Microsystem Fabrication with Advanced Manufacturing Techniques

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Lecture - 4

Welcome back. So, today I would be actually talking about in continuation to my earlier lecture about silicon processing, and the various non conventional techniques which are available for processing silicon particularly with the MEMS perspective.

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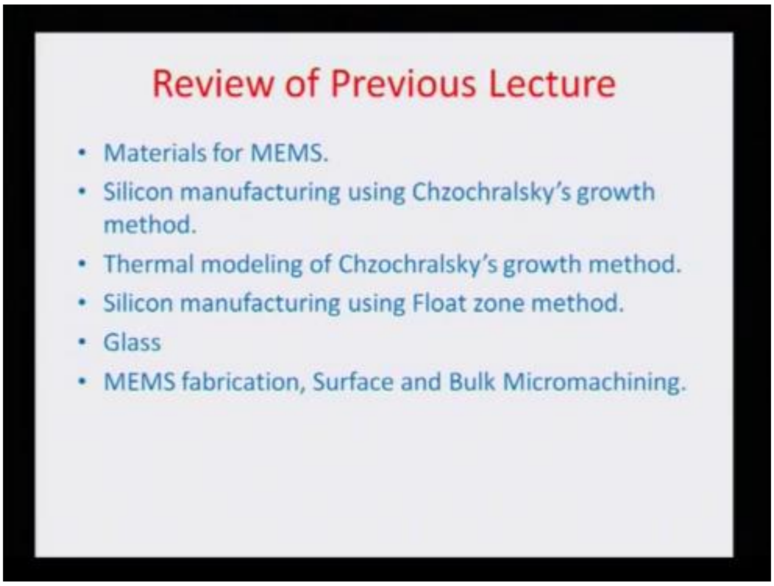

Review of Previous Lecture

- Materials for MEMS.
- Silicon manufacturing using Chzochralsky's growth method.
- Thermal modeling of Chzochralsky's growth method.
- Silicon manufacturing using Float zone method.
- Glass
- MEMS fabrication, Surface and Bulk Micromachining.

So, let us just briefly review our previous lecture. In last lecture we talked about discuss some of the materials, which are used for MEMS. MEMS is the micro electro mechanical systems. And basically one of the primary materials for MEMS, because the processing of MEMS actually is nothing but borrowed from the micro electronic industry. Therefore, MEMS is more suitable to processing with silicon.

So, therefore we studied some of the silicon manufacturing techniques using the Chzochralsky's growth method. Where a crucible maintained at an inert atmosphere was rotated in a seed crystal was lowered into the crucible for getting a bowl. And this bowl would be sort of directional growth of the fused 99.99 percent pure poly crystalline silicon, which would there be, which would there, which would be there in that in the crucible. And you can basically do the post processing of this bowl to obtain wafers with good super finish on the surface as well as you know various thickness or etcetera.

So, we also did some thermal modeling of the Chzochralsky’s growth method, wherein we talked about things like one dimensional heat transfer equation. And try to understand how much the heat flow would be from the liquid side of the, of the crucible to the zone effusion and from zone effusion to the solid. And the net heat balance was equated to the way that mass is formulated and in terms of its bonds of formation of the solid phase. So, we also obtained an optimum pull rate based on this modeling. And also try to optimize based on you know indicators like point defects, and thermal stress related dis locations. And so, then we actually refer to a different model of silicon manufacturing using float zone method.

Finally, talked about glass which is another very important material for MEMS. And then we just started to which some MEMS fabrication strategy, particularly the surface and bulk micro machining, surface micromachining again being and additive process and where it can be deposit I mean the layers of, layers of thin films can be deposited on the surface. And bulk micro machine can be a subtractive process, where you can remove material from the volume of the particular wafer for doing machining. Let us look at some of the alternate MEMS fabrication processes which are available.

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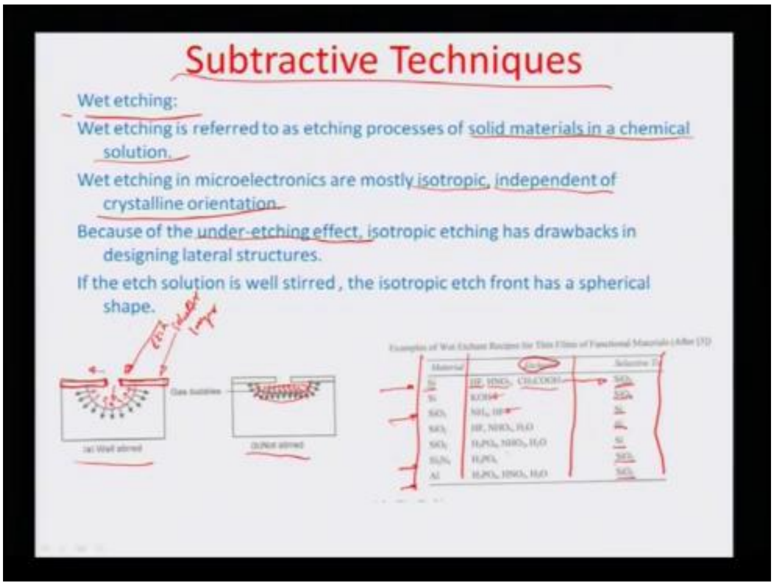

Subtractive Techniques

Wet etching:

Wet etching is referred to as etching processes of solid materials in a chemical solution.

Wet etching in microelectronics are mostly isotropic, independent of crystalline orientation.

Because of the under-etching effect, isotropic etching has drawbacks in designing lateral structures.

If the etch solution is well stirred, the isotropic etch front has a spherical shape.

Material	[illegible]	Selective T
Si	HF, HNO$_3$, CH$_3$COOH	SiO$_2$
Si	KOH	SiO$_2$
SiO$_2$	NH$_4$F, HF	Si
SiO$_2$	HF, HNO$_3$, H$_2$O	Al
SiO$_2$	H$_3$PO$_4$, HNO$_3$, H$_2$O	Si
Si$_3$N$_4$	H$_3$PO$_4$	SiO$_2$
Al	H$_3$PO$_4$, HNO$_3$, H$_2$O	SiO$_2$

And for doing that, I would like to highlight this etching technique, subtractive techniques. So, what is really etching? Etching is the, you know is referred wet, etching can be dry as well as wet. And let us first see what wet etching is. So, wet etching is really a process, where solid materials can be immersed in a chemical solution, and the solution can displace atoms or molecules from the surface of this material because of certain chemistry is in reaction.

So, when we talk about wet etching in microelectronics, mostly etching processes are isotropic or homogeneous in nature. Which means, meaning there by that the etch rate would be independent of direction and it would be homogeneous in all the directions. And it would also be independent of the crystalline orientation. So, let us say if you are trying to etch this surface of silicon, and you have made this etch protective layer on the surface, which is not I mean able to the etching process or in another words, it does not co-wrote or etch out if you are using a certain etch.

So, this can form a sacrificial mask on the top of the surface. And it can expose the silicon material, which is underneath it in this particular region, so the etching can go and eat away the material. Then, it can go and start etching in all the directions homogenously, thus obtaining a hemispherical crater like this. What is also important is because there is a rate of etch in the lateral as well as the vertical direction. Lateral etch would actually led the silicon cut to a size more than what it is intended to by this sacrificial mask. So, this process of extra cutting is also known as under cutting.

So, because of this under etching or a under cutting effect, isotropic etching has drawn backs in designing lateral structures. And therefore, we will have to always assume an etching allowance for this kind of etching to take place. If the solution is very well stirred, there is no accumulation of material coming of from the surfaces and you can have this kind of homogeneous profile. However, if you do not etch, or if you do not stir the solution well, the atoms which come out from the surface are not been able to dissolve properly in the etching solution.

There by creating a situation where because of high density near one zone, there may be diffusional restriction on the etch and may not be able to etch in a particular manner. Whereas, other materials which are etched from, let us say the sides may be having a greater etch rate, resulting in a directional etch rate. So, in this particular case lateral etch is much faster than the vertical etch because of the accumulation of materials coming out of the material, of the silicon. So, that is what happens when the solution is not stirred.

So, there these paradigms are kind of used off and on for describing wet etching. What is also important is something called an etch selective layer. So, for example, you saw this mask here, the mask does not get effected by the etching itself, although whatever is underneath the mask gets effected. So, this is called an etch selective layer which is not amenable to the particular, etching which is been used in this context. So, this called the etchants selective layer.

So, if we look at a table of materials which are commonly used in MEMS or microelectronics fabrication, you have the silicon, silicon dioxide, silicon nitrite, aluminum, these are the common materials. So, these etching materials can be for instance the combination of hydro fluoric acid, nitric oxide or nitric acid and a acetic acid, or for example the material can be a simple solution or a combination of hydro fluoric acid and ammonia so on so for. So, these etchants are amenable to removing materials by etching action, which are mentioned on the table on the left.

But the table on the right, the column on the right is basically indicative of what these materials are selective to, which means that if you are using this etchant solution of HF, HNO 3 and CH 3 COOH as you can see here. It can etch Si, a silicon or and it can stop whenever it faces layer of SiO2. So, that is what selective or selectivity of the etch process means. How selective the etchant is by in terms of it stopping the etching action is what selective to would means. So, here the bunch of materials on the extreme right column, which actually indicates what are the selective layers for the particular material and etchant combination that we are actually looking at here.

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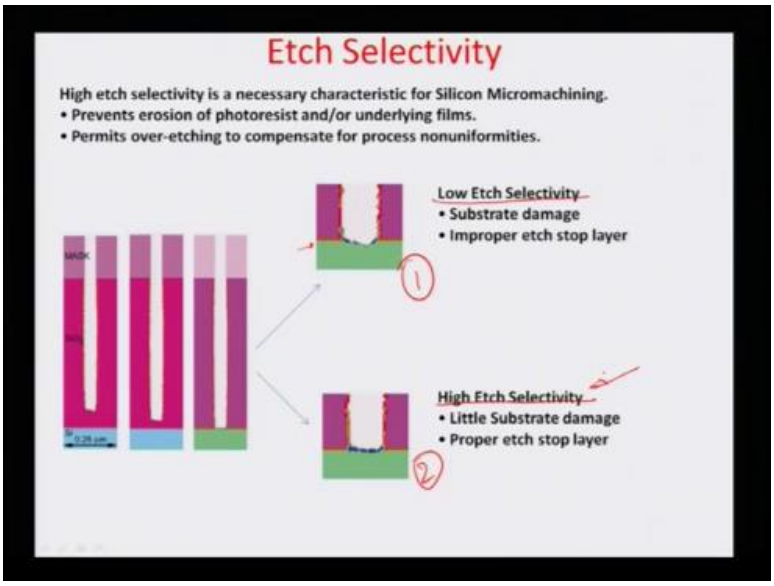

Etch Selectivity

High etch selectivity is a necessary characteristic for Silicon Micromachining.
- Prevents erosion of photoresist and/or underlying films.
- Permits over-etching to compensate for process nonuniformities.

Low Etch Selectivity
- Substrate damage
- Improper etch stop layer

High Etch Selectivity
- Little Substrate damage
- Proper etch stop layer

So, that is all about sort of wet etching and the selectivity can also be defined by the way that the etching performs while meeting selective layer. For example, there are 2 illustrations here, case 1 and case 2 as can be seen in this particular example. So, here for example the etch selective layer, which is this yellow layer between the green and the pink. The etchant is not very selective so it has lower selectivity. Thus, even though there is stopping yellow layer, the etchant goes and disturbs the green material and it crosses the etch selective layer.

Whereas in case 2, which a higher selectivity, so we can see that the etchant is more or less homogenizing the surface and it stops whenever it meets the etch selective layer. So, that is the advantage of etch selectivity. So, a higher selectivity is definitely desirable for MEMS processes to maintain control on the dimension, because of dimensions itself a very small as well.

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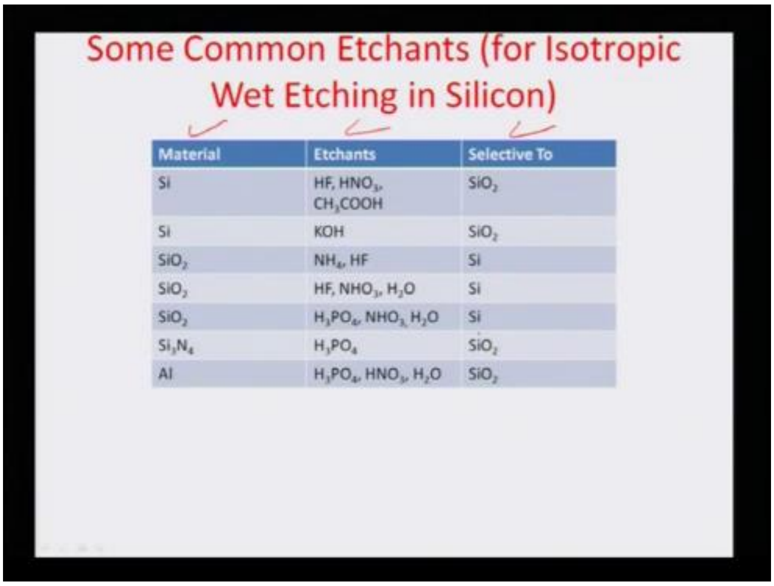

Some Common Etchants (for Isotropic Wet Etching in Silicon)

Material	Etchants	Selective To
Si	HF, HNO_3, CH_3COOH	SiO_2
Si	KOH	SiO_2
SiO_2	NH_4, HF	Si
SiO_2	HF, NHO_3, H_2O	Si
SiO_2	H_3PO_4, NHO_3, H_2O	Si
Si_3N_4	H_3PO_4	SiO_2
Al	H_3PO_4, HNO_3, H_2O	SiO_2

So, let us now look at some of the common etchants for isotropic wet etching and this we had actually mentioned before. So, you have the material to be etched, the etchants which are used and what it is selective to, and this stabilized being well described before as well. So, just for the records, these are very important for realizing some of the basic MEMS processes which would require this kind of wet etching action on the top of silicon substrates.

Etching can be wet or etching can be dry as mentioned before. Dry etching is basically a technique where we use a certain corroding, gaseous atmosphere to eat away parts of the material which you are etching. So, therefore dry etching is again something, which you know a gas phase causes a reaction with an atom on a molecule on a surface by absorbing onto a free site, and then taking away or caring away the atom or molecule out of the surface. So, that is what the dry etching the processes are...

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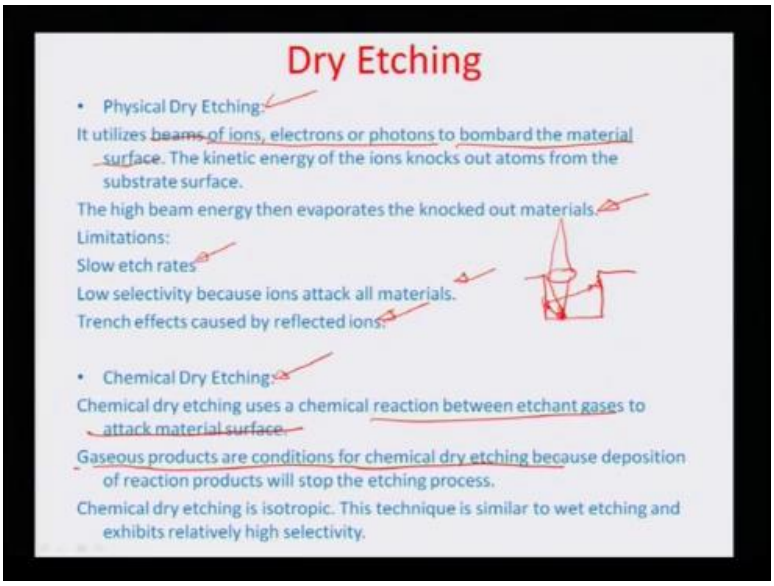

Dry Etching

- Physical Dry Etching:

It utilizes beams of ions, electrons or photons to bombard the material surface. The kinetic energy of the ions knocks out atoms from the substrate surface.

The high beam energy then evaporates the knocked out materials.

Limitations:

Slow etch rates

Low selectivity because ions attack all materials.

Trench effects caused by reflected ions.

- Chemical Dry Etching:

Chemical dry etching uses a chemical reaction between etchant gases to attack material surface.

Gaseous products are conditions for chemical dry etching because deposition of reaction products will stop the etching process.

Chemical dry etching is isotropic. This technique is similar to wet etching and exhibits relatively high selectivity.

If you look at the different dry etching processes, you have physical dry etching is number 1, which utilizes just beams of ions, electrons or photons. And what we mean by that is that essentially these beams are high energy beams, which would deliver energy and bombard their own constituents like ions, electrons or photons on to the surface. And that would result in the damage of the material surface. So, it would kick off the material which is rather placed on the surface and well bonded. So, there is an exchange of kinetic energy of these ions and atoms come out from surface because of this kinetic energy delivered on to the substrate.

The high beam energy evaporates sometimes the knocked out material. And we will actually study in great details these the mechanics of you know, removal of material when we talk about the electron beam machining or EB machining. So, the limitations that this process has that, it has a slow etch rate and it is not very selective, which means that it attacks everything that comes in its way. And it can actually damage the whole surface very rapidly because of which there is nothing called an etch stop and etch selective layer which you can use for this physical dry etching.

Another very interesting fact here is basically the Trench affects, which is caused by reflected ions. So, this is illustrated here in this example. That if you have a pit of this nature and let say, you have a E beam which is coming and hitting on to the surface and is trying to deliver some electrons. So, there is obviously a deflection or bombardment of the electrons which would actually go and strike the surfaces like this. And the momentum is still not consumed properly, and some of these electrons would bounce back. And so they would actually create a rough surface, which is also known as the trench effects by the reflected ions or the reflect electrons. So, that is an obvious disadvantage of physical dry etching.

The other technique that we have is a chemical dry etching, where we are using a chemical vapor and probably getting a reaction between the etchant gas that we are using and the surface material so, the etchant gas would chemically attack the material that you need to remove. And basically, the gaseous products are conditions for chemical dry etching because deposition of reaction products will stop the etching process.

So, you have to be very-very choosy about what gases you are using for the chemical dry etching phenomena. And chemical dry etching is actually is highly isotropic in nature, and it is similar to the wet etching because there is no ex selectivity what so ever. The material, the gas phase which comes and etches away the mate you know the substrate surface is really not very well directed. It is like a vapor atmosphere which is attacking, surface into question and therefore, it is very homogeneous and very isotropic in nature. So, that is about dry etching.

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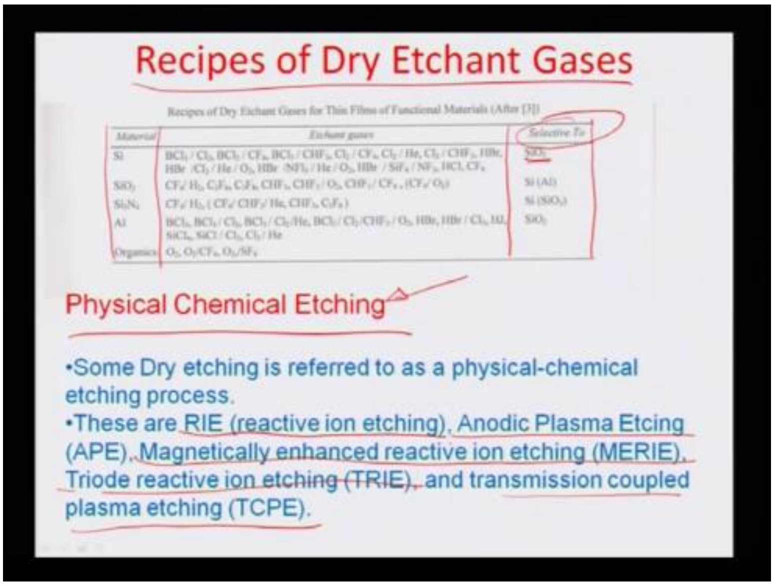

Recipes of Dry Etchant Gases

Recipes of Dry Etchant Gases for Thin Films of Functional Materials (After [3])

Material	Etchant gases	Selective To
Si	BCl_3/Cl_2, BCl_3/CF_4, BCl_3/CHF_3, Cl_2/CF_4, Cl_2/He, Cl_2/CHF_3, HBr, $HBr/Cl_2/He/O_2$, $HBr/NF_3/He/O_2$, $HBr/SiF_4/NF_3$, HCl, CF_4	SiO_2
SiO_2	CF_4/H_2, C_2F_6, C_3F_8, CHF_3, CHF_3/O_2, CHF_3/CF_4, (CF_4/O_2)	Si (Al)
Si_3N_4	CF_4/H_2, $(CF_4/CHF_3/He$, CHF_3, $C_2F_6)$	Si (SiO_2)
Al	BCl_3, BCl_3/Cl_2, $BCl_3/Cl_2/He$, $BCl_3/Cl_2/CHF_3/O_2$, HBr, HBr/Cl_2, HI, $SiCl_4$, $SiCl/Cl_2$, Cl_2/He	SiO_2
Organics	O_2, O_2/CF_4, O_2/SF_6	

Physical Chemical Etching

- Some Dry etching is referred to as a physical-chemical etching process.
- These are RIE (reactive ion etching), Anodic Plasma Etcing (APE), Magnetically enhanced reactive ion etching (MERIE), Triode reactive ion etching (TRIE), and transmission coupled plasma etching (TCPE).

So, then there are other techniques and before going ahead, I would just like to illustrate some of the recipes of the dry etchant gases as you can see here. So, here you have let say and this is as far as the chemical dry etching process goes. So, the materials again are all indicated on the very left column and then, there are these etchant gases recipes like for example, boron tetra chloride and chlorine or boron tetra chloride and carbon tetra chloride or BCL 3 and CHF 3. All these different combination of gases are basically etchants, or they act as etchants for the material silicon. And then they are again selective to SiO 2 because there is some degree of selectivity that you can use in chemical dry etching, although the process not very well directed and is very-very isotropic in nature.

So, these are some of these the recipes which you can think of while etching silicon or silicon dioxide and nitrite or any other material of importance for the MEMS point of view. And the column here shows what these recipes selective to. Meaning there by that presence of these would act as an etch stop and the etch will stop because facing of such a surface.

Another very interesting example of etching is this physical chemical etching, which is actually a combination of chemical gaseous environment with some degree of you know, mechanical or physical movement of the gases. And this comes into existence because of form of or state of material called a plasma. So, as you all know plasmas are nothing but made up of ions and electrons with the certain level of density of these ions and electrons across the bulk of the material. Although, the bulk is otherwise uncharged because you have equal number of positive and negative charges, but then these exist as ions and they can be driven to a surface, and they can be used for carrying all these etchant gases or gaseous environment.

So, if we can create a plasma and then create a chemical gas environment, then the directionality of the etching can be very well maintained. Some of these processes are very-very important from MEMS point of view. For example, the reactive ion etching process where you create a plasma and the plasma is semi chemically reactive in nature. So, therefore one aspect of the plasma is how the plasma comes and attacks the surface. Another aspect of the plasma is basically there is a chemical reaction on a surface which it attacks.

So, therefore the physical chemical etching referring to a plasma and a chemical reaction both taking place together. There are some other examples of these physical chemical etching. For example, a Nordic plasma etching, magnetically enhanced reactive ion etching. And we will do these different forms of plasmas in great details in a little bit later. Then, the triode reactive ion etching, and the transmission coupled plasma etching. These are some of the processes which can be categorized as physical chemical etching processes.

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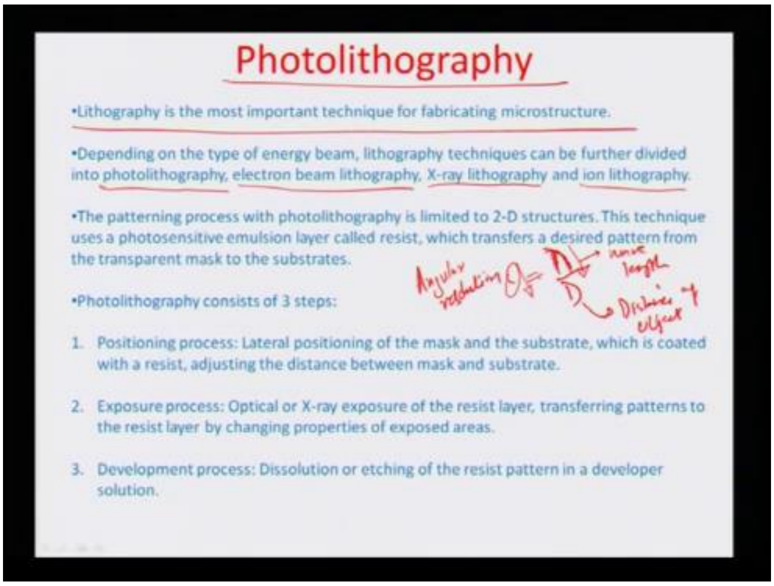

Photolithography

- Lithography is the most important technique for fabricating microstructure.
- Depending on the type of energy beam, lithography techniques can be further divided into photolithography, electron beam lithography, X-ray lithography and ion lithography.
- The patterning process with photolithography is limited to 2-D structures. This technique uses a photosensitive emulsion layer called resist, which transfers a desired pattern from the transparent mask to the substrates.
- Photolithography consists of 3 steps:

Angular resolution $\theta = \frac{\lambda}{D}$

λ → wave length

D → Distance of object

1. Positioning process: Lateral positioning of the mask and the substrate, which is coated with a resist, adjusting the distance between mask and substrate.
2. Exposure process: Optical or X-ray exposure of the resist layer, transferring patterns to the resist layer by changing properties of exposed areas.
3. Development process: Dissolution or etching of the resist pattern in a developer solution.

Let us now look at a very interesting example of the basic of how you can go small. And whenever we talk about carving or creating thin features and structures, almost always the term which comes to our mind is photolithography. So, what is lithography? Many of you may have earlier done photography in your school days as a, as a hobby. And in a photography what happens really, is that you have a photo film, and this film is actually used to project whatever is there on the film using a beam of light onto a photo paper.

And then once before the paper is exposed, the areas which are exposed on the photo paper has a chemical reaction because of interaction with the photons. And you can actually develop it or dissolve this portion in a chemical solvent and it results in creation of black and white pixels on the surface. So, that is what photo photography typically is. Especially in the olden days, when the digital cameras were not there, that was the only mobility which was used for developing or printing of the photographs.

Lithography is an identical process, only difference here is that, it can be used at the micron scale. And instead of visible light sometimes, we use ultra-violate radiation, which is very-very sensitive to resists and the photo paper in a photography is replaced in a photo lithography by something called a resist. So, let us see what is lithography in details. So, it is a definitely the most important technique for fabricating micro structures. And depending on the energy of the beam, lithography techniques are quite divided into photo lithography, electron beam lithography, x ray lithography, ion lithography so on so forth.

As is obvious, if you use light waves for doing lithography, it falls within the domain of photo lithography. If you increase the beam energy, it falls within the domain of e beam lithography or x ray lithography and ion lithography. Ion lithography you can increase up to any extent by accelerating the ion using an external electric field. So, I would like to mention here that, the higher is the wave length of particular beam, lower is the beam energy and vice-versa.

So, high energy beam is typically characteristic of a lower wave length and the low wave length means, that you can actually resolves at a better sensitivity. And so, if you go high on the scale, you have better resolution of the system. So, as we all know the very famous equation of resolution theta. The angular resolution theta is actually expressed as lambda by D. Lambda of course is the wave length of the incident radiation, and D is the distance of the object from the telescopic eye piece.

So, basically as you see here in this example or in this illustration, the lambda goes down and the wave length of light goes down meaning by thereby that the wave, concerned wave is the high energy wave. Then obviously the angular resolution theta will also go down, which means, that you can actually distinguish between two objects placed by a closer distance more appropriately or better in a better manner.

So, therefore the resolution really depends on the wave energy. Also if you keep on pumping up the wave energy, the resolution there by increases meaning that you can be able to distinguished two objects by writing them together, at a closer distance and be able to make independent objects out of them. So, the patterning process with photo lithography is really limited to 2 dimensional structures and features. It is actually called 2 and a half D process because the thickness of the features are defined by the spin speeds of the resists, that you spin on the surface. And you can use the x y 2 d surface for doing the patterning in what so ever manner you want.

Therefore, you can only dissolve at a 2 dimensional levels. So, this technique uses a photo sensitive emulation layer call resists as I mentioned before. It transfers the desired pattern from the transferring mask to the substrate. So, if you look at how photolithography is placed really. There are three steps in which photography happens, one is the positioning process, where the lateral position of the mass and the substrate which is coated with the resists is made, adjusting the distance between the mass and the substrate.

Then, there is an exposure process, where the optical are its exposure of the resist layer is made. There by transferring the patterns from the mass surface to the resist layer by changing the properties of those exposed area. And then of course there is a third step of development, where whatever as just in photo photography whatever has been imprinted onto the top of the resist from the mask can be removed by physically developing it into a etching solution. Then, whatever parts are exposed are either removed or they keep there. There by formulating micro size features or vias whatever is needed.

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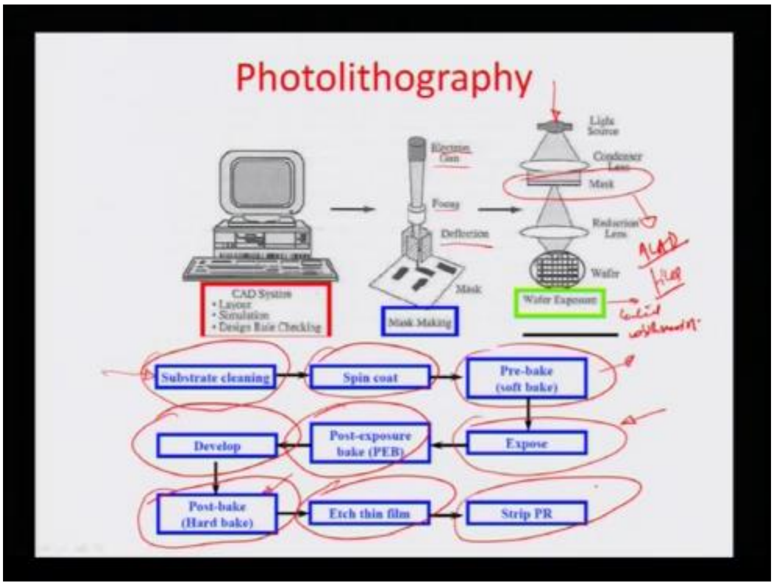

Photolithography

Substrate cleaning → Spin coat → Pre-bake (soft bake) → Expose → Post-exposure bake (PEB) → Develop → Post-bake (Hard bake) → Etch thin film → Strip PR

So, if you look at photolithography in a step by step manner, we lead is illustrated here as an example. So, you have a mask surface as you can see here, this is the mask. And this mask is actually made more or less using the power of A cad or auto cad files, and they are printed on transparency or hard masks. And then there is a light source at the top here what you can see. So, the light falls on to the mask and passes through the mask and there by whatever features on this masks are made for blocking the light, would block those portions of the light. And whatever features open are open and light passes through them and falls on to the wafer, which is actually coated with the resists.

So, wafer is coated with the photo resists and thereby it creates the imprints onto the top of the wafer which you can develop and expose, you know which you can actually develop later to formulate the features. So, for making masks you use typically an electron gun and you focus it using deflection coils, magnetic deflection coils. And you can very finely scribe a film of chromium, a thick film of chromium made over a glass and this we call as hard mask.

In case the mask is soft even that option is available, where you can get a printed transparence mask where there is a kodak mailer film, which you can actually print at a high resolution of about 5000 DPI, dots per inch using a photo plotter. And the power of the cad again be used for printing different features and structures on the soft mask and instead of using the hard mask in a very complicate which is actually fabricated using very complex, you know e beem or and scribing on to the surface, we use this soft mask which can actually imprint or serve the same purpose.

However in case of a soft mask or a polymer mask, the main difference or the main disadvantage is that you cannot go to a very high resolution because it is limited by the way that dots are printed to formulate the images onto the transparency mask. So, typically these are the processes that would be used for photo lithography. You start with a silicon substrate and clean the substrate properly, sometimes using recipes like piranha or even AMD, acetone, methanol d i water and there after doing the substrate cleanings, you basically spin coat the resist. In fact it resists which is actually the polymer material which is photo exposable.

There by you actually do a prebake, where whatever solvent was used for spinning the resist uniformly on the top of the wafer is evaporated, there by solidifying the resist film on the surface. When then after doing this pre bake you do the exposure using the masking process of the photo resist, so that whatever windows have been made in the mask are kind of printed onto the resist. And then, with this printed shapes you can do a post exposure bake, where the resist is again baked at a certain temperature, so that the heat is acting as a catalyst there.

The photo exposure process typically is either a cross bonding or a D bonding process and the bond initiation between the polymer matrix actually gets either enhanced because of heat or sometimes bond breakage becomes enhance because of heat. So heat is a ketal catalyst, which acts to fasten the reaction and the way that the photo resist is the developed or exposed.

So, after doing this post exposure bake, you do the development of the resist by using a solution, which is actually something which takes away the resist which is either exposed or unexposed depending on the type of the resists that we are using. And there after developing, you do another step of bake here, that whatever is remaining on the surface of the wafer can get properly hardened and settled will also the developer can get removed from different places of the wafer. There by you get, you know of a certain feature or set of features or patterns onto the surface of the resist wafer.

And then, you can do various things like an etch using those patterns or you can actually strip the photo resist later after depositing metal so on so forth. So, this is the whole complex process of photo lithography.

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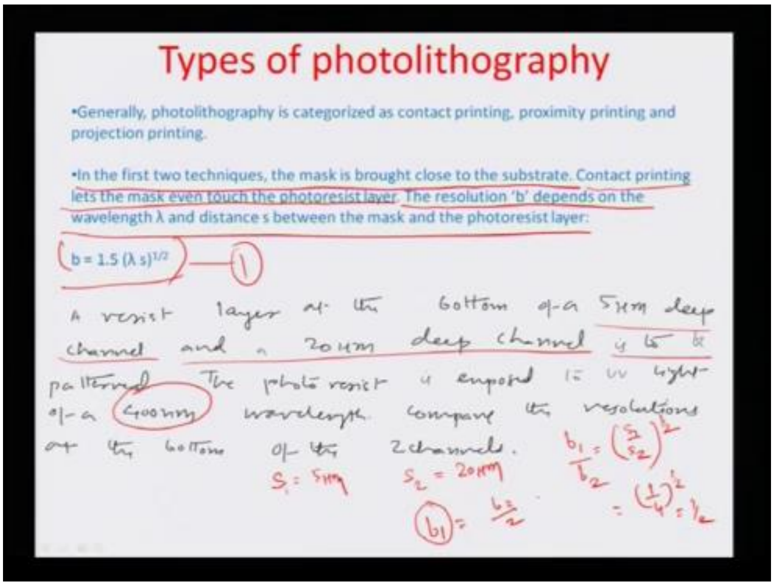

Types of photolithography

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

$b = 1.5 (\lambda s)^{1/2}$ —— ①

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

$s_1 = 5\mu m$ $\quad s_2 = 20\mu m$

$\frac{b_1}{b_2} = \left(\frac{s_1}{s_2}\right)^{\frac{1}{2}} = \left(\frac{1}{4}\right)^{\frac{1}{2}} = 1/2$

$\boxed{b_1} = \frac{b_2}{2}$

If you look at the types of lithography for there are typically three different types of lithography which exist and it really depends on the relative orientation of the substrate with respect to the mask. So, there is, there are three kinds as I mentioned, one is contact lithography or contact printing where the mask and the substrates are in very closed proximity almost touching each other. Approximate printing or approximate lithography which are actually close, but not that close because there is a layer of about 20, 30 microns of air, which is a space in between the mask and the substrate.

And then, we have projection lithography, which is actually used in the industry as proximity and contact are typical laboratory processes. For high yield processes, there is always disadvantage of resist coming in contact with the mask and going away. So, therefore projection lithography is more or less used in the industry, where you have a mask at some distance from the wafer, which is again spin coated with a resist. And then, expensive optics is used to guide the lights, so that diffraction effects can be minimized, and then whatever is projected from the mask, passing from the mask is projected directly onto the resist film.

So, in the first two techniques, again the mask is brought close to the substrate as I have just indicated. Contact printing lets the mask even touch the photo resist layer. The resolution beam on such a case depends on the wave length lambda, and the distance s between the mask and the resist layer, and b is expressed as 1.5 lambda times of s to the power of half. Again, lambda is the wave length, s is the distance between mask in the resist layer. So, I have a small problem, designed for you guys to solve.

So, let us say, we have resist layer at the bottom of a 5 micron deep channel and a 20 micron deep channel. So, there are two different illustrations, one the channel is 5 micron deep, another the channel is 20 micron deep. And this is to be a pattern using a contact lithography. And the photoresist is exposed to UV light, which is about 400 nano meters in wave length. And we want to compare the resolutions; these of you know the bottom of the two channels. So, in one case s therefore equals 5 microns at the bottom of this deep channel. And let us call it s1 and in the other case s2, you know the distance at which lithography has to happen is about 20 microns.

Assuming that the contact of the mask is actually at the top of the channel, and the channel is below the mask. So, that is what we are assuming here. So, therefore you will have the resolutions b1 and b2 as basically, s1 by s2 to the power of half from equation 1 here, and therefore this release one-fourth to the power of half or half. So, therefore the resolution in case of where the 5 micron channel is exactly half the resolution in case of the 20 micron channel, which is illustrated here. So, therefore as you seeing here, the resolution b1 and the case of the 5 micron deep channel is better in terms of resolution distances right. So, b1 is half the distance of resolution of the 20 micron channel.

Meaning there by that, deeper the channel the blurrier will be the images. Therefore, the resolution would accordingly change. So, shallower on the channels or lesser the channel depths the distance by which you can resolve two objects is lesser in comparison to, if the channels are deeper. So, that is what is contact lithography?

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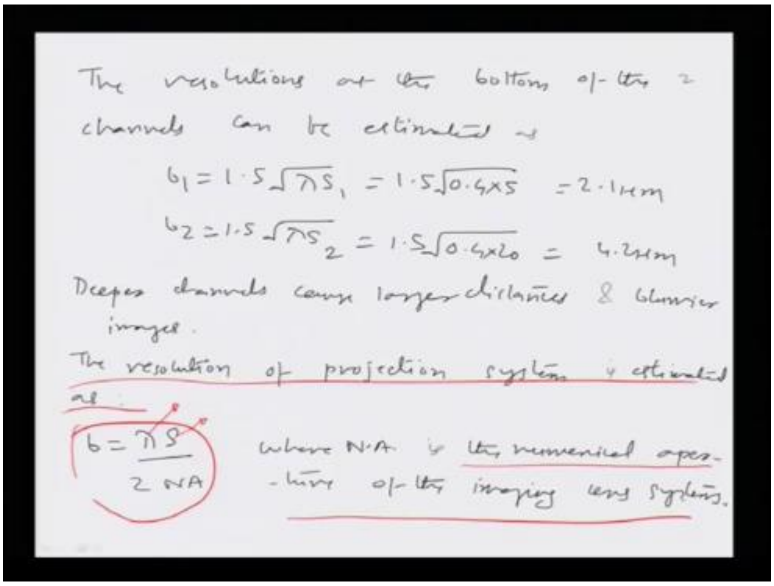

The resolutions at the bottom of the 2 channels can be estimated as

$$b_1 = 1.5\sqrt{\lambda S_1} = 1.5\sqrt{0.4 \times 5} = 2.1 \mu m$$

$$b_2 = 1.5\sqrt{\lambda S_2} = 1.5\sqrt{0.4 \times 20} = 4.2 \mu m$$

Deeper channels cause larger distances & blurrier images.

The resolution of projection system is estimated as

$$b = \frac{\lambda S}{2 NA}$$

where N.A is the numerical aperture of the imaging lens system.

Typically you can have the, you know projection lithography the resolution equation expressed in little different manner. It is given by this lambda S by 2NA, where lambda again is the wave lengths, again is the distance of the object from the masking layer. And then, NA is basically the numerical aperture of the imaging lens system. Mind you, in projection lithography you have to use expensive, you know optics for guiding the light. So, that there is no refraction effect, because it comes through typically very long distances from small windows. So, therefore projection lithography system, I would have a resolution b expressed by lambda s by twice the numerical aperture of such a system.

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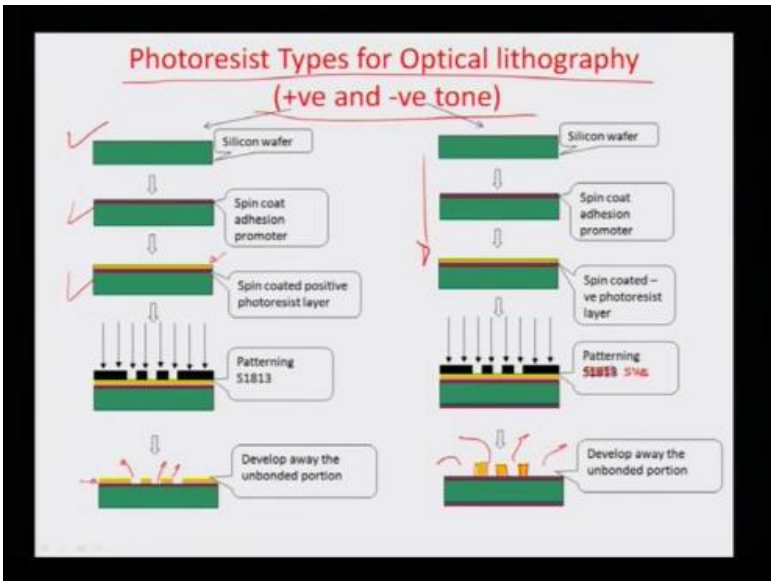

Photoresist Types for Optical lithography
(+ve and -ve tone)

Silicon wafer

Spin coat adhesion promoter

Spin coated positive photoresist layer

Patterning
S1813

Develop away the unbonded portion

Silicon wafer

Spin coat adhesion promoter

Spin coated –ve photoresist layer

Patterning
~~S1813~~ SU8

Develop away the unbonded portion

So, typically there are two different kinds of resists which exist. And this particular illustration here, kind of shows what would be the role of the two different kind of resists. One is the positive tone resist and other is a negative tone resist.

So, in a positive tone case as you see here, you start with the silicon wafer then, you spin coat. Let us say, a small layer of adhesion promoter which sometimes sticks the resist onto the surface of the particular wafer. And then, you spin coat a photoresist layer, which is represented by this yellow color here. And then you selectively expose the photoresist by this masking strategy, so that you could have patterning of the resist in this particular manner. And so you develop away the unbonded portions.

And so in one case which is the positive resist actually, the resist which is exposed gets de-bonded and it goes away. So, a positive resist is signified by making vias or trenches. So, that is what the positive side of the resist is. The negative resist is on the other hand, resist where wherever you are exposing basically cross bonding. So, therefore it goes with the same cycles as you are seeing on the right side here. There is adhesion promoter, there is photoresist layer, there is a masking strategy which you have made.

And then finally, you are exposing selectively these portions. And wherever it gets exposed the resist is back because it gets kind of cross-bonded. And so, you can develop away the remaining areas, and so basically the features and structures are once which are exposed. So, it is a completely different form of you know lithography, the masking would be different, everything else would be different. This is SU-8, is not as 1813.

So, therefore you know with these two types of resists, in one case you will actually get features and structures like vias inside the resist. That means, wherever it is exposed it goes off on development, and the other you have a structures and features and micro features actually itself where there is cross bonding and wherever it is exposed it stays back, the remaining portions go away. So, a combination of both these resists would play a major role in building up micro systems as we will see in future lectures to come. So, that is about photo lithography.

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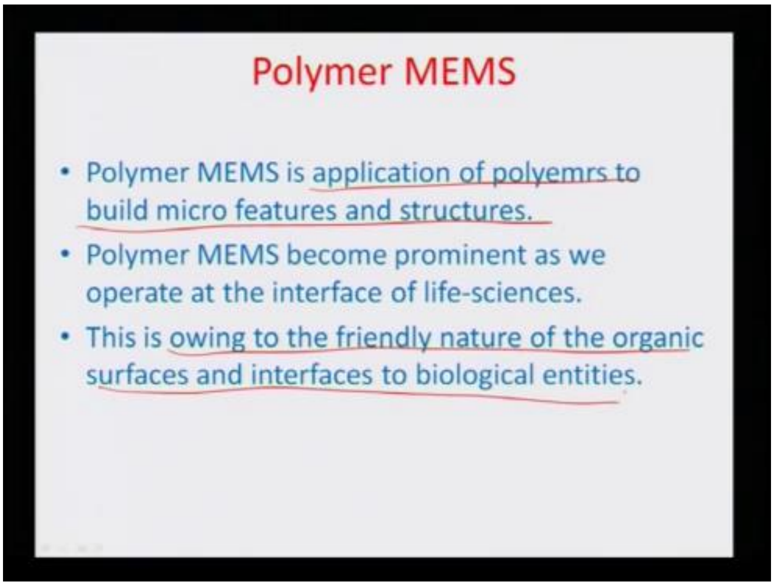

Polymer MEMS

- Polymer MEMS is application of polyemrs to build micro features and structures.
- Polymer MEMS become prominent as we operate at the interface of life-sciences.
- This is owing to the friendly nature of the organic surfaces and interfaces to biological entities.

Now let us look at little, you know different field of MEMS, which is also called polymer MEMS. So, as you know that increasingly because of the application of MEMS to the biological side. For bio remediation, diagnostic, clinical detection, polymers become very amenable materials, because their friendly as such with the biological systems. And therefore, there is a huge initiative in the area of polymer MEMS, which automatically comes in because of this merger between the biological word and the micro systems in generally.

So, what is polymer MEMS? A polymer MEMS is off course the application of polymers to build micro features and structures. And this is basically going to the friendly nature of organic surfaces and interfaces to biological entities as they can identify. Most of the biological entities themselves are organic in nature, so they can identify each other very well and so they are very-very friendly with each other. So, their behavior could be absolutely normal if they meet surfaces or systems made up of polymers, rather than inorganic material. So, if you look at some of the materials and their properties particularly talking about polymers.

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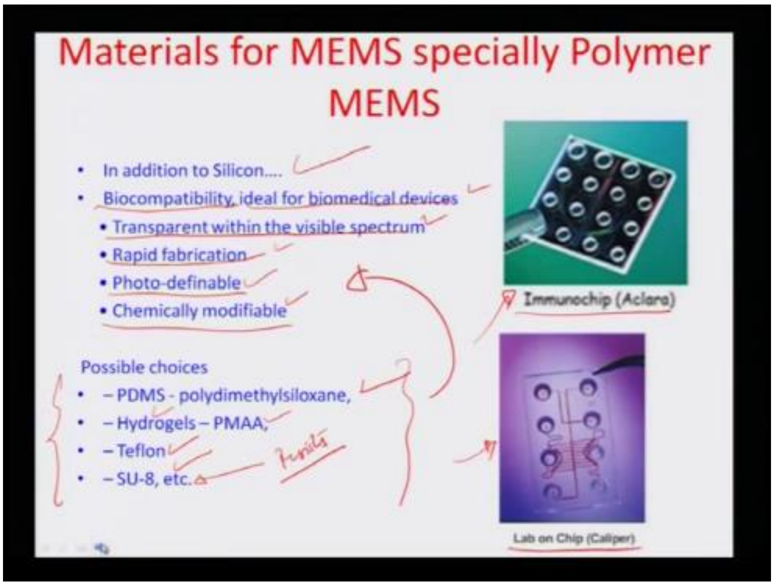

Materials for MEMS specially Polymer MEMS

- In addition to Silicon....
- Biocompatibility, ideal for biomedical devices
  - Transparent within the visible spectrum
  - Rapid fabrication
  - Photo-definable
  - Chemically modifiable

Possible choices

- – PDMS - polydimethylsiloxane,
- – Hydrogels – PMAA,
- – Teflon
- – SU-8, etc.

Immunochip (Aclara)

Lab on Chip (Caliper)

So, in addition to silicon you know whatever polymers you are using must have this property of biocompatibility, should be ideal for biomedical devices. And the polymer should be transparent within the visible spectrum. It should be rapidly, you know fabricated so, the fabrication strategy should be very rapidly be able to develop. It should be photo definable; which means that you can actually expose it and based on that you can define the features and structures in a manner and then, can be chemically modifiable.

So, these are some of the desirable properties that would be in polymer MEMS. You know that it has biocompatible, it is optically transparent. It has properties of rapid fabrication; it has photo definability, and then chemical modifiability. And if you look at some of the choices that the polymeric systems offer with one or more of the properties indicated here. There are polydimethylsiloxane of course, it is one of the very fundamental, you know materials used in the biomes domain.

Then, we have hydrogels, hydrogels are very highly crosslink network of polymers, which has, you know the capacity of absorption of water or some other you know specific p h materials, and expand to almost 4, 5 times its own volume. So, that is how hydrogels are very-very important. PMMA, which is you mean resist again polymethyl methacrylate is a very-very useful MEMS material for purpose of micro nano work. And then off course teflon which is again highly hydrophobic in nature with a contact angle of around 120 degree also in the room temperature. And then off course some of the polymers like SU-8 acetylene 13; these are the classes of polymers known as resists.

So, all these are some of the choices that polymers have to offer for with one or more of the properties that have been indicated here. And to exemplify a few polymers used in as on date available commercial MEMS platform, you can look at this chip, it is a immuno chip from aclara technologies or as a matter of fact this lab on chip from caliper systems, which are actually commercially available and they are totally made with optically transparent, for to definable polymer material. And they find great use and great normality for many biological diagnostics and detection modalities.

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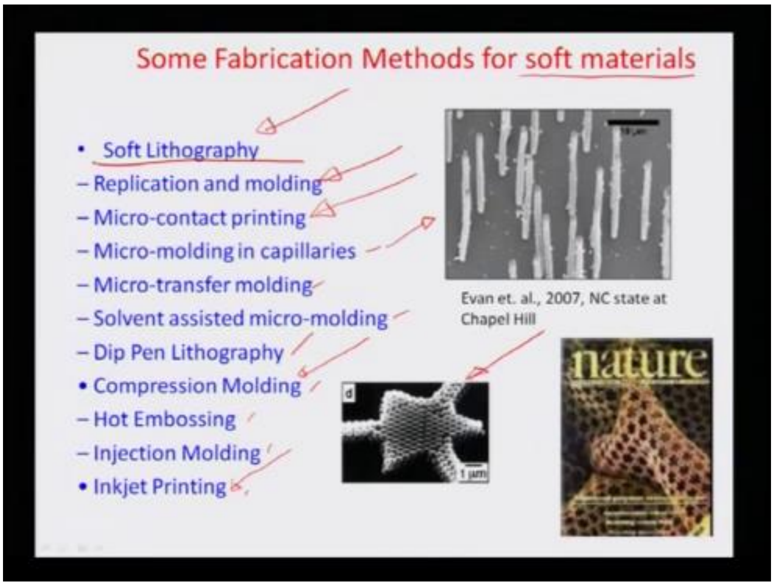

Some Fabrication Methods for soft materials

- Soft Lithography
  - Replication and molding
  - Micro-contact printing
  - Micro-molding in capillaries
  - Micro-transfer molding
  - Solvent assisted micro-molding
  - Dip Pen Lithography
- Compression Molding
  - Hot Embossing
  - Injection Molding
- Inkjet Printing

Evan et. al., 2007, NC state at Chapel Hill

So, let us look at now some of the fabrication strategies and methods which can be used with polymers. And we really classify these polymers as soft materials by virtue of their properties. You know it is they have a sort of softness in terms of strength when you consider these polymers, so that is why they are called as soft materials. And the soft material domain also includes biological materials apart from polymers. And all these fabrication has really started from white side scrub, which can be called the sort of founder of how to fabricate some of the polymer MEMS.

And the domain of process, which is used mostly for the fabrication of the soft material is also known as soft lithography, just because you are using soft polymers. And you have to use one step of lithography which can be then used, you know the mold that you eventually create can be used many times to have, you know soft material again and again molded across that mold. So, you have one step lithography followed by soft material driven, micro molding which would result in features and structures of the micro scale. And you can prototype it very-very rapidly as well.

So, some of the soft lithography techniques of course, replication and molding is a major technique again developed at white sides laboratory. Micro-contact printing again, micro-molding in capillaries, micro-transfer molding, solvent assisted molding, micro molding. And then these two processes Dip Pen lithography and compression molding, which includes hot embossing or injection molding and inject printing. These are some of the methods which can be classified under the domain of polymer MEMS. So, soft lithography is a class or processes. Compression molding is another class of processes and the inject printing is a third class of processes. These are some examples of what can be done with polymer MEMS.

For example, this is an illustration of how PDMS is doped with the Fe 2 O 3 particle can be used to make this high aspect ratio structures. So, these structures must be about close to 20-30 microns high, and may be about 2 microns in diameters, and this can be used as tentacles. Just because they have Fe 2 O 3, there is a tendency of an external magnetic field to move them and they can be used for paddling action, which can move forward the organism which would have or possess these tentacles.

So, similarly this is an interesting example of what soft lithography can do. You can see this replication of a natural surface using polydimethylsiloxane. And very high aspect ratio or application is possible because of the unique property of this polymer, which is actually liquid at room temperature, but it crosslinks and cross bonds once you heat it at a certain temperature. So, let us look in to some of the details of these processes.

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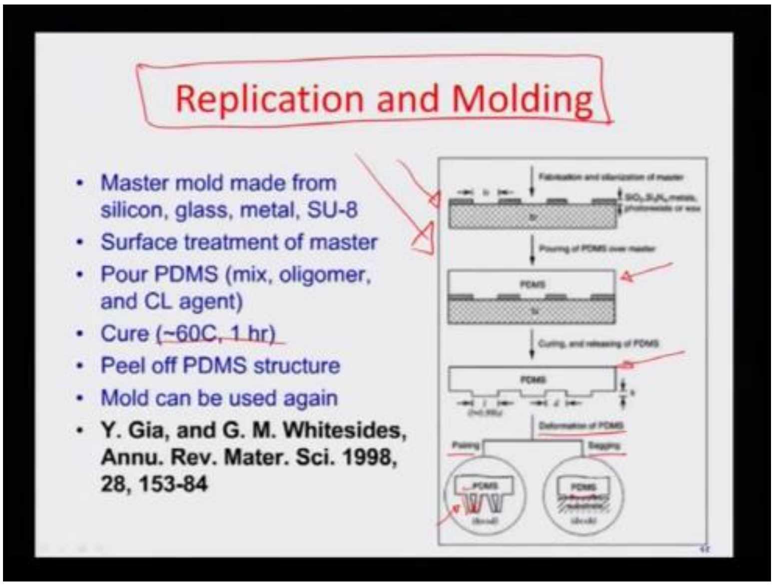

Replication and Molding

- Master mold made from silicon, glass, metal, SU-8
- Surface treatment of master
- Pour PDMS (mix, oligomer, and CL agent)
- Cure (~60C, 1 hr)
- Peel off PDMS structure
- Mold can be used again
- **Y. Gia, and G. M. Whitesides, Annu. Rev. Mater. Sci. 1998, 28, 153-84**

So, the first process which comes to our mind is replication and molding process, which is actually illustrated in the schematic towards the right here. So, what happens is that, you create a master mold which is made up of silicon glass metal or SU-8 resist. Using lithography you can create this mold, and this mold has as a sort of negative impression of whatever you would like to realize on the surface of micro features and micro structures. So, the mask is exactly the opposite inverted or negative of what features you are wanting to obtain. So, once this mold is prepared the mold is basically coated with some surface treatment is done with some layer of HMDS or some hydrophilic, hydrophobic material. And after this coating is over, basically after this treatment of, you know putting a mold release agent is over.

So, this is a mold release agent that we talking about. You pour a PDMS, which is actually available as a liquid form and it is a mixture of silicon matrix and a curing agent and you mix it in a proper ratio of 10 is to 1 or 5 is to 1 by volume. And the curing agent basically ensures the cross bonding between the silicon rubber on of the material. So, once you pour this polymer on the top of this mold which already has been coated by a mold release agent, the heat cure this PDMS for about 60 degrees and about 1 hour, so that it gets finely cross bonded.

The cross bonding reaction is again heat catalyzed, so if you put it in the normal ambient room temperature, it can still get cross linked, but it would take a huge amount of time. So, in order to accelerate the process you have to actually heat cure it. Applying heat is equivalent of applying a catalyst and so it gets into rubbery form. And then, because the mold release agent is already there on the mold, the robbery form can be withdrawn from the mold without any much problems. And then, you can have the exact negative of the features which were there in the mold imprinted onto this PDMS. So, it is like a rubber stamp that you are making in this process.

And then, you have to be little careful because PDMS is a soft material, so there are issues of aspect ratios where length and the width can be very-very critical if you have to. So, if it is a high aspect ratio then there may be a tendency of these features to kind of stick to each other as you remove them from the mold. If this low aspect ratio that means the, you know the height is much lesser in comparison to the width. There is a problem of the PDMS sagging down its weight. And then closure of the feature or structure can be achieved this way.

So, therefore you will have to be careful about these two phenomena pairing and sagging, because of the soft nature of the PDMS material, but again it is a very useful process where you can actually make a, you know a replica, which can be having structures and features of the size range of about 10s of microns on to the surface. And you can use it as a stamp, you can do variety of other processes based on that. And it is one on the fundamental processes in soft lithography this replication and molding technique. It is very-very easily doable in any laboratory with just a little bit of infrastructure.