Carbon Materials and Manufacturing
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Lecture - 28
X-Ray and Nano-Imprint Lithography

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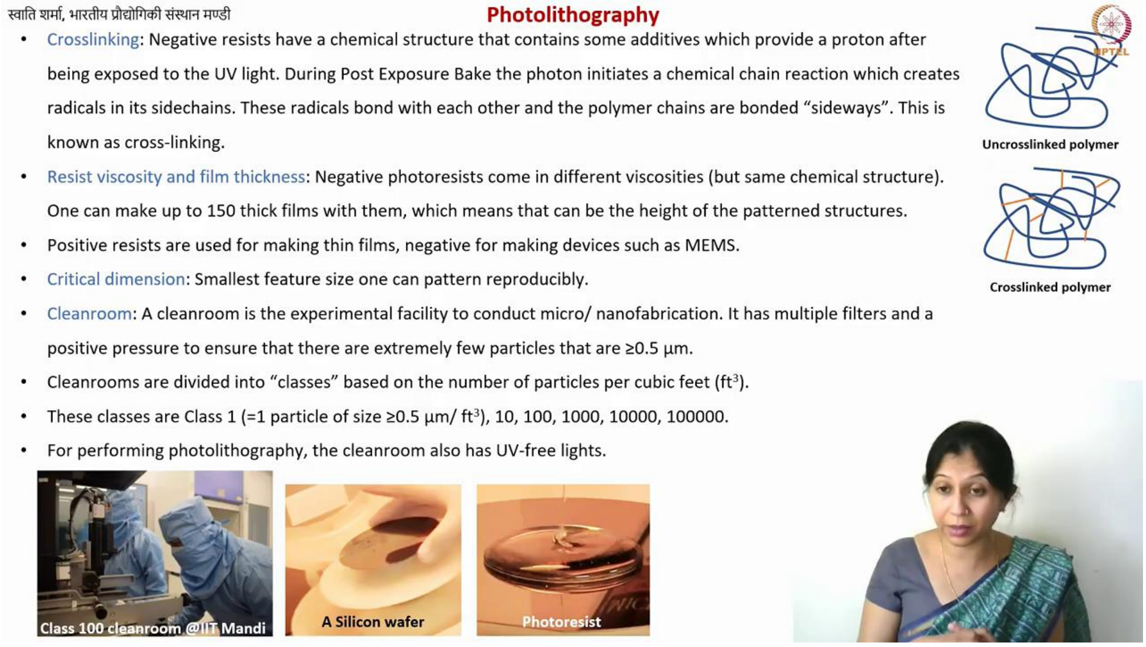
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Photolithography

- Crosslinking: Negative resists have a chemical structure that contains some additives which provide a proton after being exposed to the UV light. During Post Exposure Bake the photon initiates a chemical chain reaction which creates radicals in its sidechains. These radicals bond with each other and the polymer chains are bonded "sideways". This is known as cross-linking.
- Resist viscosity and film thickness: Negative photoresists come in different viscosities (but same chemical structure). One can make up to 150 thick films with them, which means that can be the height of the patterned structures.
- Positive resists are used for making thin films, negative for making devices such as MEMS.
- Critical dimension: Smallest feature size one can pattern reproducibly.
- Cleanroom: A cleanroom is the experimental facility to conduct micro/ nanofabrication. It has multiple filters and a positive pressure to ensure that there are extremely few particles that are ≥0.5 µm.
- Cleanrooms are divided into "classes" based on the number of particles per cubic feet (ft^3).
- These classes are Class 1 (=1 particle of size ≥0.5 µm/ ft^3), 10, 100, 1000, 10000, 100000.
- For performing photolithography, the cleanroom also has UV-free lights.

Hi. This is the continuation of our previous lecture on Photolithography. I had mentioned that we use silicon wafers for photolithography, and also, we talked about photo-resist. Here are two images. So, the first one shows the silicon wafer, this thin circular object is your silicon wafer and someone is placing it on top of a vacuum chuck, which is basically the vacuum holder of your spin coater.

And after that, in the second image, you see that there is a photoresist that is being poured on top of it and this resist as you can see has a reasonably high viscosity. You can also get lower viscosities. After pouring it then I will spin coat it at whatever x rpm, let us say 3000 rpm and then I will get a certain film thickness.

Now, these films are actually highly reproducible. The same thicknesses you can get, no matter how many times you perform this operation. I will pour let us say 2mm of the resist, I can sometimes end up pouring 2.5mm. So, is it just the quantity of the resist that you pour? The answer is no, irrespective of the quantity, of course, you should not pour too much because then you are wasting the material. But, irrespective of the quantity of the resist that you pour, you will get the same film thickness because any extra resist will be thrown away due to centrifugal force. When you are spin coating then a certain combination of a resist viscosity and the rotations per minute will always give you the same film thickness and this is the highly reproducible fabrication method.

In this lecture, we going to talk about some fundamental definitions that you need to know when you are performing photolithographic operations or any other lithographic operations as well, we'll talk about them. So, the first one is cross-linking. I said that when you use the negative tone photo-resist, then what happens?

When it is exposed to the UV light it gets cross-linked or at least the cross-linking process starts and then when you do the post-exposure bake your cross-linking process initiate. So, how does that happen? What is cross-linking in the first place? So, think about the polymer chain.

So, you think about these chain-like molecules. What if they had some sort of functional groups on their sides? So, long chains, but they have certain functional groups on the sides. What are functional groups? Means, something that can react, something that can perform a certain function.

In the case of most of the phenol-formaldehyde resins, SU 8, the resin which we were talking about which gives you gives us reasonable carbon, these groups can be epoxy groups. Epoxy groups are like these triangular groups with two oxygen's in the corner and the third one is attached to your parent atom or molecule.

Now, these epoxy groups when there is a UV light can be opened with relatively less energy, relatively lower activation energy. You have these epoxy groups and in these photo-resist, the commercial ones because they are very highly optimized for the lithographic processes. They contain something known as photo-initiators.

So, photo-initiators are certain materials, which are very sensitive to UV light and that is number 1. And number 2, when they absorb the light of a certain wavelength. they undergo a certain chemical reaction which would release, let us say a proton. That proton will then hit your epoxy bond, open it and in that reaction another proton is generated.

This is how chain reaction then continues and because of these, your epoxy bonds will continue to open. These were in the sides of your polymer molecule. Now, when this epoxy bond opens, there you have a functional group or something that is a radical where you had epoxy open.

Radical means it has an unpaired electron. It can form a bond. So, now, it will form a bond with whom? Now, it will form a bond with its neighbouring radical. So, that is how these sideways chains will start to connect and there your overall material will mostly get solidified because it now has this also side chains that are linked.

In this image, you can see that you will have the same kind of polymer molecule, but now, the side chains are also linked to each other. So, this process is known as cross-linking. This is what we talked about it in the case of UV-sensitive materials, but you also can have thermal cross-linking. In many cases, it depends on the bonds, it depends on the chemical nature of the material.

If it is possible to perform the cross-linking just by providing certain heat? That is in fact, done for a lot of polymers. But in the case of lithography, you are more specifically using photo initiators because you need to use the UV light in a very controlled fashion and that is why there you have photo initiators mixed into your material, and then the entire process is optimized.

What else? What else is important for performing lithography? If I give you a certain resist, I say you need to make a film, which is 5μm, will it be possible to always do it? The answer is no. If the viscosity of your resist is too high, then no matter how you rotate even at 10,000 rpm, you might not be able to get a film that is extremely thin.

This is very common sense that the viscosity of your resist becomes very important and in fact, these commercial resists are available in very well-defined viscosities. And you have set of the parameter given to you that, this particular resist at 3,000 rpm will give you this film thickness. And at different rpm it will give you different thicknesses.

But each resist will have a range, it may not be able to give you thinner than a certain thickness. So, each resist will have a range of operation. So, the viscosity becomes very important. In the case of phenol formaldehyde resin, it is relatively easy to control the viscosity because you can keep on changing the ratio of phenol and formaldehyde. If you remember we learnt that phenol formaldehyde resins are of two types resole and novolac. And it is the novolac ones that are in the liquid form at standard room temperature pressure, and the resole is in the solid form.

One more interesting thing is that typically the positive resists have lower viscosity and that is why they are used for making thin films. So, they are typically used as what is known as sacrificial material. They are also relatively inexpensive, they utilize very common chemicals for their developing process.

These positive resists also do not carbonize very well or they do not use very high quality carbon. So, for our purposes, we will rather use the negative photo-resist for carbonization purposes. But generally, in the IC industry when you are using positive resist then you are using them for making thinner films.

When you want to make higher structures and why would you want to make higher structures? For example, when you are making MEMS devices, or you are making microelectrodes; if you are making electrodes what you need? You need high surface area. So, the higher the structure the more surface area you can attain. In that case, surface area becomes more important to you. So, you want to make higher structures. Also, in several MEMS devices you might want to use higher surface area or you may have suspended structures, cantilevered like structures. In that case, you may have to etch away certain layers. You may have to make certain sacrificial layers complicated structures. There you will rather go for the negative resist, and our negative resists also carbonize better. So, for us mostly it is going to be negative resist processing.

One more important definition which is not just for photolithography, it is a general definition for all microscale devices is the critical dimension. For all microfabrication techniques, the critical dimension is the smallest feature size that you can reproducibly make using any fabrication technique then that is the critical dimensions of that fabrication technique.

So, you will say the critical dimension of my photolithography technique is 5 μm. Now, that will depend on what photo-resist you are using, whatever is your process. So, it is not just critical dimension of lithography in general, but of your certain a process.

In some cases, given a combination of a particular resist and an equipment let us say I design a nanoscale 3D printer that only works with a certain type of ink or certain type of resist. In that case, using the combination of this resist and my instrument then I can say this is the overall critical dimension of the process, the process that can be performed using this particular equipment.

So, what else? Now, all of this process is performed, all nano microfabrication processes are typically performed in specialized rooms that are called clean rooms. Why are they called cleanrooms? Because not just that they are clean physically, but the fact that the air, which is there is very clean. And that is not just clean, but we have a very specific definition for it.

This is the facility that contains multiple filters and it ensures that any particle that are larger than 0.5μm in diameter, you minimize the number of such particles. Now, why do we do that? Because what we are making here is only a few micrometer in size.

So, let us say if you had a particle, which is 20 μm, but the structure that you are making that itself is 20 μm. So, that one particle if it drops onto your resist or somehow your resist catches that particle, it falls onto your resist that will look like a big mountain on that little structure because your overall structure is pretty much the same size as that particle.

So, you want to ensure that particles that are smaller that are bigger than 0.5μm are absent in that room. So, this is a very small dimension. You remember that human hair the diameter of human hair is also approximately 70 μm, it depends on what kind of hair, but 70 to 100 μm is the diameter of a human hair, which means you think about how small are the things that you are talking about.

So, you cannot afford to have dust particles and larger particles inside the cleanroom. What is also important is that the biggest source of contamination in a cleanroom is actually human beings. In fact, the very sophisticated clean rooms in the companies when you are fabricating your chips for your computer in that case they are fully automated. Humans are not allowed inside. So, humans are the ones who cause contamination, change in humidity by breathing and things like that. You have to completely gown up when you go inside the cleanroom. Clean rooms are these facilities, where you perform micro and nanofabrication.

Now, clean rooms are also divided into different classes and these classes then you can imagine are based on the number of particles per cubic feet depending on the number of particles. So, if you have class 1 cleanroom that would mean that you have not more than 1 particle of which is bigger than 0.5μm in 1 cubic foot.

You have these different classes 10, 100, 1000 and so on. For most of the research purposes, you would use a 1000 class cleanroom. 100 is used but only in very very sophisticated industrial facilities.

Some research institutes also do have, I mean we have class 100 cleanroom here in IIT, Mandi, but that is also used only for extremely important applications when we are dealing with very small feature sizes, and not for general photolithography learning purposes.

And one more important thing is that you need to perform this entire operation when there is no UV light. That is common sense because if your material is photosensitive. So, you want to make sure that you store your chemicals in UV free area and whatever operations you perform you will in UV free area, and that is why these two images that I had shown you before look yellow.

Because this yellow light is what you will have when the light is UV free. So, commonly students would call these rooms yellow rooms. I used to call it yellow room when I was performing these things during my PhD. So, these are the UV-free lights and UV free rooms where you perform the entire operation.

Here is an image of somebody performing some experiment inside the cleanroom. Now, I show this image to you because I want to tell you how you gown up. You need to really completely cover yourself. Also, in this particular case, this guy is not wearing goggles because he was looking into a microscope, but you also wear goggles.

Basically, you want to completely cover yourself so that you do not contaminate the cleanroom and this is the point that is you are the source of contamination. So, this is about the cleanrooms and this is these are the places where you perform photolithography.

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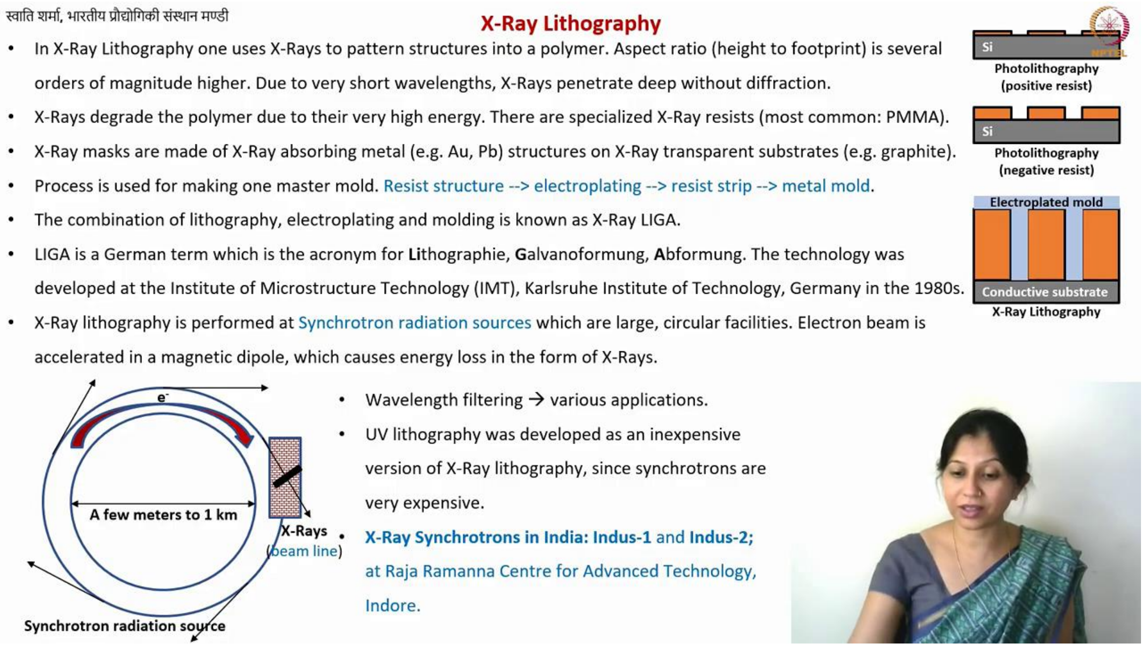
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X-Ray Lithography

- In X-Ray Lithography one uses X-Rays to pattern structures into a polymer. Aspect ratio (height to footprint) is several orders of magnitude higher. Due to very short wavelengths, X-Rays penetrate deep without diffraction.
- X-Rays degrade the polymer due to their very high energy. There are specialized X-Ray resists (most common: PMMA).
- X-Ray masks are made of X-Ray absorbing metal (e.g. Au, Pb) structures on X-Ray transparent substrates (e.g. graphite).
- Process is used for making one master mold. Resist structure --> electroplating --> resist strip --> metal mold.
- The combination of lithography, electroplating and molding is known as X-Ray LIGA.
- LIGA is a German term which is the acronym for **Li**thographie, **G**alvanoformung, **A**bformung. The technology was developed at the Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology, Germany in the 1980s.
- X-Ray lithography is performed at Synchrotron radiation sources which are large, circular facilities. Electron beam is accelerated in a magnetic dipole, which causes energy loss in the form of X-Rays.
- Wavelength filtering → various applications.
- UV lithography was developed as an inexpensive version of X-Ray lithography, since synchrotrons are very expensive.
- **X-Ray Synchrotrons in India: Indus-1** and **Indus-2;** at Raja Ramanna Centre for Advanced Technology, Indore.

The question is, are there also other techniques, other than photolithography where you can get these structures, which can be converted into carbon? So, the answer is yes we have these certain photoresists that can be converted into carbon.

Now, with these resists you can also perform other types of lithographic operations. One very well-known lithographic technique, in fact, is the one that was used before photolithography that is known as X-ray lithography. You can imagine that what are we doing here, rather than using UV light we are using the X-rays. Rest remains the same.

What will change? If you think about it, spin coating remains the same. Baking also depends on the chemicals that you are using, so that baking process and all that remains the same. Let us say the resist that you have, is sensitive to the X-rays. A lot of things are sensitive to X-rays.

X-rays are higher energy electromagnetic radiations. Now, what will be very important is the exposure step and how will you make the mask. If you make the mask using any general black ink or even a lot of metals allow the X-rays to pass through. So, you need to make a mask using a metal that blocks the X-rays then you will be able to mask that part of your resist from the X-ray.

So, that is the part that changes. The rest remains the same. Because you can really the X-rays go straight down through the material without any diffraction. And they can actually degrade very very thick films also. UV lithography has its limitation after 150μm thick structures.

Then, the thicker structures will have more diffraction of light and you may not be able to cross-link completely. Even 150 is not easy when you are experimentally doing these operations, you need to be really careful, even that is to think for UV lithography.

And also, that is why the structures that are fabricated using photolithography are called not 3D structures, but 2.5 D structures. Why 2.5D and not 2D? Because 2D structures look like this, this first image. When you perform lithography with a positive resist, thin film-based structure then thin films are known as 2D. So, these kinds of structures are much thinner, compared to their length they are not too thick. Those are called 2D structures.

Now, you have something in the middle, you have a certain height, but you are not able to create structures in the z-direction. You are able to just increase the height of your 2D structure, that much control you have in the third dimension, but not more than that. You cannot pattern anything in 3D.

These kinds of structures are known as 2D structures. 3D structures would look something like this. These are the kinds of structures we want to make them in the resist. These are the structures that you can make using X-ray lithography because of the fact that X-ray is a very high-energy radiation. And because of their wavelength, they do not have much diffraction.

So, you can get really clean walls and really tall structure using X-ray lithography, tall is high aspect ratio structures. So, this is the advantage definitely. Now, one more thing that I have written here is a silicon substrate, silicon substrate in the conductive substrate. You can also perform X-ray lithography on silicon, there is no rule, nothing against that. But what we can also.

We want to make a master mold out of this structure. And that is why we need conductive substrate. So, how do we make that master mold? These are the metals that we use for making. Gold and lead are the kind of metals that we used for making the mask. Now, the mlod fabrication, why is it that? X-rays are very expensive, and X-ray lithography process is also relatively expensive because you do not have these facilities everywhere.

Number 1, X-ray generation facilities are not available everywhere and also it requires a lot of safety free features and so on. Number 2, the masks are very expensive that also makes this technique expensive. In fact, one of the biggest factors that add to the cost is the cost of the mask. So, altogether X-ray lithography is very expensive. However, you can make very beautiful structures, really tall, beautiful straight lines in the case of photolithography.

The moment you go for higher aspect ratio structures, you need a really good experimental hand to perform those experiments otherwise you will get either T-topping or sometimes the structures are like this. So, this is the problem there. If I need a very high aspect ratio structure for certain applications, so what I can do is? I can make just one structure using X-ray lithography.

Now, this is a very expensive structure. I can use it as a master mold for making a mold. I can use it as a negative structure for making a mold and then I can use that mold to make my other structure. So, only for making the master mold, I can use X-ray lithography. For that what do I do? I make this resist structure and I do electroplating on top of that.

What is electroplating? Electroplating is a very well-known technique where you make an electrode out of your structure and then you have a very specialized solution of an electrolyte that would deposit a certain type of metal atom by atom. When it is atom by atom, and it is a liquid electrolyte then that means, it can go inside these deep walls. Remember these walls are still just a couple of micrometers and they have very high aspect ratio.

If you have conductive substrate then it will attract these atoms of the metal and then you will atomically have this layer deposited of the metal. And then finally, you will get a mold that looks like this. You will have then electroplated metal for example nickel. If you now remove the resist. Resist removal is not that difficult that, you can do it using a developer solution. And if it is crosslinked also there are certain chemicals that can still dissolve the entire polymer, so it is easier to dissolve it. Now, you get rid of your polymer and what you have is the mold, negative structure of what you prepared before.

Now, that your mold can be used for making the same structure and the other polymer, just press it and then that is how you make it. This entire process where you do you first do the X-ray lithography then you perform electroplating and then you use that mold for making further structures this entire process is known as X-ray LIGA. And this LIGA comes from Lithography, Galvanoformung, Abformung. So, galvanoformung and abformung are German words, lithography also.

So, this technique was developed at IMT in Karlsruhe Institute of Technology in Germany, in the 1980s. And this is a German term that is used for these kinds of technique X-ray LIGA. Now, if you think of just the LIGA part, lithography and then galvanoformung means electroplating, abformung means molding, making something using the mold. So, these kinds of things you can also use with a UV structure for photolithographically patterned structures. Then what would you call it? You would call it UV LIGA. But UV LIGA is not used very much because it is already a reasonably inexpensive technique, so, you might as well just make several structures in a batch fabrication. But actually lithography since its very expensive than you only use it for making a master mold and then you perform the LIGA operations.

Now, where do the X-rays come from? So, there are these cathode ray tubes and you can have for medical purposes you can have different sources of X-rays. But you also have something known as synchrotron facilities or synchrotron radiation sources. What happens in these synchrotron sources is that you have a really large facility, you construct a building which is circular.

You see in this image, the diameter of these facilities can be up to 1 kilometre. And you have basically a building constructed, it is a circular building where you have 1-kilometer diameter. And now, what you do is you pass electrons through this entire building.

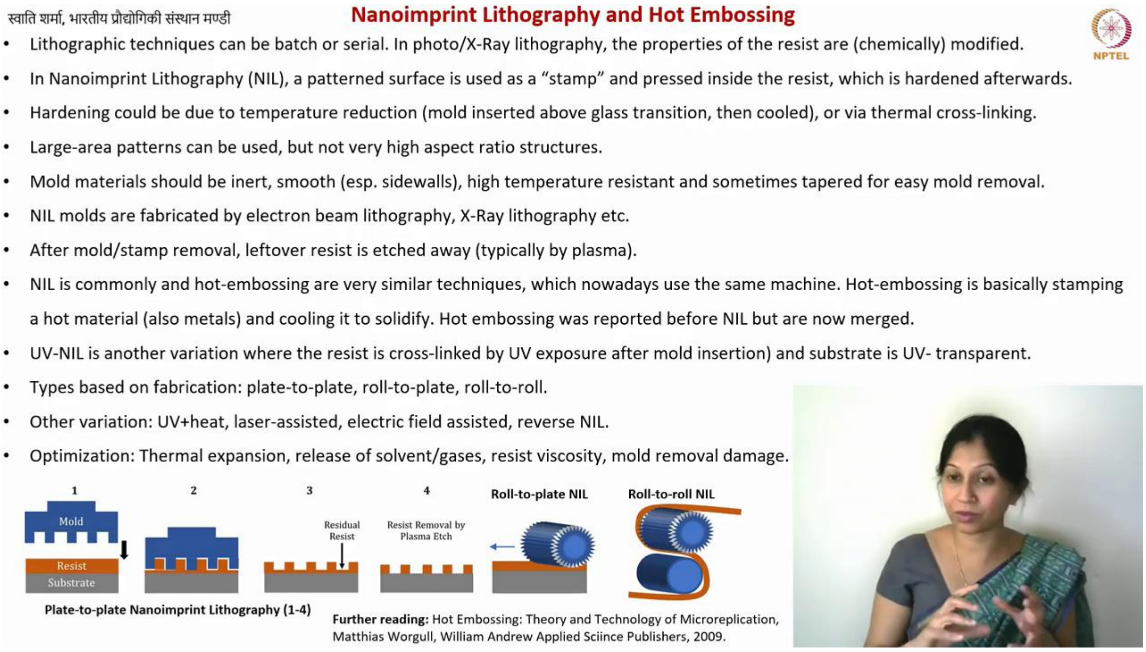
So, it is a tube basically that goes through that building and this is the high vacuum tube and you will have electrons accelerating, circulating in that big huge building. What will happen? What happens when you have charged particles? And then you also have magnets by the way. So, you have a magnetic dipole, and when you accelerate a charged particle inside it, what will happen? It loses certain energy and that energy in the case of electrons is in the form of X-ray.

So, now you will basically have this tangentially coming the X-rays when you have this circulation of electrons. So, now, at different places, now you make your office there, you make your lab there, different places, that tangentially many X-rays are coming out and now at different locations then you make collection sources.

For example, my office is there, I sit there. Then what I have? I put a screen there, I have these beautiful parallel X-rays coming out. If I need it then I can also filter the wavelengths, for lithography purposes whatever wavelength I need or if the range of mixed wavelengths can also work for me, that is where I put my mask in that where I perform my lithography operation.

Now, this synchrotron radiation is the very basic schematic, again they have various other parts of it and these radiation sources are basically used for making a lot of particle physics experiments and laser physics experiments and so on. And they are also used for X-ray lithography.

And in case you are interested or you want to do your research in X-ray lithography or anything related to the synchrotrons, there are two synchrotron facilities in India known as Indus 1 and Indus 2 in Raja Ramanna Centre for Advanced Technology, Indore. (Refer Slide Time: 27:30)



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Nanoimprint Lithography and Hot Embossing

- Lithographic techniques can be batch or serial. In photo/X-Ray lithography, the properties of the resist are (chemically) modified.
- In Nanoimprint Lithography (NIL), a patterned surface is used as a “stamp” and pressed inside the resist, which is hardened afterwards.
- Hardening could be due to temperature reduction (mold inserted above glass transition, then cooled), or via thermal cross-linking.
- Large-area patterns can be used, but not very high aspect ratio structures.
- Mold materials should be inert, smooth (esp. sidewalls), high temperature resistant and sometimes tapered for easy mold removal.
- NIL molds are fabricated by electron beam lithography, X-Ray lithography etc.
- After mold/stamp removal, leftover resist is etched away (typically by plasma).
- NIL is commonly and hot-embossing are very similar techniques, which nowadays use the same machine. Hot-embossing is basically stamping a hot material (also metals) and cooling it to solidify. Hot embossing was reported before NIL but are now merged.
- UV-NIL is another variation where the resist is cross-linked by UV exposure after mold insertion) and substrate is UV- transparent.
- Types based on fabrication: plate-to-plate, roll-to-plate, roll-to-roll.
- Other variation: UV+heat, laser-assisted, electric field assisted, reverse NIL.
- Optimization: Thermal expansion, release of solvent/gases, resist viscosity, mold removal damage.

Plate-to-plate Nanoimprint Lithography (1-4)

Further reading: Hot Embossing: Theory and Technology of Microreplication, Matthias Worgull, William Andrew Applied Sciince Publishers, 2009.

Coming to the next type of lithography; nanoimprint lithography. We were talking about micro scale structures till now and we can also make nanoscale structures. Anyway when you convert carbon structures they shrink, and then they convert from micro to nano.

If you already have a nanoscale structure then you can even get very small structure, nanoscale structures will remain in nanoscale. After a certain point, when the structures are extremely small your material densifies so much that you cannot really shrink it any further. But if you make let us say a 10 nanometer structure and your carbon yield is 30 percent then you can get a 3 nanometers structure out of it,.It can be translated in that scale.

So, you can get very small structures. But, how do we perform lithography at nanoscale? There are various techniques, one of them is known as the nanoimprint lithography and the variation of that is also known as hot embossing. So, what are these techniques?

In this case also have a resist, so you will do the spin coating that much remains. So, you have a thin film of photoresist that you work with. However, rather using a mask and exposing it through the light, you have a stamp. Your material should be in a liquid-like state. Here you will not pre-bake it to convert it into a solid resist film. You will rather have a resist film that is not too solidified. So, it is a semi-solid state, the best-case scenario is rubbery state. And then you have a stamp.

Now, when you have the stamp inside your resist then you will perform the cross-linking and then remove the stamp. Now, cross-linking can be performed using the UV light that depends on the resist or can also be performed using just heating and that is why then it is called hot embossing. So, these are kind of sort of the same techniques with slight variations.

Hre is the schematic. You see that the blue color thing is the mold and then you press it in and then you remove it. You see in the third image here. So, you will also have some residual resist in the bottom and what you need to get rid of that resist. So, you will do etching techniques.

There is something called plasma etching. I have not discussed that very much in detail. You have a very high-energy plasma that etches away your resist. Etching is like eating up your material. So, if you have this high-energy plasma, that will remove that very thin layer of the resist.

Remember that the thin layer will be uniformly removed from everywhere. Let us say here we are making pillars. From the top of the pillar, you will lose some material, the same thickness that you lose from the bottom and that is why in the initial geometry you need to factor that in. So, you need to have your structure slightly higher than what you want to make, so that when you etch away the material then you still get the desired height of your structure.

This is basically the idea of nanoimprint. The structures can be in the nanoscale using this technique and that is what is called nanoimprint. And of course, large area patterning is possible if you have a big stamp, then on an entire wafer just with one stamp you can fabricate the nanoscale structures. This is also a reasonably inexpensive lithographic technique,.

So, as I said the hardening or the cross-linking can be done using both UV light and heating. One important thing, in the case of photolithography, one important definition is that of the glass transition temperature. What is the glass transition temperature of a polymer? This is the temperature below, which the material behaves like a glass. Above that temperature, it will become liquid.

So, behaving like a glass means it is solidified. And we say behaves like glass, not metal or anything else. We say glass because polymers are typically amorphous. So, that is why we say this because they will have this random cross-linking and so on. However, they will be solidified. So, below the glass transition temperature, they will behave like this solid glass-like materials, and that is where we want to make, we also play with this glass transition temperature during lithographic techniques.

In the case of nanoimprint lithography, you heat the material such that it is in this rubbery state, so slightly above its glass transition temperature. And then once you have the stamp in then you cool it down, then it can become hardened. You do not really need cross-linking altogether. This is then just playing with the glass transition temperature, just heating and cooling.

That also you can do in the case of nanoimprint lithography. Different kinds of structures can be prepared and this is very easy and simple technique, but there are challenges for example, when you remove the mold, sometimes your entire structures will come off due to the adhesion of the material that is being fabricated.

So, it should not have very good adhesion with the mold. If it has, you can make your mold slightly tilted rather than making completely straight wall, so it can easily come off. So, you have to work with these design parameters such that there is minimal damage to the removal of the mold. So, you can have these tapered walls.

The molds need to be in the nanoscale, so you need very precise and nanoscale structures on top of your mold. These can be then fabricated using X-ray lithography or E-beam lithography or any of these relatively expensive techniques, but mold is the one that needs to be fabricated in the best possible way for all your experiment.

Now, hot embossing as I said, these are two very similar techniques. The only difference is that the hot embossing is also used for metal and can be used for a larger variety of features because UV exposure can only be used for something that is UV sensitive.

When we are playing with the glass transition temperature because for the metals this temperature can be very high, the melting points can be very high. So, in those cases, if you are using these things then you are limited with the materials. But when you are using heating and cooling or you can use melted materials you can go to higher temperatures. For example, if I want to use aluminum, so this does not have a very high melting point. So, I can heat it to that temperature and then I can have my stamp inside and I can remove then I can cool it down. So, this hot embossing is sort of more useful for a variety of materials. Also, hot embossing was reported before the nanoimprint lithography. However, the point is that nowadays the equipment that you get, they can perform both and the hot embossing,,.

We are talking about the batch fabrication techniques till now. You have a stamp, but the substrate where you have your polymer film that is a plate, a wafer. It is a flat and rigid substrate. There are variations of these techniques. Because you can do large area patterning. You can also do is what is known as roll to plate.

Rather than a stamp, it can be a role, it can be this kind drum-like substrate, which roles onto your polymer film. So, that is known as role-to-plate nanoimprint lithography. Also, you can have what is known as roll-to-roll, where you have like this newspaper printing kind of continuous manufacturing techniques. You can also have roll-to-roll nanoimprint lithography.

So, these are the variations, and because it is a large-scale print patterning technique that is why you can use all of these variations. There are also some other advanced variations where you use lasers and we also use electric field-assisted patterning and so on. So, you can read about all of these things. The point is that there have been nanoimprint lithography patterned structures that have been converted into glass-like carbon. Again, using the same technique that we use for lithography, there we just need to do the carbonization put it in the furnace 900 °C in at atmosphere. But, these kinds of structures when they are converted into carbon, then they become very very useful because number polymer structures were insulating for most cases. But our carbon structures are conductive. So, already we can already have so many other applications. Now, glassy carbon is very much mechanically stronger compared to the polymer. It has an inert surface while polymers may degrade over time or corrode over time, but that does not happen with glassy carbon, how stable a glassy carbon is. All of these properties which I had discussed with you for the large-scale structures when we were thinking about making the vessel liners using glass-like carbon or whenever we were making large scale electrodes.

So, those properties are also true for the nanoscale or micro-scale glass-like carbon. And that is why after you convert these structures into carbon then you can have many other applications, which were not possible using polymers. Now, other things about these optimization parameters you can think about it. You can think of it yourself that thermal expansion needs to be optimized for both the mold material and also your resist material or metal whatever you are using.

Then, the release of gases if you are using a polymer when you heat it or when you cool it, there will be certain bubbles releasing, certain gases releasing also if there is any solvent then you are getting rid of it at a certain temperature, so then you need to make sure that this does not create bubbles or porosity into your structures that need to be optimized.

Viscosity, of course, here compared to photolithography or you will have low aspect ratio structures that means, you might want to use lower viscosity resist. And then, of course, the damage that happens because of mold removals, you want to make an inert mold and you want to make sure that there is as little damage as possible when you remove the mold.

If you want to read more about hot embossing here is a book that I have mentioned. This is by Matthias Worgull, this is on hot embossing, you can if you are further interested.