 10 micron features. And then instead of ink we have a way to print molecules and this can also be very important bases of making diagnostic assess like: protein micro arise or DNA arise. Let us look at this very important technique of micro conduct printing which can be used for making or realizing such prints or stamps

and stamping process there in. So, the process starts with step a here, where you can see that this is a piece of PDMS which has been replicated and molded.

So, with the power of photo lithography you can go very-very small up to 10 micron into 10 micron size features can be produced in the PDMS. And then this PDMS surface is actually inked up and this ink can be something like: self assembled mono layer, alkanethiols, proteins, DNA so on so forth. So, whatever molecule you would like to ink on you first ink on the PDMS surface.

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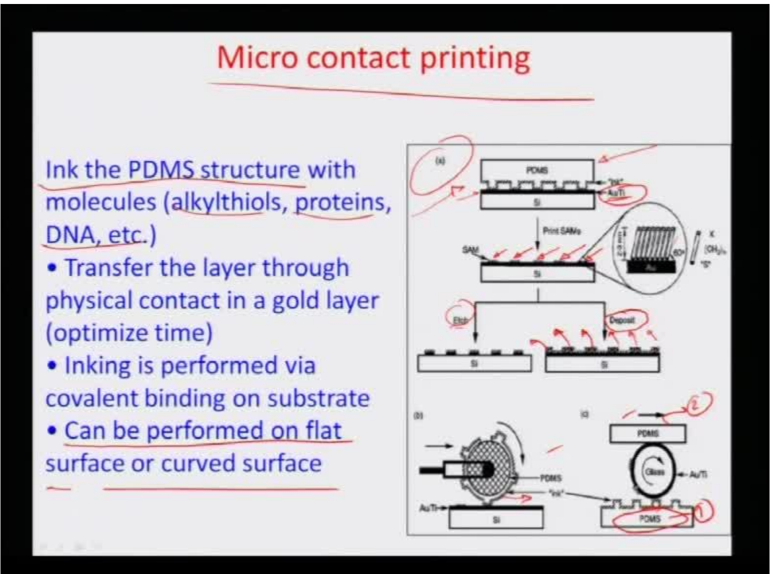

So, once this is inked up the PDMS surface can be pressed and held against a layer, which is actually a layer which is the receipt receiver layer like just like the photo the just like the paper in case of stamping for example. So, in this particular case let us say you have a gold titanium layer, which is the receiving layer. So, there is a transfer layer which is represented by these hatched lines which is actually the layer of the molecules and then there is a receiving layer at the bottom here, which is a gold titanium made layer at the bottom.

So, the idea is that the stamp is made in contact with the receiver layer. And there is sufficient amount of time, you know which is given for the reaction kinetics to happen and the molecules transfer from this PDMS surface on to this gold surface by the virtue of absorption kinetics. So, if sufficient time can be allowed here, the rate of kinetics the

rate kinetics striven absorption of the molecules would happen and molecules get subsequently transferred from the PDMS stamp on to this thin layer or thin film.

So, you can look at these for example: alkanethiols, self assembled mono layers being transferred from these stamp as small heaps or small places the blow up view of this is here and you can see that these are about closed to 2 point 3 millimeters in height; it is an angle of 60 degrees. And you know it is a sought of self assembled monolayer. So, there is an assembly regular assembly of this structure illustrated here.

So, therefore, this is a transfer technique of sams on to the gold layer. You could actually again you know selectively etch out on this layer or even depositon this layer collectively. So, that you have various orientations, where in this particular case you may have etched off the gold films at the places, where the sams are not sticking. So, the sams can be made as a h protective layer here and the remaining portion of the gold film can be exposed to an etchant. The etchant does not affect the gold layer underneath the sam and wherever, the sam is present it gets protected.

So, you have you know steps of gold or heaps of gold protected by the sams and the remaining gold, which was exposed earlier taken off. Simultaneously you can also deposit layers on the top of this and the idea is the sams can be removed later on. So, therefore, whatever you know it is a sacrificial mask of sams on the top of this gold layer and the remaining portion you deposit and remove the sams later on. So, that you have only selective areas which are coated with a deposit.

So, you can use them as various masking strategies and steps for masking at the nano scale. Typically this process has been linearized process, but then many intelligent modifications have been made for example, in this particular case the throughput of the processes can be increased by coating the sams in a circular cylinder rather than a straight surface and then rotating the cylinder every time.

So, that it walks over this wafer containing the gold, titanium, film. And it keeps on creating a big array of these molecules and the molecules can be fed every time it moves through or rotates through the gold, titanium layer. Similarly, you can also have another you know a transfer of layer of molecule from this PDMS1 here, to the PDMS2 surface by means of a suitably rotating gas cylinders; which takes up the molecule from this PDMS layer and transfers it to this PDMS layer.

So, you can use these intelligent techniques, for high through put patterning of various layers using this micro contact printing. So, typically you know it can be performed on both flat and curved surface as been illustrated in these examples: b and c. So, that is another very high utility process or micro contact printing, which is used for you know it is1 of the soft lithography techniques for printing of molecules at a very high dissolution.

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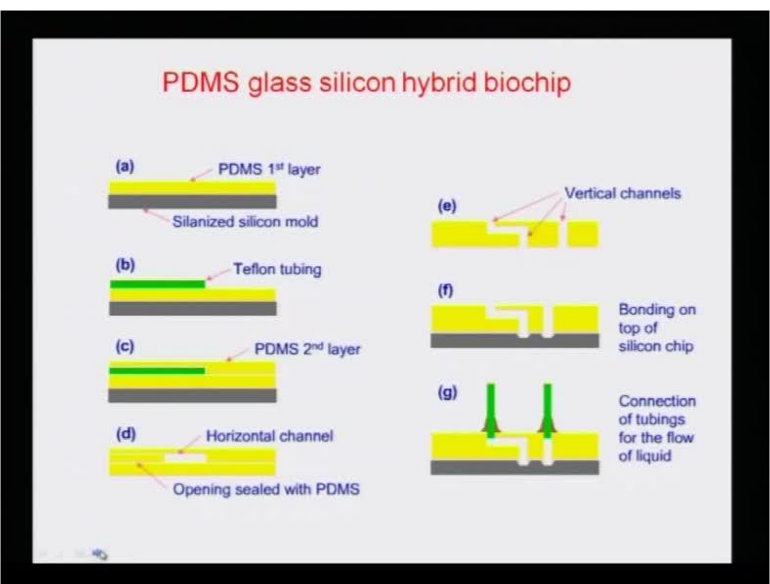

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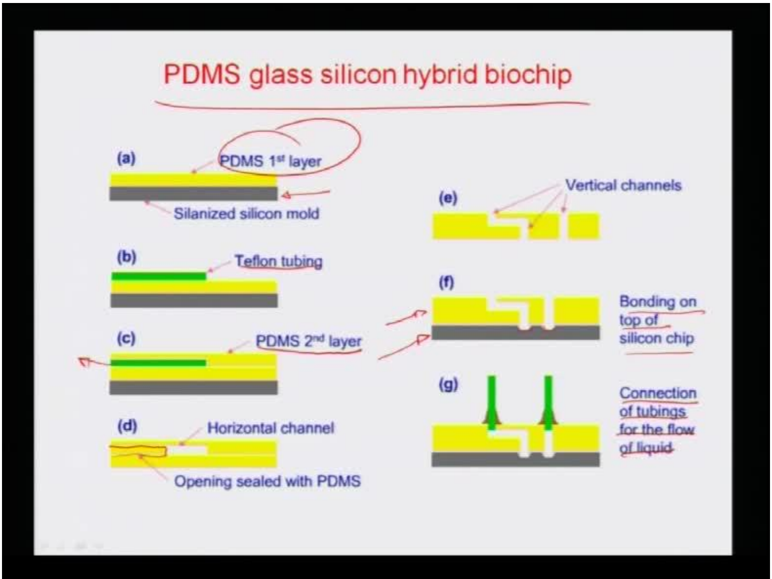

The other process that I would be interested is basically you know another replication and molding technique where you can actually make a hybrid bio device. So, for

example, in this particular case you can see there is a PDMS first layer which has been deposited on the top of the silanized silicon mold. And then you can have a Teflon tubing which has been inserted in covering a certain region of this particular you know PDMS coated silanized silicon mold.

Then there is a another layer of PDMS or second layer of PDMS; which is actually poured on the top of this layer of Teflon mounted over the lower layer of PDMS first layer. And then when you remove this Teflon tubing out you are left with the cavity which you can suitably fill with PDMS again. So, you can have a chamber you know illustrated in this manner. You can also have vertical channels; which can be drilled through by using Teflon tubing again suitably and then you can actually have a inter connect between these chambers and channels.

These can be very good bases the silicon can also be even patterned in h selectively. So, it can formulate a hybrid multi layered bio device, where 1 layer is silicon, which is patterned another layer is PDMS first layer and then second layer and subsequently many layers; which you can you know coat on the top of each other. So, then you can connect the tubings and this can be a source of a micro fluidic device.

So, again silicon hybrid you know PDMS glassed silicon hybrid bio chips are very common placed these days it is done by using again fundamentals of replication process, in unicell with some other steps. And just like hybrid machining this is a hybrid processing, which would work for you know formulating these micro channels of or features on to the surface. So, there is another interesting example: of what replication can do and typically prior to this is a almost everybody knows replication, was on a tow and a half dbasis you know.

So, it is basically on a on just on a flat surface and you had the luxury of printing in the x y plane. And all the patterns all things would be in the x y plane nobody really thought of what would happen if the replication, can be taken from a surface on to the bulk volume of the PDMS.

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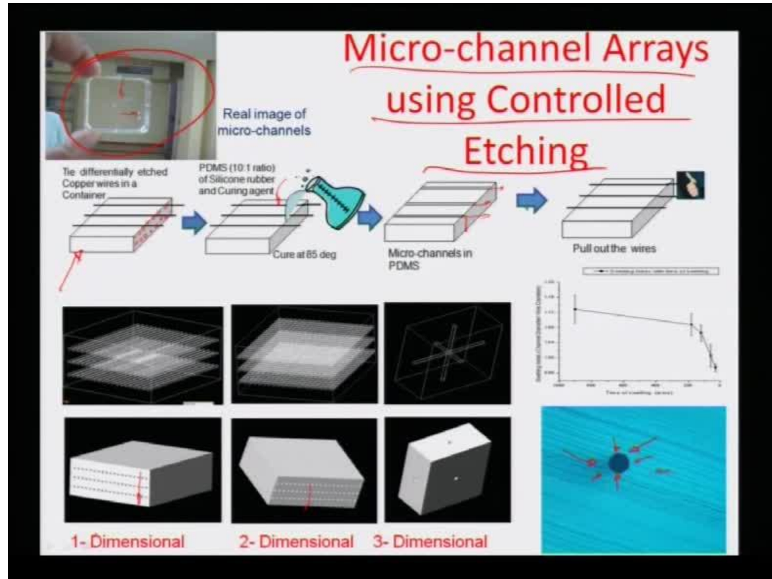

So, there is a illustration of this available in literature where you can make micro channel array is by etching of materials from the PDMS surface. So, here for example: is a PDMS slab and basically what you are doing here is you are suitably sacrificing copper wire in to the different sizes and shapes. And these wires are into the plastic into a plastic box, which is there by drilled an array of holes are drilled in this plastic box. And the copper wires are kind of heated as an array dense array, as you can see in this illustration here.

Then once these are heated these are well heated this wires are replicated. So, you pour liquid PDMS over these wires and then you know; you can actually cure the PDMS. So, that the PDMS forms hard, solid, rubbery membrane and then you can swell the PDMS matrix. So, that you can individually pull the air the wires out and that, results in your micro channels. So, you can have micro channels not only on a surface by using 2 and half d lithography, but also in the bulk or the volume as you can see in some of these illustrations.

Where you can see how the channels have been created to look at this particular figure closely, you will see a crisp cross channel created within the volume of the block there is 1 channel in this direction, there is another channel in this direction; if you look at it very closely. So, the only issue which comes here is in terms of swelling the PDMs matrix

and shrinking it back and. So, we have seen that while doing it the circularity of such a channel is very well retained and use a solvent to typically expand this PDMs.

Then you know if you evaporate it, the solvent goes away in it kind of adeswells back. And while deswelling, it kind of maintains the aspect ratio of the structures and features. So, it is a very important technique for realizing arrays of micro channels in the bulk volume of the PDMs matrix. So, this is another extension of replication and molding in the third dimension.

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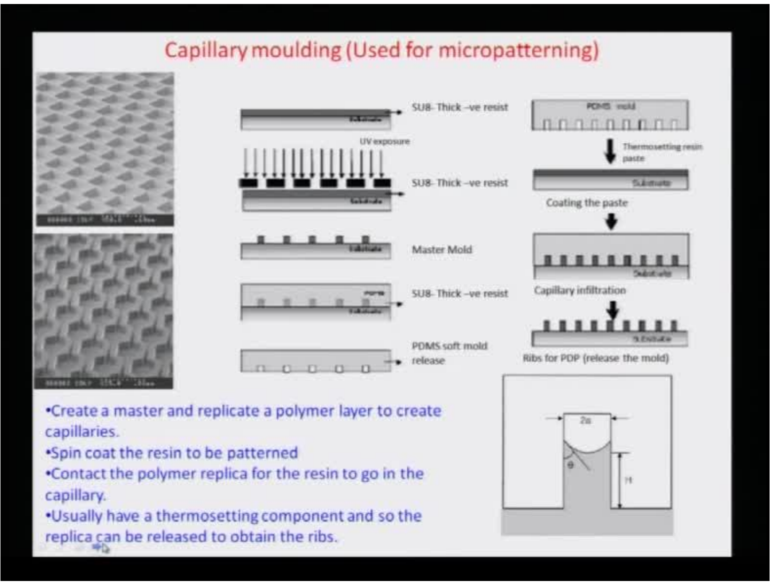

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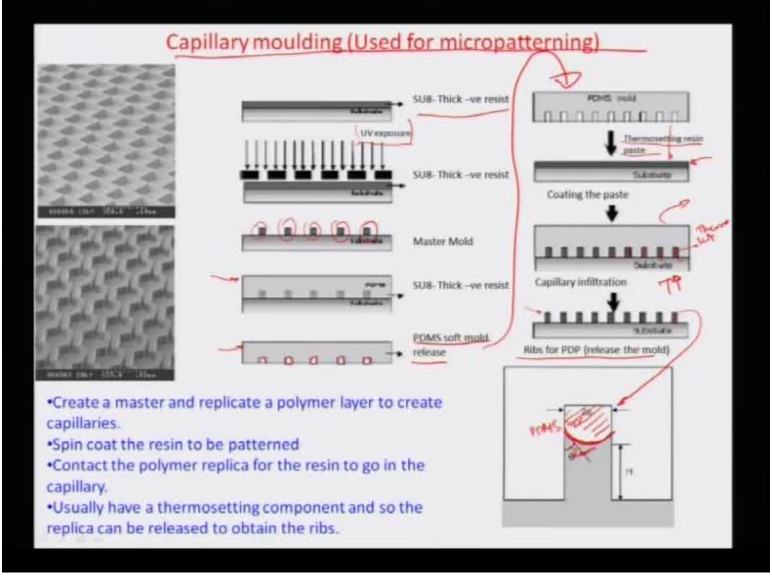

A very interesting process, which is sometimes used for display technologies, is capillary molding used for micro patterning. And here typically, the process starts with a thick assuate, negative tone resist coated on to surface which is u v expose selectively. So, that you have cross molded areas remaining as pillars, on the surface of the wafer. And basically what you do is: you take this mold and create negative replica by using PDMS and create a replica of small cavities on the lower surface like this.

To add resolution achieved by a suate PDMS and the u v exposure driven photo lithography. So, once this mold is realized this actually a PDMs soft mold and this would be used for molding thermo setting a plastic paste or resin paste; which is you know coated on to some hard substrate. So, for example, in this particular case as this mold has been realized, you can use this mold to try to create features on imprints on thermo setting resin paste, which is coated on to a substrate.

Here for example, when you pressurize this PDMs mold, on the top of this thermo setting resin the resin would go inside these cavities and fill up although they may not fillup completely there is a down side to this process and I illustrate a little bit later. But, the idea is that when these capillaries are sought of molding the thermo setting resin paste and then temperature is taken up. So, the tea is increased at this particular step.

So, these polymers which are actually molded into the capillaries are set; they are thermo set. And resulting in basically very hard natured thermo setting resin sitting on the top of this wafer and then you can remove the PDMS away whereas, the resin would not go anywhere because, it is already set on the top of the substrate and. So, you can have a very dense array of micro pillars by using this very beautiful strategy using a alternate PDMS mold to create this kind of a pillar array.

Now, only down side to the process is of course, surface extension because as you know that there is always a capillary of contact angle, which is established by the meniscus which flows into the capillary. And it is really a function of the forces of cohesion and dision between the resin and the surface and the resin and resin itself. So, it is a 3 face interface air on 1 side, the PDMS on another and the third itself, is the resin and this angle really depend on the inter play between the PDMS resin and air at this triple point or this point of interface and.

So, if there is a contact angle which is formulated in these capillaries, you can safely estimate that the capillary will not be totally felled and there would always be gap in the capillary end; when this resin occupies a portion of the capillary. And this can be a reason of inaccuracy of this pillar; when you talk many such pillars and arrays of pillars and. So, therefore, this allowance has to be taken into picture beforehand.

So, that you can have proper accurate ink printing of these ribs of the thermo setting plastic material. So, this is capillary molding used for micro patterning of substances. So, there is 1 very interesting soft lithography example.

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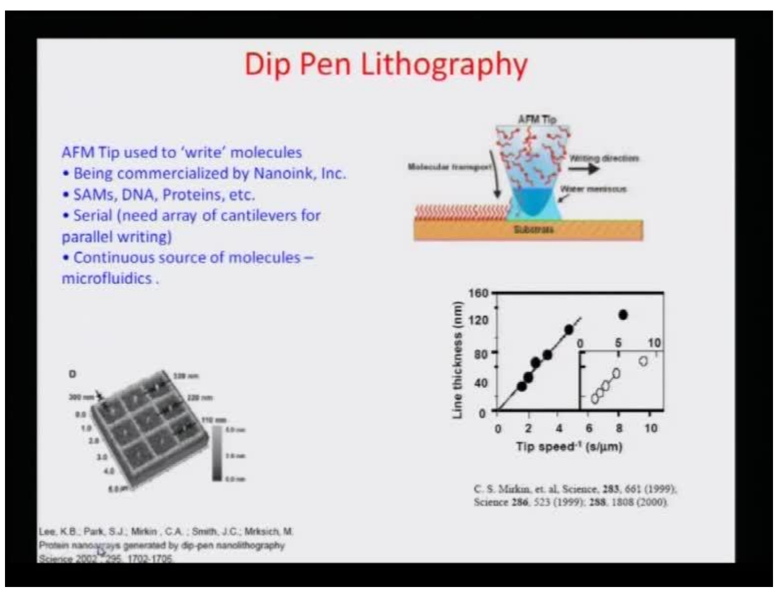

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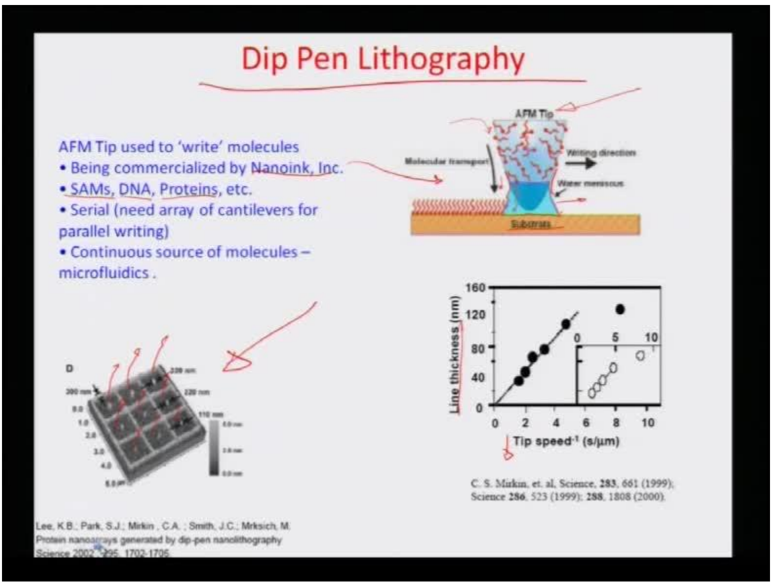

The other very important and essential technique, which people use now a days most often is the dip pen lithography. So, the other process of good importance is this dip pen lithography. And this is also another process of writing molecules and the way that this goes. In fact, this was developed by north western used pen an AFM you know tip or tip of an AFM to write the molecules.

The way it goes is that it basically creates you know an ideal condition of humidity and temperature and variant in a manner. So, that you have a thin film or thin layer of water around, this tip you know or this AFM tip or this water may be a just mono layers thick or just a few atoms just a small layer. This layer is used for transporting molecules, which you can deliver micro fluidicallyon to the surface of this AFM tip; then it floats by virtue of electric feed or some other you know and then once it goes into this small a water meniscus it automatically gets transported.

They can get imprinted or deposited on the substrate. So, the condition that is created here really is in the forces of cohesion, between the water and substrate is probably; I am sorry, between the water and the substrate is probably lesser in comparison to the region between the water and the tip and. So, therefore, this water meniscus can move along with the tip as a brush the scooting or delivering the molecules on to the substrate from place to place.

So, typically there is a company called nano ink incorporated which had actually made this process happen and when it started, it was actually a serial process, but then there have been initiators, where you can actually make this process parallel with multiple tips writing bunch of different molecules. So, you can actually use this to write self assembled mono layer again, DNA, proteins etcetera. So, this example here actually illustrates: a protein micro array where you can see you know, it is a basically almost 5 micron by 5 micron surface that you are investigating in each of these is a protein molecule.

So therefore, there are these different proteins in molecules placed, by this powerful technique dip and lithography and you can create micro arrays separated by a resolution of about almost 200 300 nano meters also that is a power of this process. So, typically if you look at the some of the characteristics of the line thickness and by line thickness, we mean the line of molecules that would be deposited on the substrate by virtue of this transport.

So, the line thickness is actually directly proportional to the inverse of the tip speed meaning thereby, the speed is low or the tip speed goes down line thickness would go up for obvious reasons that there is more amount of dual time of the tip at a certain particular place. So, that is what is this fascinating process of dip and lithography, it is again another soft lithography technique because, it can write soft molecules on to the surface using an NSTM pen.

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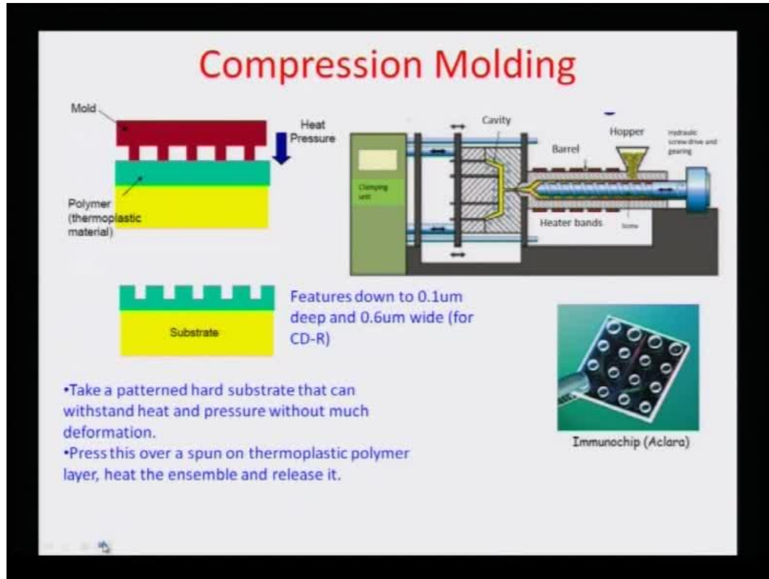

Let us know look into some of the other techniques apart from soft lithography that are available for the purpose of polymer mems.

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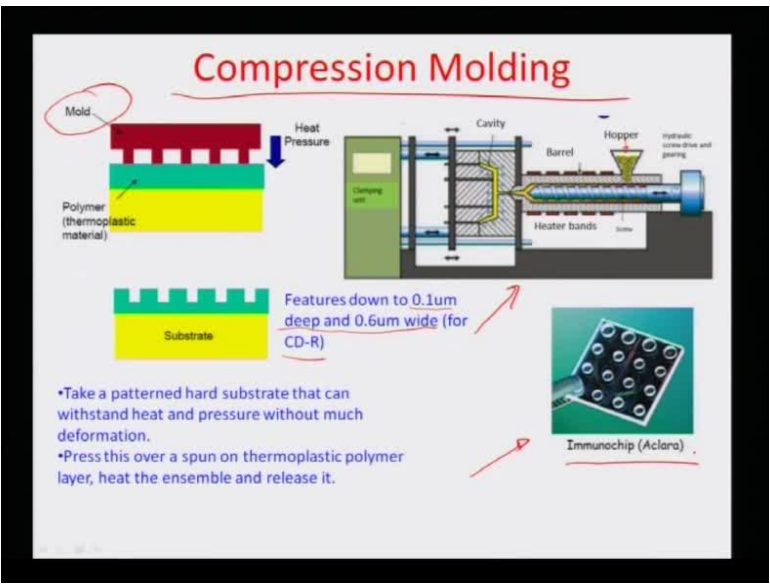

So, 1 technique which comes to the mind almost immediately is compression molding. So, as mechanical engineers some people would already be aware of what compression molding really means; essentially it means; that there is a mold which is hard and can be stand temporarily in pressure. And then there is a thermo plastic polymer, which is deposited on the top of substrate.

Basically apply heat and pressure on to this mold to imprint, this mold on to this thermo plastic material and the idea s that once this material is set at a certain temperature value. The mold can be withdrawn back and that is how you can actually make the pattern transferred on to this substrate. So, that is what compression molding is another very interesting process is injection molding and this is illustrated in this figure here, where you can see the feed of the polymeric material happen through this lead screw which pushes the polymer melt.

So, in this region there are heater bands which would melt the polymer and the polymer bend is melt is pushed forward into this dicavity. And the dicavity has some realize agents in some both sides. So, that the idea is that you can separate whatever is formulated here. So, whenever the polymer melt goes here into these areas the low temperature zone immediately solidifies and brings the shape of a die.

So, these days there is an increasing amount of use or application of these techniques for creating CD roms and features down to almost point 1 microns deep and point 6 microns in wide a width in feature separated by this kind of a distance scale and easily be know made by this process for developing CDR'S

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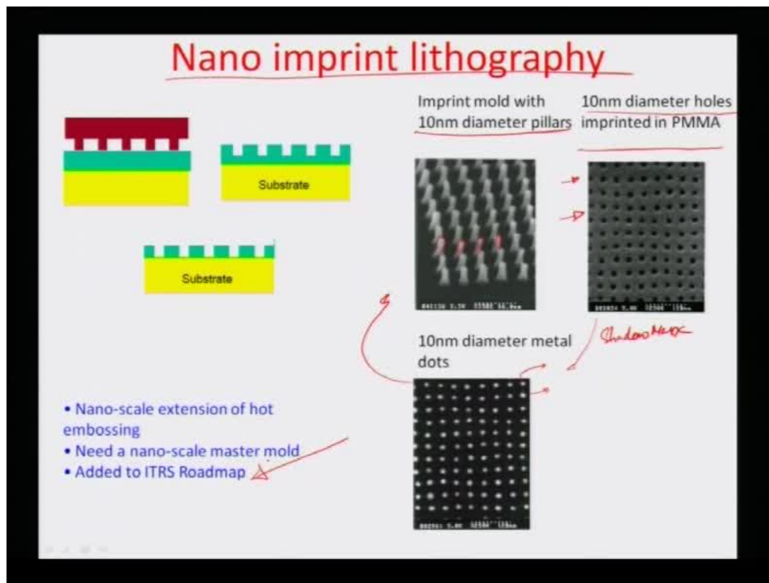

So, some of these processes like; I already mentioned about this immunochip fromaclara technology are actually made using compression molding process. So, if you can actually take this down to the nano scale a very interesting process develops out of it; which is

called nano imprint lithography and it is a nano scale extension of hot embossing or impression molding as, I illustrated in the slide before. So, here for example, is a very you know interesting example of nano imprint lithography.

So, what you do is you take a PMMA or poly methale methacleremethachlirite and then use E beam lithography, to drill these holes which are all at a distance of about 10 nanometers and they are having diameters of about 10 nanometers also. So, the power of the electron beam you can actually do this lithography. And drill it you know make a through hole in it using this; this e beam lithography. So, this can be used as a shadow mask typically for depositing material.

So, let us say if you use this PMMA as a shadow mask you can deposit 10 nanometer metal dots separated by about 10 to 20 nanometer distance as, you can see in this particular illustration here. And this metal dot coated substrate can further be used as the mold the hard mold to pattern polymers. So, you can actually make a patterning of these 10 nanometer diameter pillars, with these dots shadow graphed or shadow deposited on the top of this silicon using this PMMA.

So, the power of electron beam is translated in terms of resolution or this dot is further translated in terms of the formulation of this micro this nano pillars at a scale; which is very small and minuscule. So, typically this nano imprint lithography is such an important technique now, that it has been added to the ITRS road map particularly for end of the device. And these days there is an increasing use of nano imprint lithography in micro electronics for depositing you know gate the electrics or even the sometimes metal insulators.

So, metal gates so on, so forth. So, that is very important process done nano imprint lithography. So, we come to almost the closure of a polymer mems here and some of the very interesting techniques; which are available would once again go back, to photo lithography and would like to illustrate some of the experiments that you do for the photo lithography process.

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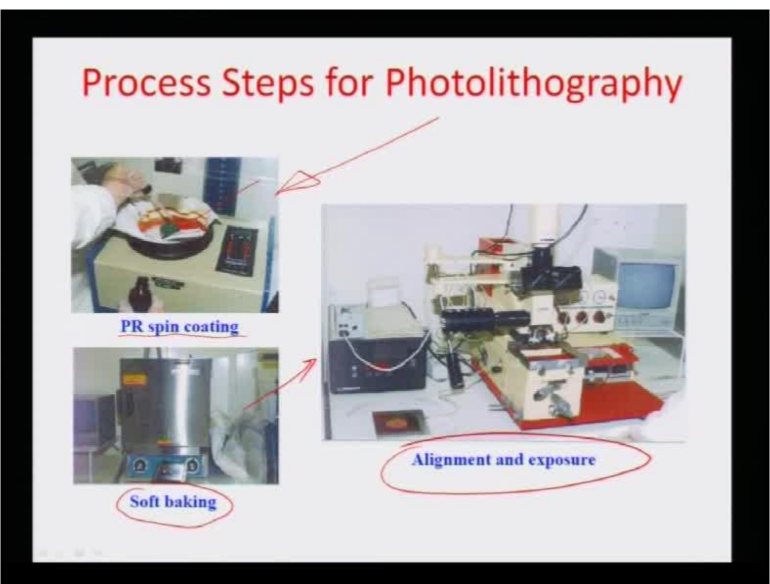

So, this for example, is the spin coating of the polymer resist as, I mention photolithography as a very important process of coating a thin layer of resist material on to the wafer surface. This for example, is actually a wafer surface, when you applying the resist on the top and this is the spin coat. So, it would spin at a certain controlled RPM and you can spin thickness as defined, by spin speeds on to the top of this wafer. Once it is spin coated you can heat and soft bake the resist.

So, that whatever liquid is available here, for carrying the resin material is all evaporated and the resin is all set and the next process of course, is this photolithography where you align and expose; this wafer with respect to mask and you can actually imprint the pattern, onto the resist through the mask using this alignment and exposure tool. So, this is these are some of the processes associated, with photolithography of course, you will have to do the mask alignment by using these microscope objectives and microscope eye pieces; where the objectives are in this particular region and you can actually see visible differences in terms of alignment of the wafer and the mask.

So, typically it is a sequential process you can have, multilevel masking technologies where you know more than 1 level of mask is needed to fabricate mems structures. And the therefore, alignment between the 2 different levels also, metimes becomes very critical and for that, some very well engineered and designed alignment marks are given on the cad files. So, it can be replicated on to the hard marks.

So, that between steps 1 and step 2, there is a always well aligned domain and there is no chance of a dimensional inconsistency between the various layers of lithography. So, these are the 3 steps of photolithography. So, once you have exposed the resist then you have.

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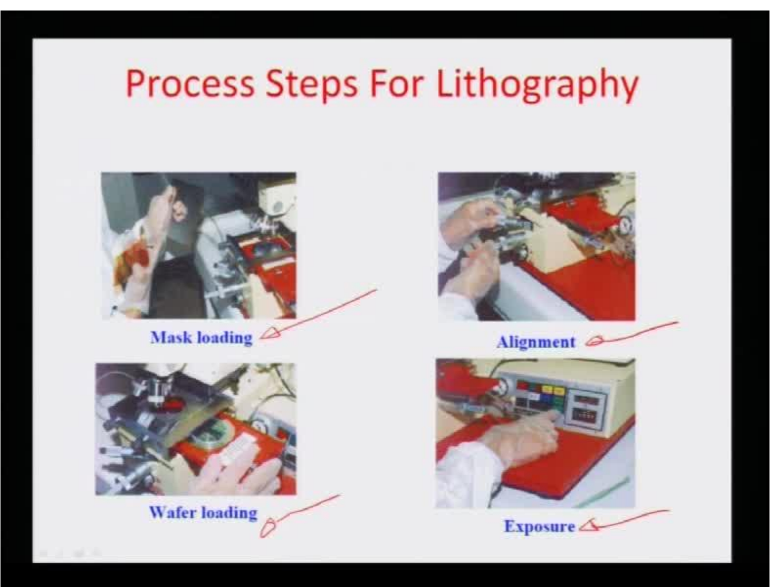

So, before exposing you basically do the mask loading ok. So, the wafer loading and the alignment these are all represented here. So, the alignment can typically be done by set screws; which are you know to give rotation to the stage or given x and y movement. And there is also a zee movement of the stage; which can take the resin the resist coated wafer close to you know the surface of the on the mask. So, that you can have contact lithography and then you do the exposure, where you can preset the in density dow such as well as the time of exposure.

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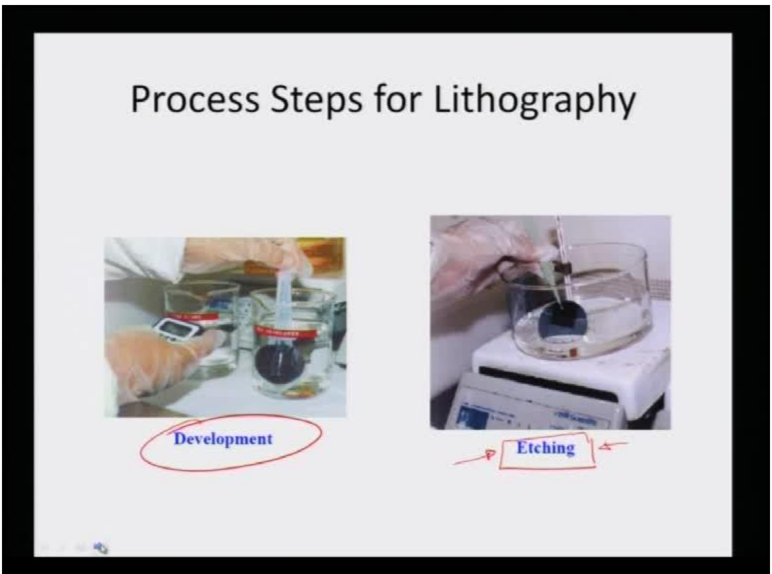

Then following this you do the development, where you know whatever resist has been exposed. Let us say if, it is a positive tone resist in the development of solution the area as the regions; which are exposed would come out and then you would have vias and crunchers in those places and after doing this the resist can be made as a sacrificial mask where wherever, the vias and crunches have been opened can be etched off or etched out using the etchant solution that you have a patterned etch on the surface the silicon wafer.

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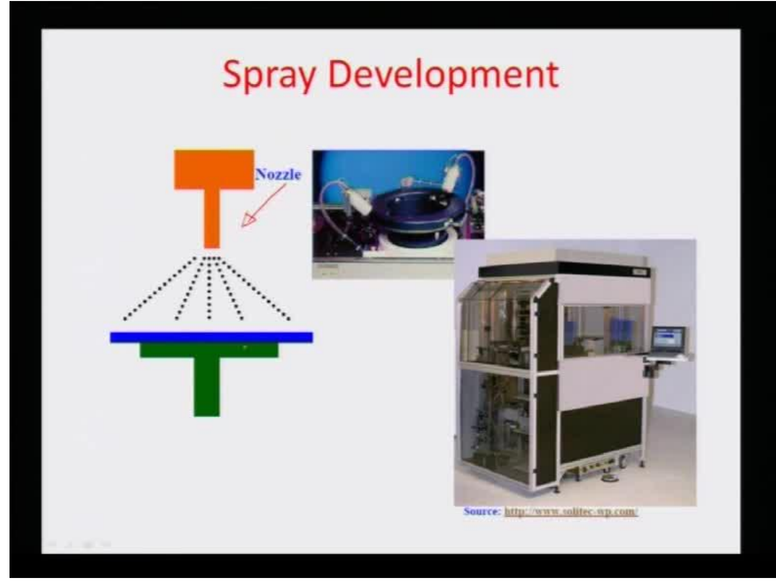

So, these are the various steps of photo lithography done in a laboratory. So, typically in high through put processes sometimes, there is a nozzle to do spray development of the resist and then you can have big transfer lines, where you can have these different processes of substrate cleaning resist coating, heating, prebaking of the resist exposure and development allautomated in a in a particular manner. So, you can have high through put production of these wafers. So, that is kind of practical demonstration of how photolithography can be done.

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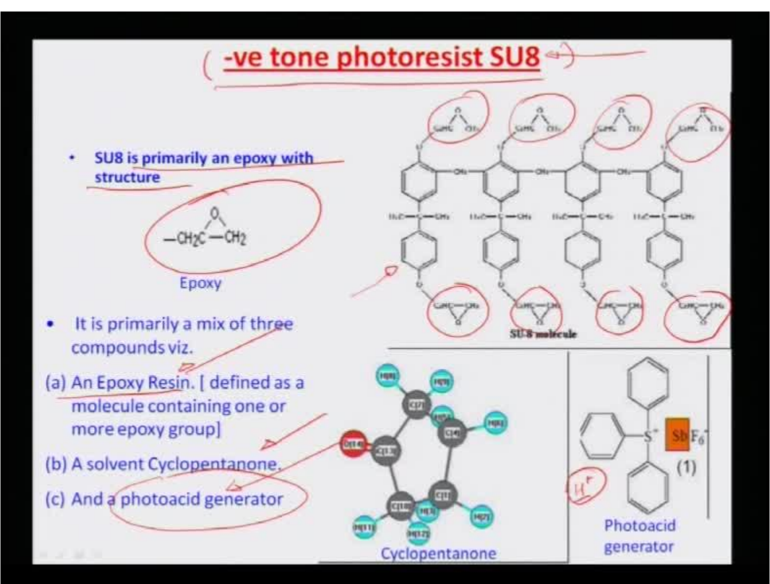

Let us now, understand a little bit about what are the changes or what are the chemical changes, which would result when you actually bring in photo resist. So, why is it that exposing the photo resist to a beam of light would; actually make chemical change happen on the top of the resist surface. So, here is again an example illustrated, where we are talking about negative tone resist as sueight.

So, su 8 is great resist available from a commercial manufacturer called micro cam and they are available at different viscosities and varying from 2005 2001 2025; as you go along the higher grade of the resist more thick and more viscous the resist actually becomes and. So, you can have a thicker film spun or thicker features, which are realized with the higher grade of the resist and thinner features when you go to it is lower grade of the resist.

So, what is the constituent of the su 8. So, basically su 8 primarily is a epoxy with a structure like this and this is a COC bond which typically, looks like the epoxy group. And you can see here that this is actually the su 8 molecule, with this epoxy rings at both the ends. So, there are various rings at both flans of the molecule and somehow, you will have to do some you know chemical modification of these rings. So, they can cross bond and that cross bond and that cross bonding should only be on exposure light.

So, what are all the other constituents. So, you have an epoxy resin already defined molecule and then you have a solvent to carry the resin around. So, that when you do spin coating or process like spin coating, there is a solvent which carries the epoxy all through the surface. So, you have to dissolve it to change the thickness into to a you know a thinner level and that solvent needs to be as a carrier fluid incorporated there. And then there is a photo acid generator.

So, you have the mixture of the epoxy resin solvent, in this case it is cyclopentanone and a photo acid generator and what does photo acid generator does, it basically produces acid it is a acid it will produce a h plus ion or a hydrogen ion or a proton on exposure to light. The moment this h plus is created, there is a change of reaction which happens into the zone.

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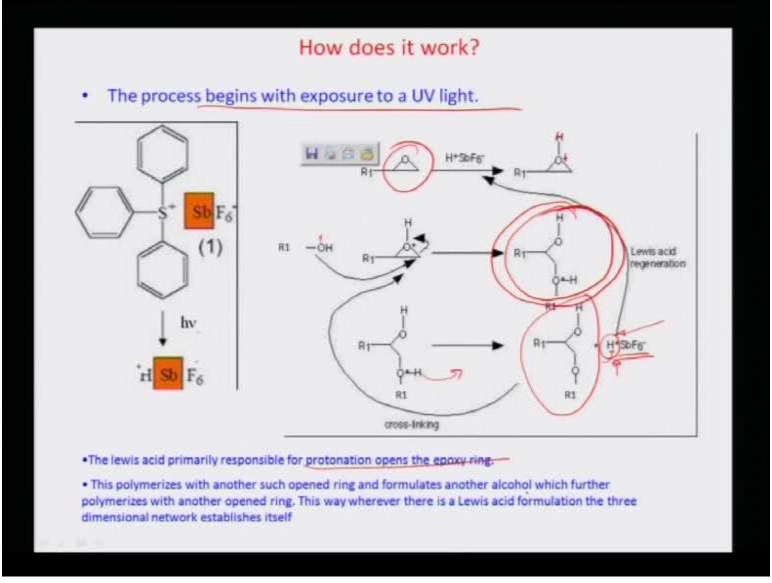

Where this h plus is released and what happens is that, the epoxy group on the photo resist actually opens in this manner. So, you have the h bonded to o and giving a plus

charge on the and then you have again similar kind of bond etch you know, from another r 1 oh which is already present and. So, you can actually club both these r 1 o plus h and r 1 o plus h in this particular manner. And once this is done the hydrogen kind of gets off and you are left with this moiety here and hydrogen plus is generated back. So, it is acts as a catalyst and adjoins the photo acid generator group.

So, you have opening of the epoxy ring which causes more that, 2 molecules to kind of play with each other and you know develop bondage and it goes out; the hydrogen ion goes out and joins the photo acid group here. So, you have a cross linked network of polymers in this manner wherever, there is this h plus ion or hydrogen ion or proton which is generated which means; that wherever, there is a exposure to light. Thus generating the h plus out of the photo acid, you would have a cross linking which would cross link the matrix of the polymer and make it solid.

So, that is how with u v light or u v exposure the cross linking of su 8 negative zone photo electric resist works. So, photo nation and opening of the epoxy ring and cross linking these are the 3 steps; which polymerizes the resist in those areas where it gets exposed to the light.

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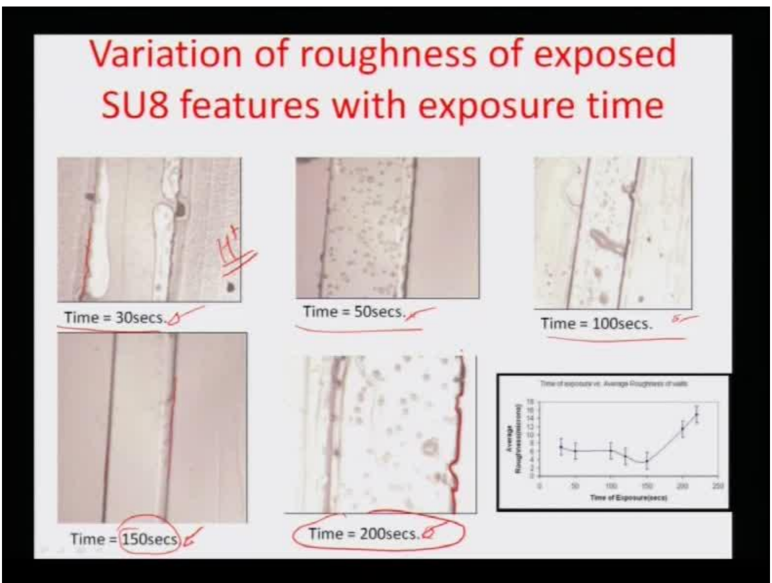

So, now let us talk about some tricky processing issues like: what would happen when the resist is either over exposed or under exposed or as a matter of fact under developed or over developed. So, as you know that there is a release of a h plus you know or a

photon hydrogen ion; which causes the epoxy ring to open. So, that you can have cross bonding, it is very natural to assume that, this h plus the way it reaches is a diffusion limited process and therefore, if the right amount of exposure time right amount of h plus is not released the and it probably it not sufficient, to make the resist cross bond in the manner that we wanted to.

Therefore, if you under expose the resist. Let us say for example, this is a very nice illustration of what happens if you change the time of exposure. So, this is 30 seconds is about 50 seconds, 100 seconds, 150 seconds and then you know 200 seconds. So, you are seeing here that, the edges of the resist are very rough when you talk about; let us say, smaller exposure time and in this particular illustration here the resist is having a perfect edge because, of the right time of exposure of this particular resist.

So, therefore, you have to do studies like these to find out what you know would give you a good feature or you know good consistent, you know consistently developed feature on micro feature on the top of the surface in question and. So, time of exposure is a very critical thing to be balanced when you talk about resist. Here for example, is a case where it has been over exposed as you are seeing there is a first of all there is a change in the dimension of the resist.

The number 2 is: that the edges are not very smooth because now, excess hydrogen ions have been produced and those create cross bonding away from the actual size or window of the mask that was available. So, you have bigger feature sizes and more rough sizes because of this time of exposure. So, you will have to balance out the time of exposure every time which is very critical for the purpose of development of the resist.

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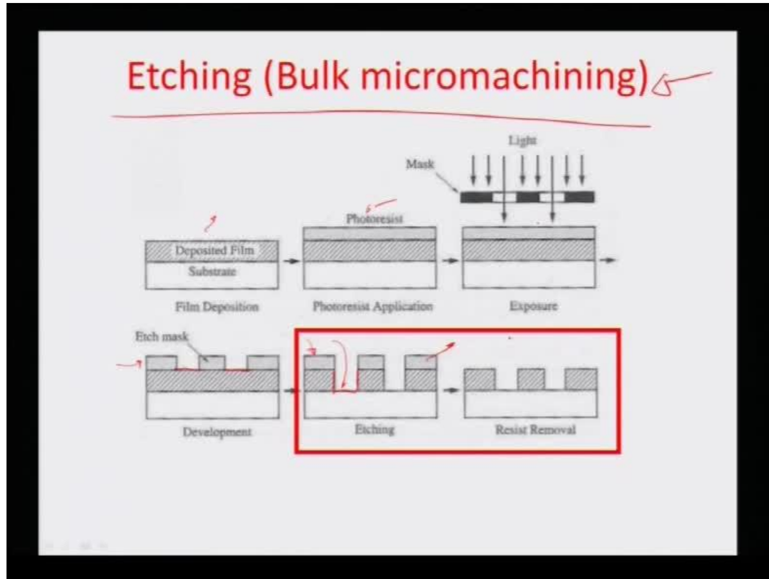

So, we referred to bulk micro machining you can combine 2 or more steps together to produce hybrid machining process, you can do the etching for example, in this illustration as can see doing photo lithography with resist and then, with that resist you patterning the resist and then with patterning. So, you have deposited film and you want to etch it selectively. So, you have a photo resist you exposure, you have patterning.

So, with this resist this patterned here on the surface as exposing these regions of the deposited film and then you can actually etch selectively, because the photo resist may not be able to edge it is a sacrificial mask on the top. So, you etch selectively thus etching these portions of you know the where; there is this no longer there or it did not protect. So, you can have these blocks of the deposited film on the top of the surface as you remove this resist out using the some other mythology. So, you can use a variety of these processes together; to formulate micro features and micro patterns.

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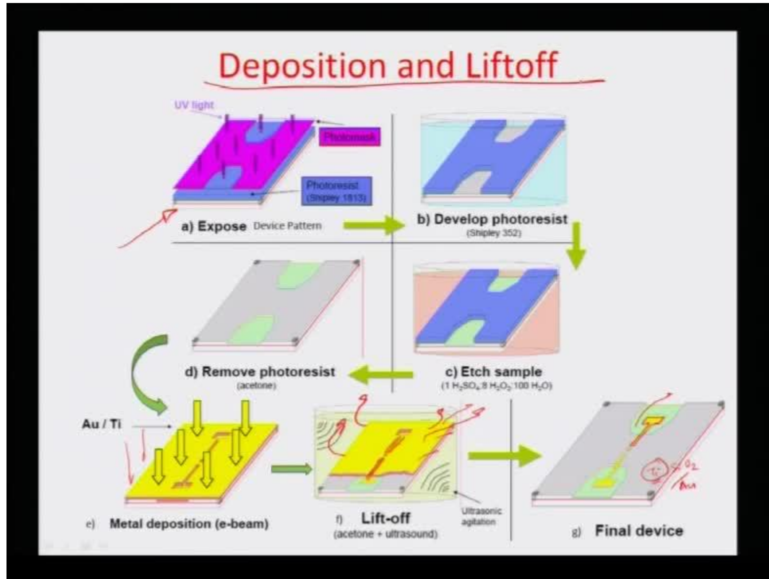

1 more example is what you do with deposition and lift off here for example, you are actually exposing, the resist to get a shape or feature through which you are doing some etching action. So, you are actually removing this grey layer here up till the green layer is probably the h selective layer.

So, it stops the etching stops here. And then on this you are having another masking strategy and using this masking strategy, you are basically trying to now deposit gold and titanium; and then trying to remove the resists in these portions. So wherever, the vias were open on the resist through the second lithography step there would be a remnant film staying there because titanium is a very good; agent which cross bonds silicon oxide or dioxide to gold.

So, basically it is sought of dision layer or desion promotion layer. So, wherever there is a SIO2 which was exposed; this was actually in this cravis here or in this cravis here. The gold state and it basically developed a bondage and remaining film even, if it is went off because of development did not allow this portion of the film which was in that open area and cravis area to go away. So, that is how you actually realize micro electronic prints or circuits, by using deposition and lift off.

So, you are lifting off the resist in the undesired area and you are depositing in the desired area and that is why the process is deposition and lift off. So, these are some fundamental processes related to mems, which are used in a combination of variety of

with a combination with variety of other processes. For realizing complex mems systems, it can be 7 layer, 8 layer, 9 layer different mask at each step, but then the idea is and you should be able to realize micro feature with accuracy, that it is intended to using a combination of some of these processes.

Let us know look at a little different aspect of mems fabrication. So, once you are able to produce the micro structures and features in different layers. The question of bonding between the layers comes into picture for example, if you are developing a bio chip and in the silicon base has carved in channels and chambers. We in the next step want to cover that with the glass plate.

So, there is a issue of bonding which is involved between the different wafer level architectures. And bonding places a critical role in proper you know functioning of the mems system and although it comes as a part of packaging of the mems system, but then still a the bonding is very important, because if suppose the bonding is not working properly then there may be leakages in micro fluidic systems or disfunctionality in terms of change in the inertness of the atmosphere; which would have otherwise be needed for proper functioning of the devise, and therefore bonding studies need to be done in great details.

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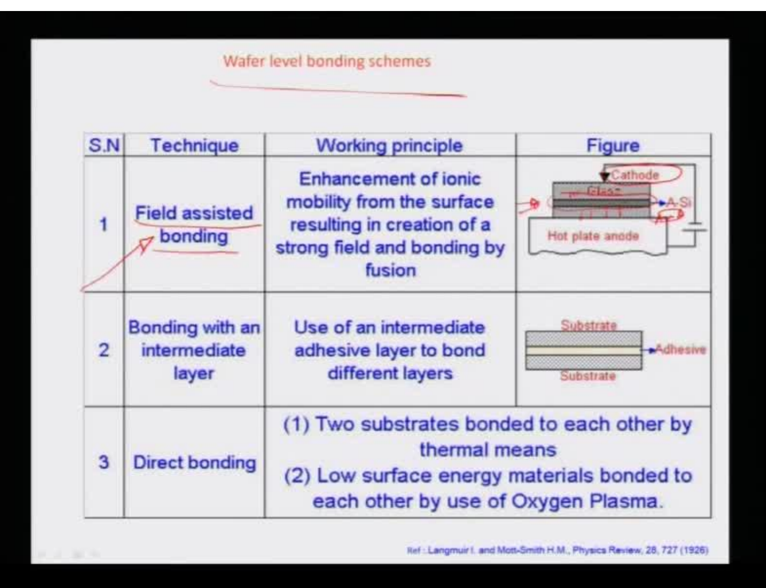

Wafer level bonding schemes

S.N	Technique	Working principle	Figure
1	Field assisted bonding	Enhancement of ionic mobility from the surface resulting in creation of a strong field and bonding by fusion	Cathode, Glass, Si, Hot plate anode
2	Bonding with an intermediate layer	Use of an intermediate adhesive layer to bond different layers	Substrate, Adhesive, Substrate
3	Direct bonding	(1) Two substrates bonded to each other by thermal means (2) Low surface energy materials bonded to each other by use of Oxygen Plasma.	

Ref : Langmuir I. and Mott-Smith H.M., Physics Review, 28, 727 (1926)

So, let us look at some of the basic bonding principles wafer level bonding schemes, which are available. So, the first scheme which comes into mind is: field assistant

bonding; which is basically you know bonding strategy driven by an electric field and here what happens is that, if you have silicon oxide or on the surface of the silicon wafer on 1 hand and on another hand you have let us say glass like soda lime gas.

There is always tendency of these sodium ions in the glass or the oxygen ions o minus 2 ions in the top of this SI surface to migrate towards each other. So, if I would give a very high field in such a situation, with the glass slide or glass side being made the cathode and the silicon side being made the anode; there is going to be a depletion layer which automatically comes up.

So, the o minus which is there on the surface of the silicon would try to go towards the anode side and the n a plus which is already there in the glass would try to go towards cathode side and the zone this grey zone here is the depletion layer which is created. So, once this depletion is created, there are certain because of the certain absence of the of the sodium or the oxygen there is latus reformulation in that particular zone.

Because of that if you apply certain temperature, there is a bonding of irreversible nature which happens between the latus of glass and the latus of silicon although glass is a is a amorphous solid it is longer solid, but the surface molecules of glass and the latus of silicon because there is no field as such present it is a depletion region and there is no ionic interaction which is happening. So, this results in permanent irreversible bond between the 2 and that is what is known by field assisted bonding or anodic bonding.

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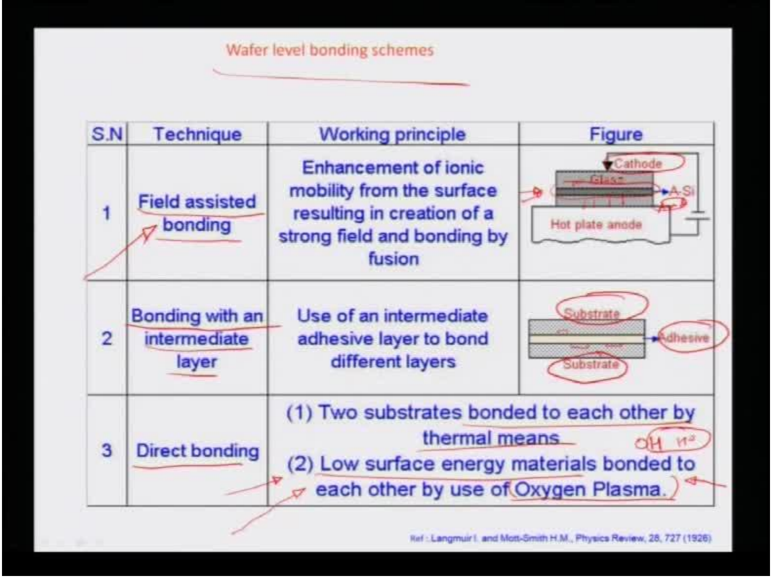

S.N	Technique	Working principle	Figure
1	Field assisted bonding	Enhancement of ionic mobility from the surface resulting in creation of a strong field and bonding by fusion	Cathode, Glass, Si, Hot plate anode
2	Bonding with an intermediate layer	Use of an intermediate adhesive layer to bond different layers	Substrate, Adhesive, Substrate
3	Direct bonding	(1) Two substrates bonded to each other by thermal means (2) Low surface energy materials bonded to each other by use of Oxygen Plasma.	

The other form of bonding which are used mostly in you know micro electronics and even mems is using an intermediate layer between, the between the 2 wafers for example. In this case let us say, you have these 2 substrates to be bonded an intermediate adhesive layer to bond both the substrates, but mind you if there is a mems architecture which is available over 1 of these substrates unless it is you know well protected this kind of a bonding between the micro structure cannot take place, because adhesive is a you know quite flow able material and it can flow in to these features and structures and block them.

So, therefore, they are only used in illustrations were probably you need to have electrical interconnects or something in that order between the different layers and BCB. In fact, is material which is used in bonding between different substrates in micro electronics of a non. So, therefore, different layers can be bonded using BCB bonding technology. Apart from these 2 processes, the third mems bonding process which is of direct relevance to some of the polymer mems is direct bonding wherein either.

Let us say, in case of glass and silicon you can bond them each other by thermal means; putting some pressure on the top of it and heating at 2 temperature were latus atoms kind of start vibrating and then start defusing into each otherso that, you can formulate the bonds. And in the other illustration you know you can somehow particularly in polymer mems case, lower the surface energy of the material by exposure to a variety of plasmas like: r1 plasma, oxygen plasma so on, so forth.

So, once the surface energy of the material is lowered and it is made high profiling, there is a dramatic absorption of over oh or hydroxyl groups on the surface and hydroxyl groups would kind of poly condensed together, to formulate a bond of irreversible kind in the different exposed layers of polymers and. So, this is a typically clean bonding recipe; which is used in most of the polymer mems devices, where polymers can be bonded to the glass or the silicon wafer very easily using this technique.

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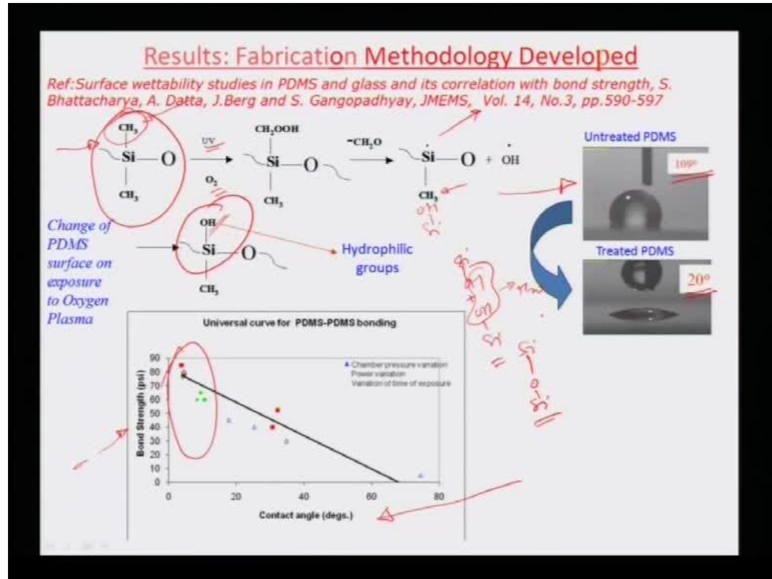

So, for example, one of the very good examples of this: bonding clean bonding procedure using oxygen plasma and the methodology involved has been reported in this paper surface wettability studies in PDMS and glass. So, what is found out is that, there is a there is a series of cations which happens on the surface of the PDMS by virtue of PDMS to u v exposure to oxygen plasma. And because of a series of reactions, there is a formulation of this sinalol group SIOH, on the top of the PDMS surface, at the cost of metthal groups.

So, basically in a oxygen plasma chamber metthal is kicked off and it replaced by hydroxyl OH and 1 of the reasons why after immediately, after the plasma exposure you find out that the surface becomes very hydrophilic for example, you know in this particular illustration you can see the total contact angle of about 109 degree or. So, of this of droplet has changed to almost 20 degrees by virtue of just plasma treatment. So, that is indicated of the fact that, there is a lot of OH lot of hydroxyl group on the top of this surface and which is resulting in a lower contact angle.

So, in order to find out the bond strength; you know the plasma parameters become very critical because, the idea here is that you should not be able to damage the backbone of this polymer molecule PDMS at the same time create enough surface reactions. So, that only had a superficial level at the surface level, there is a change or replacement of the metthal with the OH or hydroxyl group. So, these authors here, in this particular paper

have developed a scale or strategy; where they can have you know the measurement of bond strength on 1 side and contact angle they have correlated very nicely that, if the contact angle can be taken down below about 10 degrees.

So, then the bond's strength actually be very high. And these bonds are because of the formulation of this SIOH. And suppose, there 2 such surfaces; which would form s i oh together there would be a poly condensation reaction H2O goes out and you are left with SIO SI you know linkages; which is actually an irreversible bond in this particular case.

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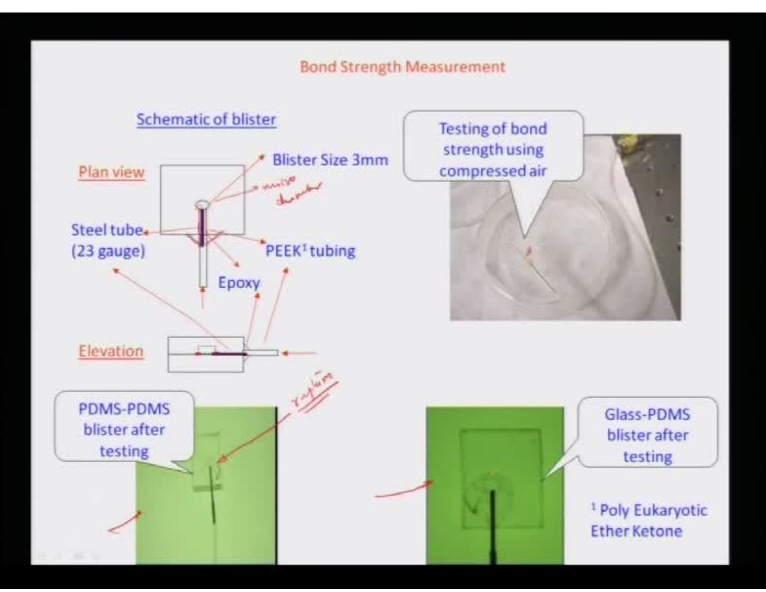

So, the you know measurements of the bonds strength in this particular example, has been done by putting you know using lithography to develop this micro chamber. And this micro chamber is again filled with air. And for that mechanism you have a steel tubing and a peek tubing; which is actually applied an epoxy is used for safe guarding any leakages from between the peek tubing and the PDMS. The peek tubing actually bites over the PDMS and creates the sought of reversible seal between it and.

So, therefore, there is a very less possibility of any air going out and. So, what would happen is that if you control this air at a certain pressure expansion of this chamber till and until it actually formulates or develops the rupture. And before developing a rupture even you can see under a microscope that the 2 layers are getting separated along the edges. So, that really is the basis, for formulating the bond strength. How much bond

strength of this PDMS to PDMS would be is dependent on at what pressure or corresponding to what pressure.

These layers separate from each other. So, you have these different cases, where you can see finally, you know after the bonds get started to get separate they had rupture and you can have a critical value of a pressure at which the bond starts to get separated.

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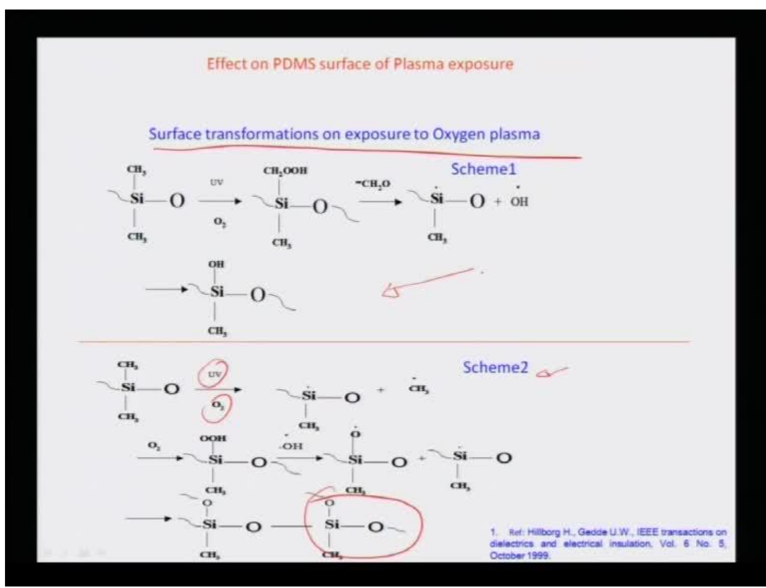

So, there are several transformations on the surface that, have been reported by various groups working on PDMS one of course, is the formulation of OH and another scheme to there is always; a series of steps of UV and O2 exposure, which leads to again the formulation of SIO. So, there are different reactions; which have been quoted by various people working in this particular polymeric material PDMS, as a basis of bonding scheme between the surfaces.

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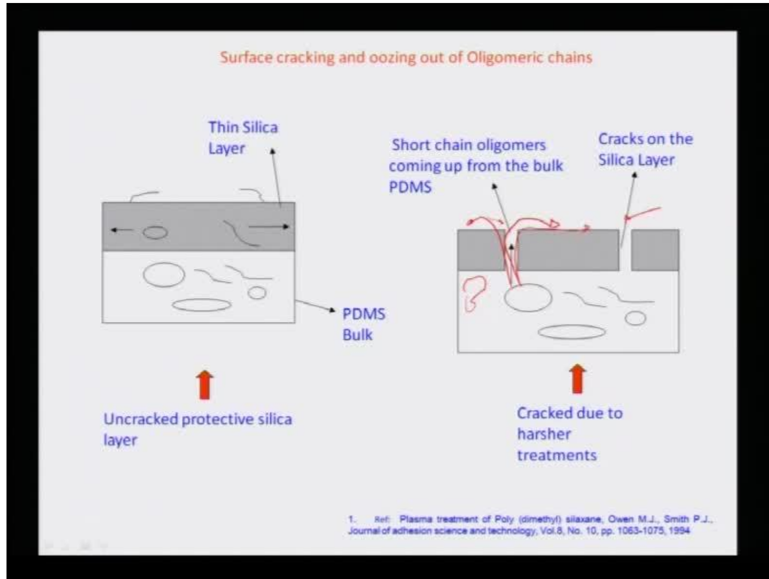

There are also certain very important illustrations, which come out for example, you know in case of PDMS. If you keep it back in normal room temperature there is a hydro fovicity recovery of the surface. And the way that happens is that there are micro cracks which are developed, because of exposure to the plasma and there is always a oozing out or you know a coming out of this short chain and long chain; which otherwise present within the small silica layer on the top of the PDMS formulated, because of the oxygen plasma exposure and.

So, this oozes out and then comes back to the surface; thus changing the hydro fovicity of the surface almost immediately. So, the bonding between the surface is an immediate process. So, whenever you have both the you know OH groups, just formulate on the surface, on the silicon layer immediately after the oxygen plasma exposure that is about the right time of bonding between the surfaces.

Because if you delay or f you wait, there is always a tendency or the hydro fovicity to recover back and a lot of metal groups to come and crowd the surface and that is actually go into rue in the bonds strength. So, that is how polymeric bonding in mems can be realized and that is brings us to the end of today's lecture.

Thank you.