BioMEMS and Microfluidics
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Lecture – 04

To this class on introduction to bioMEMS and Microsystems...

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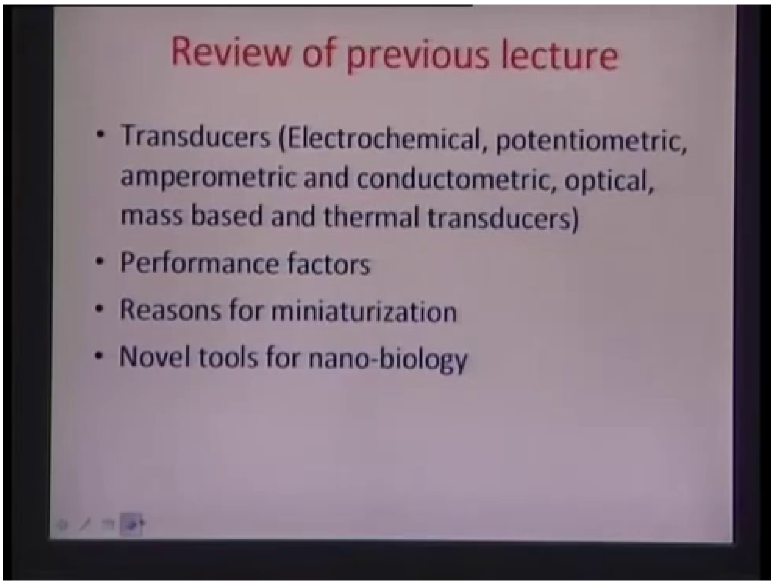

So, basically, if you look at what has been done in the last lecture, we talked last time about different forms of transducers. And, transduction again is a phenomenon, where in there is a change in signal from one form to another. So, at length, we talked about electrochemical, potentiometric, amperometric, conductometric and so on and so forth type of transducers. We also talked about different optical, mass based and thermal mechanisms of transduction process. So, we… Following this, we actually discussed about different performance factors of different sensors and some of them being sensitivity, selectivity, working life time, etcetera. You may just remember that.

Then, we at length talked about what are the needs and reasons really for miniaturizing these sensors into small platforms. Some of them being the deuced use of reagent volumes, which we use for detection – a better thermal control on the devices especially in biological micro reactors; and, sometimes control because of very less volume on the diffusional processes, which results in rapid mixing, etcetera; when you have this thermal cycling action taking place so on, so forth. So, then, we discussed some novel tools of nano-biology, where nano-biology is essentially the area, where we really study about single cell behavior in terms of processes like translation and transcription and signaling between different cells, so on, so forth.

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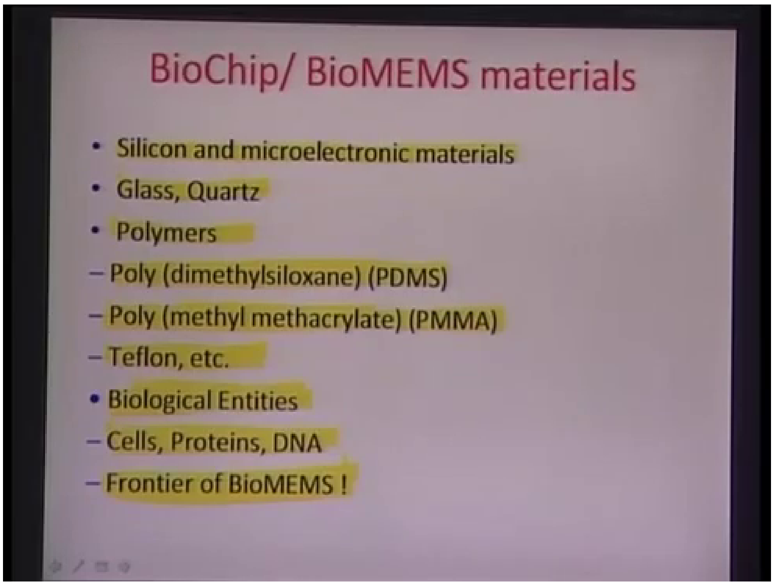

Today, we are going to look at more into the microsystems engineering and we are going to explore some of the materials that are used for designing this biochips or bioMEMS kind of platforms. We are also going to talk about some of the fabrication processes, which are related to realizing these architectures essentially as fallout of the silicon industry; it can be directly translated on to making features, which are small micro domain, etcetera. We are also going to look into some of the alternative techniques using polymers, which are available, where we can do in a very easy and inexpensive manner fabrication of such micro devices. So, if you look at some of the materials, which are used for biochips or bioMEMS device fabrication, we start with the first material, that is, silicon; and, essentially, all the processors, which are borrowed from micro electronics.

The other important material that is being used off and on is glass and quartz. And, one of the reasons why that is so is that because we are talking about transduction processes. And, sometimes, transduction means chemical to optical signal transduction. Therefore, essentially, a transparent medium like glass or quartz is very much required for covering these devices typically. And therefore, glass and quartz forms an important material for fabrication of some of these biochips. Alternate materials like polymers – we have been talking this off and on that because we are talking about biological entities or biological systems. They tend to be very happy in fluid environment and also while in the presence of carbonaceous materials and polymers being carbon-rich materials; then, process of these BioMEMS devices are slowly shifting from silicon-based processes into polymer-based processes.

One of the other important aspects of polymer is their ease and inexpensiveness of fabrication. Some of the important polymers that we use off and on for such techniques are this wonderful silicone rubber called poly dimethylsiloxane – PDMS – we use for … which we use for a process called replication and molding; we shall be talking in the next few slides. PMMA – polymethyl methacrylate, which is also an e-beam resist is very often used for realizing some of these small features and structures. And then, there is Teflon essentially, which is a very very highly hydrophobic substance. If you put a droplet of water on to Teflon surface and normal Teflon surface, the contact angle that the droplet has is in the range of about 120 degrees. And, it shows about how hydrophobic, how super hydrophobic the Teflon surface is. So, these are sometimes used especially for optical applications sometimes, Teflon, refractive index being lesser than water or lower than water, can use very well into micro architectures, but to form optical wave guides.

So, these are some of the alternate routes that bioMEMS or biochips are fabricated with. And then, there is this whole new area of trying to realize the devices using biological entities themselves. And, this is really some of – one of the novel frontiers in the area of bioMEMS. And, most of the research, which is done now mostly is how to realize devices using moieties like cells, proteins, DNA, so on and so forth. And, essentially, the whole idea is that, these biological entities tend to behave in the presence of other biological entities like cells, proteins, DNA, so on and so forth. So, we have this concept of making filters using one or more Y-shaped DNA molecules, where you could probably some day be able to actually do a molecule by molecule filtering.

So, there are several interesting and novel concepts in this particular area. So, let us look into some of the fabrication aspects and we start with what silicon has to offer as a fallout of the microelectronic industry. So, really this topic is all about the formation of structures that could be used to form senses and actuators using some of the conventional silicon processing techniques like as etching, deposition, for lithography, oxidation, epitaxy, so on and so forth.

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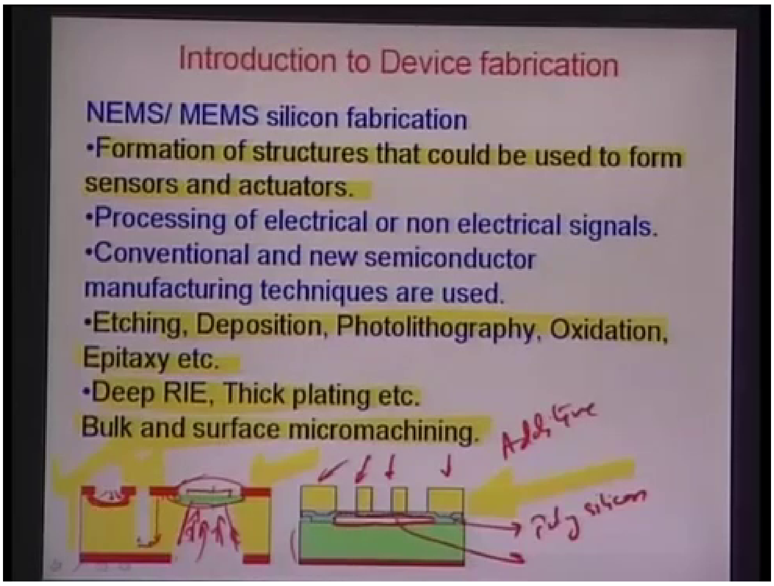

The purpose of these are to make some kind of a processing of either electrical or non-electrical signal generated by some effect, which is a result of the sensing activity. And, essentially, there are some other techniques particularly used for MEMS applications or micro-fabrication applications. And, these two techniques form a very important aspect. One is thick plating, where we can make probably more than a micron size film by electroplating on to a surface or deep RIE or deep reactive ion etching, where you can use the plasma to chemically etch silicon surfaces.

So, as I have been taking about before, if you really classify this whole area of micromachining, we could actually categorize then into bulk and surface micromachining. And, this figure here on the left really shows what bulk micromachining would look like; and, this again is surface machining. So, if you look at this figure, bulk machining is all about trying to take away or subtractively remove material from the bulk all the volume of the material. So, this essentially as you see here is silicon – is a cross-sectional view of the silicon wafer.

This red layer here as you see on the top is essentially a protective sacrificial layer, which is used for preventing the etchant solution or the etchant mechanism go into certain selected areas over the wafer, where this mask – we call it a mask – a hard mask; where this mask is absent or removed, you have this etching effect due to which material is removed. Like if you see in this particular zone, let us say in particular zone, this area has been formulated by a cratering effect, wherein an etchant has gone in and removed the material though this red mask on the top of it.

So, this is what wet etching typically does. And, if you look at it closely, you would find out that, there is always an under cut in such an etching process, wherein the irrespective of how thick the masking material is, there is always a tendency of the material to get removed from underneath the mask to a reasonable extent. So, the idea is that, you have to design the mask while designing such kind of etching techniques using or keeping this at the back of your mind. So, the mask size has to be typically a little lesser than the size that you would like to etch way in the silicon material.

This is another very interesting example of a high aspect ratio etching, wherein gas plasmas like gases like fluorine and chlorine are used to rapidly take away silicon atoms from the surface using this masking layer again. The advantage in that kind of a mechanism is that, if you look at the aspect ratio here, these processes can really make high aspect ratio features and structures; and, typically with straight etches; that is another advantage. And so, there are applications, where you need such kind of high aspect structures and MEMS, where you can use RIE-based etching.

This again is a very fine example. And, this is essentially a thin diaphragm, which has been realized by using a p plus silicon, which is achieved by doping of normal silicon. So, essentially, you are having a two-sided process, where on the front side, you use some etching action to remove this sacrificial layer; and, on the bottom side, you use – first, remove the layer and then eat away the silicon material, so that you can go all the way up to the p double plus, where the etch stops typically.

You are left with a very thin film or a diaphragm, which can be used for a variety of applications. One application could come off hand is a pressure transducer. So, if you have let us say a piezo material deposited somehow on the top of this thin ((Refer Slide Time: 10:51)) and you are having this as a part of a circuit; but, there is a pressure from this end, there is always a vibration, there is always a bending of the diaphragm due to which there is a signal. And, from that, you could calibrate the ambient pressure available from the closed end of the circuit like this. So, these are some of the illustrations, where you can see how bulk micromachining is being done. A surface micromachining on the other hand is an additive process typically, where you are actually building material on the surface of silicon. So, essentially these pillars what you see here are built on a surface of this base wafer – this mother wafer and this is essentially what surface micromachining is all about.

So, another very interesting factor is if you see this particular area here, you can find out… And, let me see whether the eraser has… Just give me one minute. So, if you see this particular area here; you find out that, it has been nicely carved on the inside of a polysilicon film. So, this is actually essentially a polysilicon small layer. And, you us a sacrificial resist layer here. You spin code this resist in a manner that, part of the resist stays over. And then, use deposition technology to deposit a thin film of poly silicon. And, later on, remove the sacrificial material away to realize this is small embedded micro channel kind of feature. However, this is also a surface micromachining process because you are considering a thin film, which is able to surround small cavity within itself and thus realizing a small covered micro channel.

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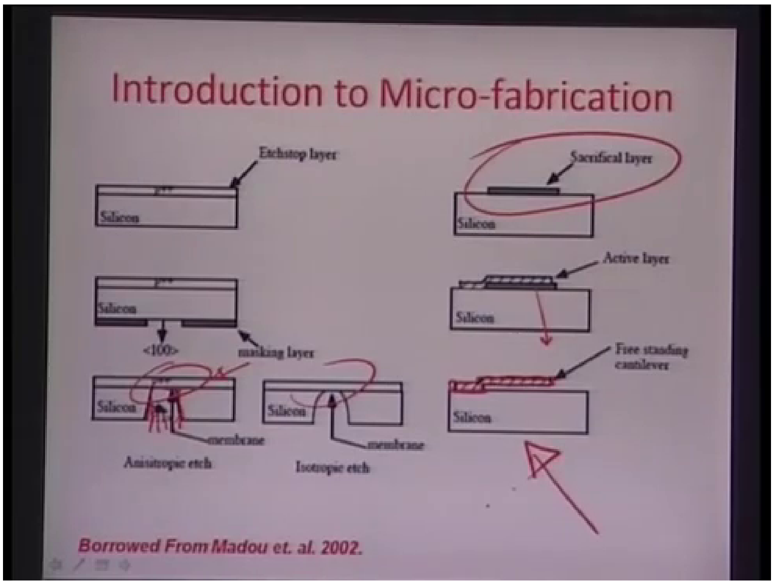

So, there are several important applications of micro fabrication processes. This slide has been borrowed from text book written by Professor Marc Madou, which talks about how the various processes can be integrated together to realize things like diaphragms, which we have already seen. So, this is a p double plus thin membrane. And, you are etching it from the back side, so that the material that we use is essentially an etchstop on p double plus, so that it does not go ahead. And so, you are left with the very thin film here.

So, similarly, if you try to build a micro cantilever, the process to do it is that, you build a sacrificial layer here as you see and the deposit something like an active layer, which is this high strength material, which is typically having high strength. And then, the idea is that, when you take away the sacrificial layer, you are left with this thin cantilever on the surface of the silicon. So, some of these schemes do help us in realizing structures and features, which are very very useful as we will see later in many applications for detection and sensing.

Now, this diagram that we have been illustrating is also known as a fabrication schematic and or a fabrication flow chart. And, typically, all the processing is planned at the outset. Such a flow chart is made to give a sequence of processes. We should go into realize the microscopic feature that we are considering.

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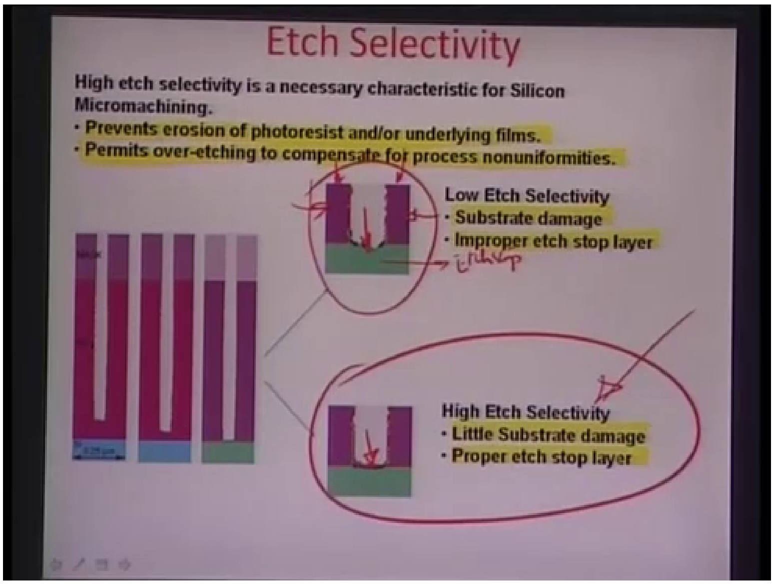

So, etch selectivity – this is a very important aspect again in fabrication. Essentially this – the way that an etchant behaves with respect to a surface over which it is etching. And, essentially, high etch selectivity is a process or is a property wherein the etchant that we are using would be able to etch up to the extent that we want to etch on the silicon. To illustrate it a little better, if you see at this, if you look at this particular figure here; so, essentially, you have a sacrificial layer as you can see on both sides here and also covering the silicon wafer – the base silicon wafer from the top. And, this is an illustration of low etch selectivity. So, essentially, when you are using an agent, which slightly eats away the material on the sides and also is not… And, also on… This essentially is an etchstop. So, this is an etchstop layer; that means the etching should stop up to here.

But, then if you look at this profile, which has been generative, the etching goes all the way through and it really does not stop at the instance that it is supposed to stop. So, this etchant – this particular etchant has a low etch selectivity on the substrate. So, it causes typically a phenomenon like substrate damage; and it is basically because of the improper etchstops, sometimes realizes features and sizes in a manner that we do not expect them to realize. So, the process has a lot of non uniformities because of an incomplete or because of an improper etching or because of a low etch selectivity. So, essentially, high etch selectivity is necessary characteristic for silicon micromachining. And, the higher the etch selectivity is, the more it prevents erosion of photoresist or underlying films; and, permits over etching to compensate for process non uniformity.

This on the other hand, if you look at the figure here on the down here is a process, which signifies high etch selectivity. So, if you look at this process, you can find out very easily and probably can differentiate between its counterpart, which I have just illustrated on the top here; you see the profile, which is generated after the etching, the post etching profile here and the post etching profile here; and, you find out that because of the high etch selectivity, the surfaces are little better or a little more uniform than the non uniformities, which you observe in the low etch selectivity case. So, essentially, if a process has a high etch selectivity, then it has a little substrate damage and there is a proper etchstop layer. And, essentially things are in your control. So, you can do what you really want to do on in terms of etching away or removing material. So, that is what etch selectivity is.

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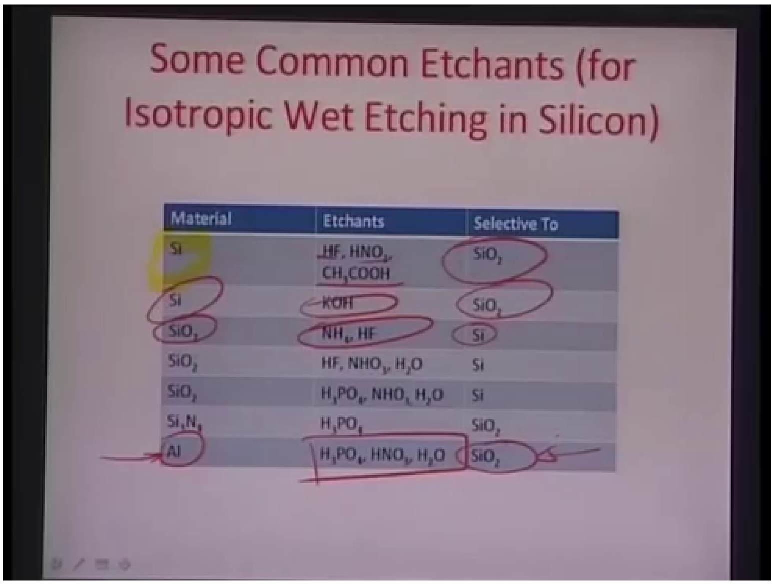

So, when we talk about some of the common isotropic wet etching etchants in silicon, we always talk in reference to what is the material that is used to etch; what is the particular etchant and what is it selective to. So, essentially, if we are talking about the material silicon, it can be very well etched by these four different etching agents – hydrofluoric acid, HNO_3 and CH_3COOH. And so, essentially, these etchants are used for etching over silicon, but it is very selective to SiO_2. Therefore, SiO_2 layer or silicon dioxide layer can be used and etchstop in these situations. Similarly, if you talk about KOH – potassium hydroxide, it can selectively etch away silicon, but at the cost of SiO_2; but it is prevented or the etching process stops when once it meets SiO_2. There are other etchants, which are illustrated in this particular table and you can probably go through – NH_4, HF used for etching SiO_2; but, it is selective to Si. So, immediately, it encounters a Si layer, the etching process stops, so on, and so forth. So, what is interesting here is there is also such etchants, which are used for metals on these silicon or other substrates.

One reason why metals are used as a probably everybody knows, is to develop interconnects between the different part of the circuitry that is being put on such a wafer. So, therefore, there has to be some etchants for metals as well, which can make them to the shape and size desirable to form the conduits or the electrical connectivity between two or more components on the wafer. So, if you talk about aluminum phosphoric acid – H_3PO_4, HNO_3, water; this combination acts as a very good agent – etchant; but, it is selective to again SiO_2; that means the moment it encounters the SiO_2, the etch automatically stops and this can be a very good masking layer – sacrificial masking layer when you want to selectively etch aluminum away, deposit it on a surface.

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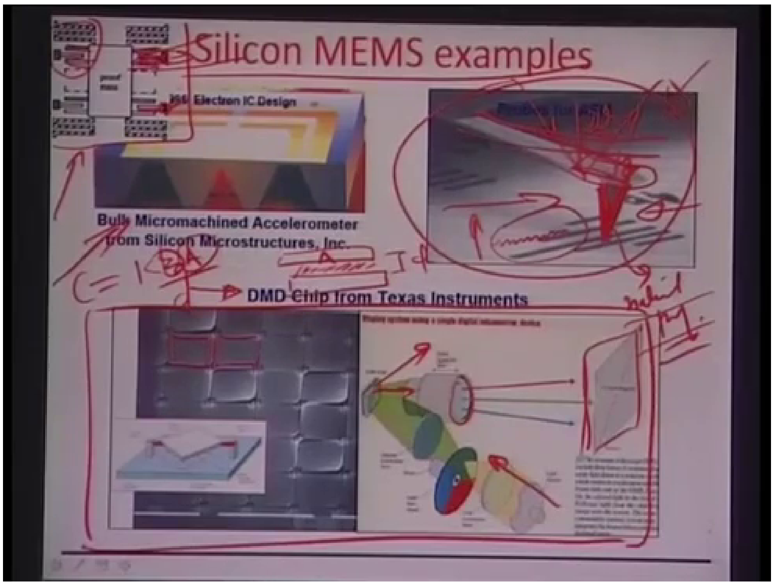

So, these are some basic processes and we will be looking into a lot more details once we come to the actual fabrication part of the lectures. How… What I would like to illustrate now is some of the applications and devices that we off and on use in silicon MEMS; and, these examples have been borrowed off and on from industrial or commercial use. And, you will probably be able to gauge what utility MEMS has in common day to day life. So, this figure here if you look at is actually a bulk micromachined accelerometer. And, this figure has been borrowed from silicon microstructures.

So, essentially, in this particular device, the basic operating principle schematically explained in this particular region – if you see here, there is a vibrating proof mass; which means that this mass is essentially on the top of a pivotal kind of structure – microstructure. And, it is able to vibrate. So, as if there is a hanging mass with a point support from the bottom and it is able to vibrate like this. So, it has several degrees of freedom. It can probably vibrate in let us say this alpha direction on a perpendicular beta direction; and then, it also can turn and twist like this. So, this is a wonderful structure, because such structures can be used to gauge very precisely or very accurately the change in acceleration roll, pitch, yaw and these different physical processes.

So, what essentially happens here is – if you look into this particular setup here; so, these two as you have illustrated here by the marks that I am making are a part of the proof mask. So, they are like wings coming out of the proof mass. So, this is the proof mass and there are the small wings on all four sides. And, these other structure which are in between here – these other four structures, which are in between here are really on the base of the silicon wafer. So, they are not really moving.

So, the wings which are along the proof mass, as the proof mass oscillates and moves, also move along with the mass. And, what happens as a result is that, there is a change in capacitance between the wings and this portion of the device because of a continuous change in distance and interfacial area. If you all recall your Physics days, the capacitance can also be written as $C=\frac{k\varepsilon_0 A}{d}$; where, A is the interfacial area of a parallel plate capacitor; d is the distance between them; and, $k\varepsilon_0$ is nothing but the dielectric permittivity of the medium. If you are putting a dialectic material in between here, then it is actually… it signifies a greater unit E value for k. And, ε_0 essentially is the permittivity of free space.

So, as the area between these three structures – the interfacial area changes because of this vibration of the wings with respect to the static structure; and, the distance also increases or decreases; there is a change in capacitance; and, we can actually correlate that change in capacitance to things like let us say acceleration, roll or pitch, yaw. And, so, therefore, this whole accelerometer – this whole concept can be used to very sensitively detect acceleration. The advantage here is that, because of a very small amount of proof mass that we are actually considering, even smallest amount of change in acceleration or deceleration related to a moving structure can be very easily recorded because of the small amount of mass that is involved. So, therefore, it is a fantastic example of what silicon micromachining can do.

This is again a very interesting example which I keep illustrating. This is one of the corner stones of nano technology. This is the AFM tip – atomic force microscope tip. The way it moves on a surface or the way that it is able to gauge a surface is by rastering on the surface with a very small sharp pointed tip here. So, it is like a cantilever arrangement. And, there is a small tip here; and, the step actually moves over in the surface. So, this is a surface that we are trying to kind of gauge. So, as it moves along, there are to modes of operation that it has: one is called the static mode and other is the taping mode. So, in the static mode, what happens is that, as it rasters along the surface due to the different forces that it encounters between the topography on the surface, which is referred smooth, it generates a set of vibrations.

One of the first principles that were used for detecting these vibrations are by using a mirror on the top of this AFM pro and shining a laser on the top of that mirror. And so, the idea is that, if the tip moves with an angle of let's say theta, the light beam here would move with an angle of 2 θ . So, essentially, this used to be a basis of finding out what is the z-displacement that this tip would have as it moves along a rough surface. And, from that, you could gauge the average surface roughness. Now, of course, there is lot of complicated electronics which goes into detecting what exactly is the z-displacement. And, essentially, the AFM image that you see is really a reconstructed image; it is not a hands-on or a real image. So, from all these z-displacements pulled together in a software, you would be able to gauge what the surface roughness is like as the A from scan of surface.

There is another mode, which is simultaneously used in a lot applications. It is called the tapping mode in which essentially this tip here is having a natural frequency of vibration. So, say you are basically exciting the tip in that case by it rasters over the surface. And, the idea is that, if it comes too close or too far away from the surface and there is a change in force; and, these forces mind you; between the tip and the surface, it could be due to many reasons; it could be due to van der Waals forces of interaction between the nucleus on one and the electron on another. Or, it could be some repulsive forces because of the electron-electron repulsion, so on and so forth. So, there is a variety of forces, which come into play. So, as these forces are executed on a vibrating tip, there is a change in the fundamental frequency of vibration because of that. And, from that, you could gauge what is the surface roughness, which the AFM is trying to measure. So, it is one of the most fascinating tools probably that this technology – this MEMS technology has given to the field of physical sciences. And, we all probably know how important the AFM is in terms of gauging a very small fine structures at the submicron domain.

Another very fascinating example of how silicon MEMS are used in the industry is this.

Digital micro mirror device chip from Texas Instruments. The projector – the common laboratory projector – because of which, essentially I am being filmed and I am able to give this lecture is based on the MEMS technology. And, essentially, the idea is very simple that you have so-called a mirror, which is pivoted on these two pivots on both sides. And, this mirror has an electrical imprint on its backside. So, we are talking about the small plate here – the shiny plate here made up of metal, which has an electrical connection on its backside. The base over which these pillars used for pivoting this mirror are resting also has simultaneously electrical connections on its surface. So, if you are considering this thin film, which is hanging between let us say two pivotal points and there is a surface in the bottom; there is essentially an interaction going on between the electrodes based on the backside of this mirror or this film and the surface of the silicon material. And, because of this electrical force, there is a tendency of the mirror to rotate about the pivot – pivotal point.

So, let me just illustrate this little more clearly here; just give me a minute. So, if you look at this particular structure here; it is very fantastic way of rotating. The rotation takes place over these two edges here. And, essentially there is an array of such mirrors. And, these mirrors are very very tiny, let us say about 10 micron into 10 micron or so. It corresponds to what you called a pixel. And, essentially, when there is a light beam, which is reflected of this mirror, we can actually deviate the light beam into the path of the image or outside the path of the image by just reflecting this mirror. So, in one instance, maybe the beam, which is coming from let us say this particular source goes into one of these mirrors here; and, the mirror is able to deflect the beam through the lens on to the screen for the projection.

In other instance, because of this electrical actuation, the mirror goes out of view and the light is not passed through the lens in the process. So, what we are essentially trying to do is to switch on and off the various pixels. So, one of these mirrors forms one pixel and there are millions of pixels, which makes an image. So, if there is a tendency of these mirrors to rotate and out focus, some of the pixels would be switched off essentially. And so, therefore, the image on a computer is in a digital manner transferred to such a device – DMD chip form of device, where these light beams are essentially used for switching off and on various pixels on getting signals 1's and 0's. And, digitally, an image can be transferred from a computer to a projector. So, these are some of the examples of commercially available silicon MEMS.

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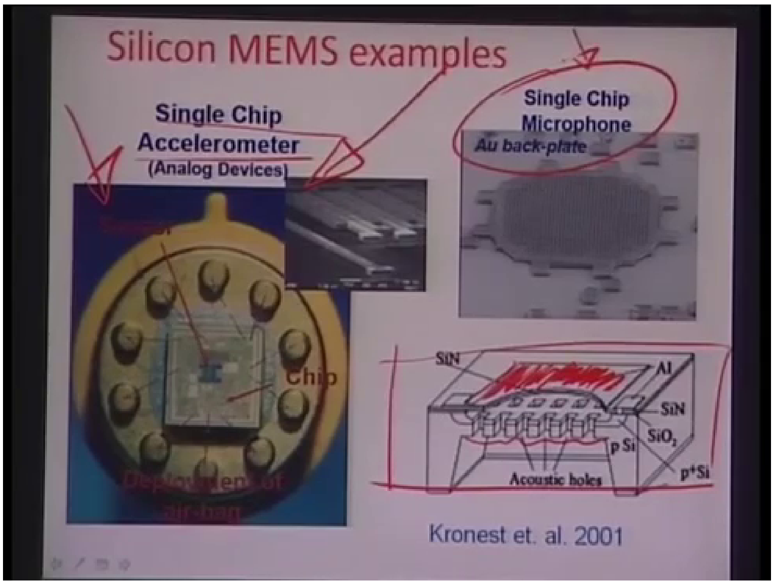

Let us actually look into a little more of what other applications are possible. This is a fascinating example borrowed from analog devices. And, by the by, analog devices is one of the commercial companies, which sells a lot of these accelerometer chips. Essentially, all the auto wheels have the mechanism called… That, there is a mechanism, wherein there is an accident prevention by actuating a balloon. Wherever there is a crash, there is a safety mechanism in most of these auto wheels, where there is an airbag, which comes out. We call it the airbag technology; but, essentially, it is an air balloon, which comes out and prevents the driver from crashing into the steering.

These chips here – these accelerometer chips here are essentially used to control – sense such accelerations; the moment it crosses certain limit, where there is a tendency of this driver to be driven. And, this happens only when a high speed auto wheel is suddenly brought to rest. Huge deceleration is there. And so, in that case, it opens a nitrogen bottle and it suddenly just fills the airbag; and, the airbag comes out in the steering area, so that a crash is prevented between the driver and the steering wheel. So, such devices are very very successful, commercially available, and repeatable. And, these are potential application of MEMS.

Another very interesting application is this – single chip microphone. The small button mike, which I am actually using for speaking today is essentially based on MEMS technology. So, if you look at the basic structure of such a mechanism, it has a perforated diaphragm at the microscopic lens scale. And, there is a piezo material on the top of this diaphragm. So, the idea is that, whatever we are speaking… What is speech really? Or, why is it that, if I am saying something, you are able to hear. So, sound wave as you know is a set of compression and rarefaction. So, when this whole… When we are trying to communicate, we are trying to essentially move the air from our mouth by various movements of our tongue and creating a series of this compression and rarefaction which goes are emanates from my mouth and that waves goes ahead and you are able to get the same sensation. And, your ear is essentially a transducer which tries to get a signal based on that.

Now, if you look at the same process in a silicon microchip, this diaphragm here is a very sensitive – is a very thin and very sensitive vibration-based mechanism, where these compression and rarefactions can be really actuated into electrical signals. And, that is by means of this piezo layer, which is stacked on the top of this perforated diaphragm. And so, therefore, whatever we are speaking is converted into electrical signals. And, they are transported long distances essentially. And then, they can be again reconverted back by again similar kind of diaphragm, which produces the inverse effect; that means electrical signal is converted back into mechanical vibration. And, that is what the speaker essentially does – the loud speaker essentially does. So, that is a very fine example of what again silicon MEMS can do; it is a single chip microphone.

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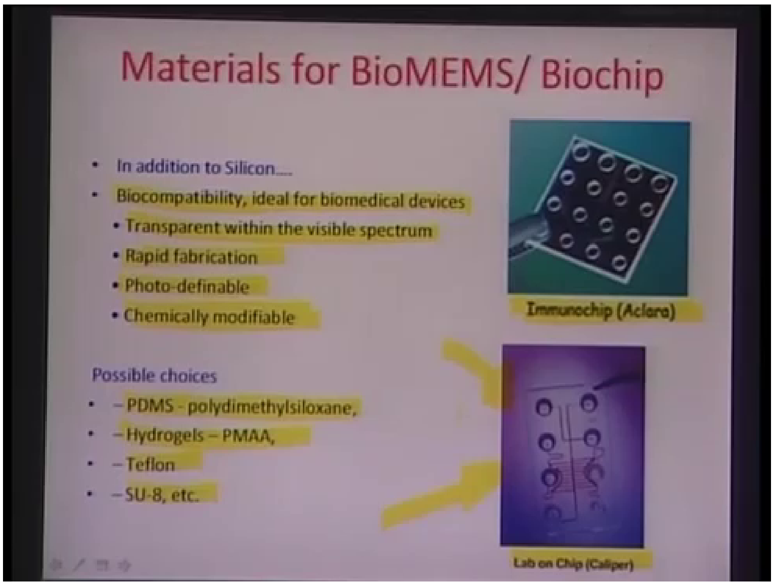

So, after discussing this, I would like to shift my focus a little bit into polymer MEMS. And, especially MEMS with a perspective of biology, because the area that we are mentioning is bioMEMS or biochip. So, as I indicated earlier, in addition to silicon, because of biocompatibility aspects, there is huge demand of polymer-based microsystems. Some of the possible choices that I mentioned before and I am going to retreat here are polydimethylsiloxane as you can see here in this; hydrogels – a very interesting polymeric systems, which are used for making these bioMEMS kind of devices – PMAA – poly methyl methacrylate, teflon and SU-8; it is a negative tone of auto resist. In our first lecture, we talked a little bit about what negative tone resist does. Basically, something which gets exposed to live and gets cross bonded. So, it can remain…

So, what are the requirements really for material selection? Or, what are the material selection criteria for realizing bioMEMS or biochips. So, one aspect of course is biocompatibility – whether the material we are using is an ideal material for the biological entities to keep happy and function in a normal manner. Then, optical transparency again within the visible spectrum is a very important aspect of such systems. Basically, the materials – most of the transaction processes, where we convert a chemical signal into an optical signal involves the reading and reading of the light. So, optical clarity or transparency is really one of the major issues, which we should consider in material selection for bioMEMS devices.

Rapid fabrication again – how rapidly you could manufacture; we had to manufacture many of those MEMs devices within a short amount of time; polymer being expensive. There is a tendency of the industry to make mostly reusable chips. And therefore, they have to be produced at a great rate to keep up with the pace of diagnostic requirements of the industry. And then, of course, a polymer material or material should be such that it is photodefinable in the way that micro features or micro structures are translated are majority are done mostly through light as a means. And so, therefore, photodefinability or ability to be defined by using light or photons is a great criteria, which is very important for selection of materials.

Also, just because we want to study chemically active species, the material that we are using should be chemically modifiable. So, therefore, then we really do not want materials which are inert in nature; they should be easily be able to modify – get modified, so that we can attach recognition elements using covalent linkage or maybe using cross-linking agents. And therefore, chemical modifiability again is a very important aspect of these devices. So, if you look at these technologies, the immunochip from Aclara technology is again is an example, where plastic cartridge is used for doing immunological tests. Similarly, this right here is an illustration from Caliper technologies; it is a lab-on-chip platform, wherein micro channels and features are used to do a lot of diagnostics. But, again if you look at it, it is a transparent plastic that is used. Several such devices are available commercially. So, once we are actually…

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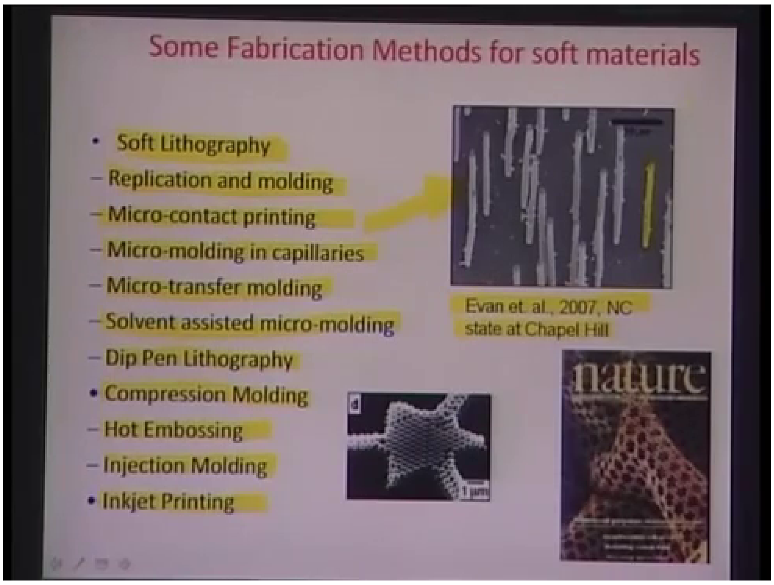

Once we have the selection criteria well-defined, the next question is how specially in case of polymers, we can fabricate these devices. So, this approach really started with Whitesides Group way back in about early part of the 90s. And, this approach is also known as soft lithography. So, essentially, there are several processes, which has come as a result of this basic replication and molding technique, which I am going to illustrate in details a little bit later. So, there are various approaches – replication and molding, micro-contact printing, micro-molding in capillaries, micro-transfer molding, solvent assisted micro molding, dip pen lithography. And then, there are some other approaches like compression molding, which encompasses hot embossing and injection molding. And also, nano imprint lithography. And then, you have inkjet printing. So, all the bunch of these processes are combination of such processes are sometimes very useful for realizing MEMS devices.

So, some illustrations that is reflected here. This is a work done by Evan et al. from North Carolina Chapel Hill back in 2007, where he talks about the fabrication of structures and features, which are above 80 or 90 microns in length and almost 2-3 microns in size. And, they are like cilia. We have been talking about cilia. If you remember, while we were talking about nose as a sensor; cilia is essentially a hair-like moiety So, how we make it? Essentially we use this material PDMS – polydimethylsiloxane and then try to increase the strength by making some nano particle addition to the material. And, with this high strength material, we can replicate the material once it is in liquid form and over some kind of a dye, and then solidify the material and pull off the dye to realize the cilia. So, the idea here was in this paper that, they wanted to use the additive iron-based – ferromagnetic additive for trying to move the cilia around with an external magnet. And, the idea was… The idea can be used for providing locomotion of a species like of the same range bacteria. Typically, bacteria also float around in the solution by this hair-like tentacles called cilia sometimes; which lets it go by with the pedaling action of this cilia there.

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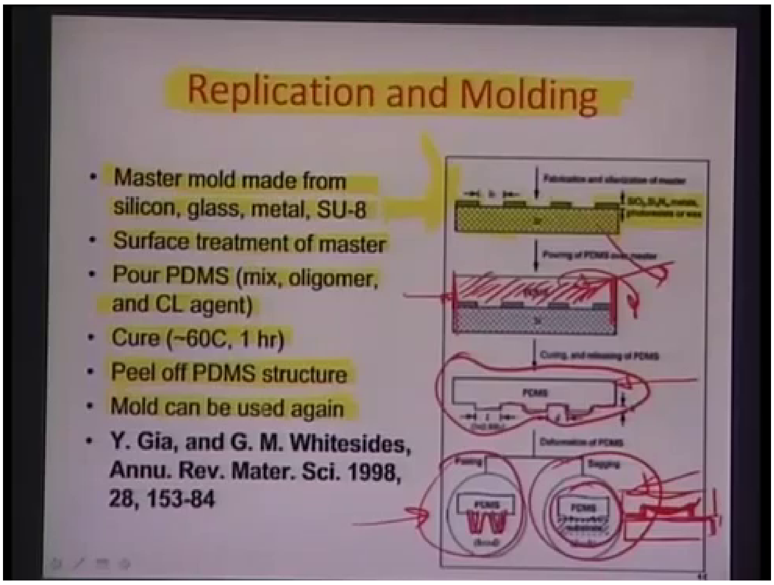

So, now, let us talk about the details of these processes one by one; so, replication and molding again. And, I would like you to focus now more on this figure here on the right of the slide. So, the process starts with something called a mold; and, this mold is essentially made up of silicon, wherein by using variety processes like maybe etching – wet etching – lithography and wet etching – you could realize these small small features on the top of this silicon wafer. So, these features are essentially the mold. And, as you are all aware, probably, that mold is something; it is a shape that is used for getting impregnated onto a liquid, which later on can solidify and take the inverse shape or negative shape of the mold. So, once this mold is realized and this mold mind you can be made using… And, these features here that I have been illustrating here can be made using silicon dioxide, silicon nitride, metals, photoresist, wax, so on and so forth. And, the thickness of this could be really very very small in the micron range. This mold is done.

Then, you pour this liquid material called PDMS – polydimethylsiloxane. And, let me give you a little more details about what PDMS really is. So, PDMS is actually a silicon rubber. And, essentially, it has two components: one is the resin part and another is a Bonderer cross binding agent or cross linking agent. And, we mix these two components in a certain ratio with maybe 10 parts to 1 part of the resin to the cross bonder or 5 parts to one part. And, the cross bonder is always of course, lower in volume than the basic resin. And, once – the property – the unique property of this material is that, once such a mix – after thorough mixing, is heated to a temperature of about 80 to 85 degree celsius for about close to 40-45 minutes. It cross links the polymer matrix and develops a rubbery kind of membranous structure.

What is also important to know about this material PDMS is that, it can actually replicate very high aspect ratio structures. So, suppose you have let's say a 25 paise coin and you want to replicate what is there on one side of the coin, which is essentially some features coming out; you all must have seen. So, if you can replicate this; so, you pour the PDMS, heat cure it and then remove this. And, you will be amazed to see that, whatever features are there on this 25 paise coin are the negative of those features are transferred on to the PDMS surface in toto. So, it is just a verb attempt transferred. So, that is the beauty.

So, this PDMS is a material, which goes into all the crevasses be it short, narrow, whatever; and, try to replicate everything very accurately. So, essentially, if you look at this slide back again, the PDMS in liquid form is poured over this mold material. And of course, there are walls on the side, which can prevent the flowing back. And so, therefore, the new heat cure it of course. And, the PDMS develops a rubbery kind of material in this particular area. And then, you can use, you can remove this material – this PDMS from the mold. Thus, the PDMS is left on the surface with a negative of the impression of the mold.

Now, these two steps need a little bit of pre-processing, because sometimes it is a very important; especially, if the PDMS layer is thin to keep it in one piece as you are removing. And therefore, we use these agents called mold release agents. So, essentially, this master when you fabricate, you ensure that, you treat or you pre-treat the surface with an agent like let us say trimethylchloresilane or some agent, which can preferentially do silanization on the surface and make the surface hydrophobic in nature. So, therefore, the idea is that, you put molecules and you put some groups or linkers or molecules I would say; not linkers on the surface of the mold, which is able to kind of fight with the PDMS molecules. So, it kicks it back. So, the only way to do that is to lower both the surface energies, so that you can separate or you can have an easier separation.

PDMS by the by is a very methyl-rich material with a lot of CH3 groups on the surface. And, if you look at the contact angle of PDMS material, it is about 108 degrees or so. So, you get the inverted replica of what you want to develop as mold. And therefore, the mold is planned in a manner, which is exactly the negative way of what you want as features or impressions on to the PDMS surface. Mold of course can be defined by photo lithography; it means where you prepare a cat file, expose a wafer, use a sacrificial layer, do etching or some other processing mechanism; and then, the mold is realized.

So, some issues with these processes is that, you really cannot go using normal PDMS over a certain aspect ratio, because if you look at these two typically processes – these two products; in this case, there are these long standing arms of the PDMS material. And, if they are just hanging by themselves, there is a tendency to kind of adhere to each other. One property of PDMS is that, it makes fine reversible bonds with any surface that is near about it. So, if you put it on a glass surface or a silicon surface, it results almost immediately in a reversible seal. So, that is the beauty of this particular material; it being soft, it can confirm to the surface of interest very accurately; and so, typically remove all air, which comes in between while this reversible region is going on very quickly.

This is another pitfall that, if you want to develop the PDMS in the form of a chamber and then you bond that upper layer of PDMS with a flat surface, you have to be careful about the aspect ratio here, because if it is too high, then this kind of a problem may happen. And, because of the weight, the PDMS may sag down like this and adhere to the surface and you are left with blocked reaction chamber essentially or a blocked chamber essentially. So, the process steps again highlighted here. So, you start with the master mold made up of silicon glass, metal SU-8, so on and so forth; you surface treat the master by using a silanization protocol, where you put some groups, which kind of repel the PDMS material.

You mix the oligomer and the curing agent and then prepare the PDMS and pore the PDMS on the top of this cured or silanized mold. And then, essentially, you hear it from 60 to 80 degrees for about 1 hour or so and then peel off the PDMS, so that whatever features are there on the surface of the mold, get replicated. And then, another advantage of this process is the mold really can be reused again and again. So, that is why it is extremely rapid also. So, it is identical to saying that, one mold can be used 20 times or 30 times. So, you do not have to make the mold again and again. And, you can just keep on pouring, curing, peeling off and then again reusing it. So, of course, it is a very economical and a very rapid process. So, the process was developed by Whitesides group again way back in 1998 when he reported that, this kind of techniques can be used for micro devices fabrication.

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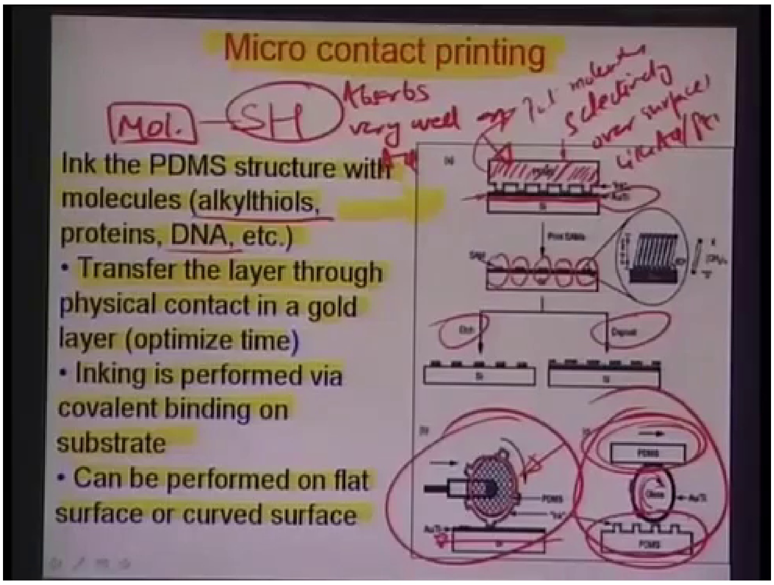

The next process that I would like to illustrate this micro contact printing; and it is again a very important process for the biological industry. So, in this process, what you do… And, if I would like to seek attention here to the figure. So, you would start with again a PDMS stamp. So, this is if you look at a PDMS stamp, which is developed by probably a replication or molding kind of technique; and, here you can… The basic purpose of micro contact printing is to put molecules selectively over surfaces like gold maybe or platinum. So, the whole idea is that, you start with the PDMS replica and then you coat this PDMS replica as you are seeing this region here with some kind of a molecule, which you would like to transfer.

Now, there can several kind of things that you could do for this transferring; you would actually transfer alkylthiols, you could transfer thiolated DNA or thiolated proteins on to the surface. So, essentially, something the molecule which has a feature wherein there is an adsorption of a part or a group of the molecule over the surface in question. And then, you have this silicon surface, which is coated with a thin film as you are seeing here in the top of gold and titanium. So, essentially, what you are talking here is that the titanium is used as an adhesion layer for under gold. So, you have a small film of titanium on the top of the silicon all through.

Let me just try to draw it here probably in this region. And then, beyond that, you have another thin film; this black film – gold. And so, there is a very highly stabilized structure. And so, what you do is this micro contact printing is essentially a stamping process. So, what happens in a rubber stamp? So, you take the stamp and putting it on the ink pad; and, you press it on the ink pad, so that ink gets transferred on to the stamp surface. And then, you take that stamp over on a piece paper and then put that stamp and wait for the paper to absorb the ink from the stamp surface by capillary effects. Once it is done, you remove the stamp and you find out that, whatever was there on the stamp, the negative of it has been printed on to the paper. So, this is an identical process.

Here instead of the paper, you are using a gold film on the surface; and, instead of the ink, you are transferring thiolated molecules. So, probably, some of you are aware that a molecule with the thiol group means SH adsorbs very well on gold surfaces. So, here we take the molecule and we press the stamp against the gold and wait for the whole reaction kinetics – the reaction of absorption to happen fully. And, there is a certain time constant with which it happens. And, we wait for that time and then pull off the stamp, so that the molecules, which were there on the stamp get transferred on to the gold surface as small heaps.

Now, there is an immense amount of use of this process especially when you are talking about hybridization arrays, where there is a requirement of putting, making, realizing a library of different capture probes for capturing different target DNA molecules. We need in a sense or surface on which we can put the small heaps of molecules of certain types and then we also should be able to know what is there on which column or which row of this matrix or array of molecules that we have created. So, micro contact printing essentially is a very important process for those kind of application. In sensory science, sensory technologies, micro contact printing is used off and on for such applications. And, you could use this process etching away or depositing; and, etching away means that you have a layer of these molecules already deposited – predeposited on the top of a gold surface from which you are probably taking a gold coated stamp and then putting it on and taking away some of the molecules.

So, that is etching and, deposition is a reverse, where you are actually leaving the molecules on to the surface. So, there have been some intelligent designs so far of modifications of this process, wherein a high throughput formulation of this molecule laying out on the surface is realized. This is one instance, where there is the roller mechanism, which actually picks up the molecules from some source probably and then it delivers rapidly on to a surface, which also moves in a direction conducive to the direction of rotation.

Similarly, there is this mechanism again. You can that, the molecules have been transferred from the PDMS stamp want to this PDMS by a central cylinder, which essentially picks up the molecule and places the molecule on this particular upper PDMS structure. So, in an actual, the following steps are involved in micro contact printing; you ink the PDMS surface with molecules – alkylthiols, proteins, DNA; transfer the layer through the physical contact in a gold layer and optimize the time, so that there is a good amount of time for the adsorption to fully take place. And then, of course, the inking is performed because of that via covalent binding of the substrate on the substrate or physisorption on the substrate. And, it can be performed on flat as well as curved surfaces. So, this is another important soft lithography process into question.

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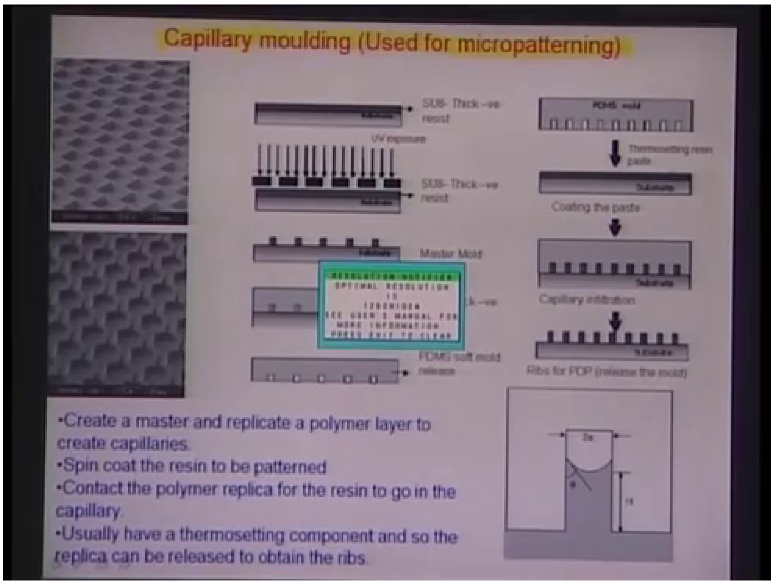

The other process, which is very important and sometimes used in display technologies is capillary molding. And, essentially the concept is again similar that, you essentially… So, essentially, the next process that we would be talking about is capillary molding used for micropatterning. And, probably this and subsequently some other soft lithography techniques we will cover in the next lecture.