Microfluidics
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Lecture - 22
Microfabrication Techniques (continued...)

Okay, so we have been talking about photolithography, the first step in photolithography is to create the mask, and the mask design would depend on the design of the structure that we want to fabricate okay. And the first step in the fabrication is to clean the wafers, we talked about RCA 1 and RCA 2 cleaning procedure, and after cleaning the wafer the procedure would be to grow an oxide layer.

Oxide layer will be important in situations where we are going to passivate in electrical connection between different parts of an electrode or between electrodes, and it will be also required to enhance you know the bonding between the photoresist and the silicon wafer okay. So let us look at what oxidation process is.

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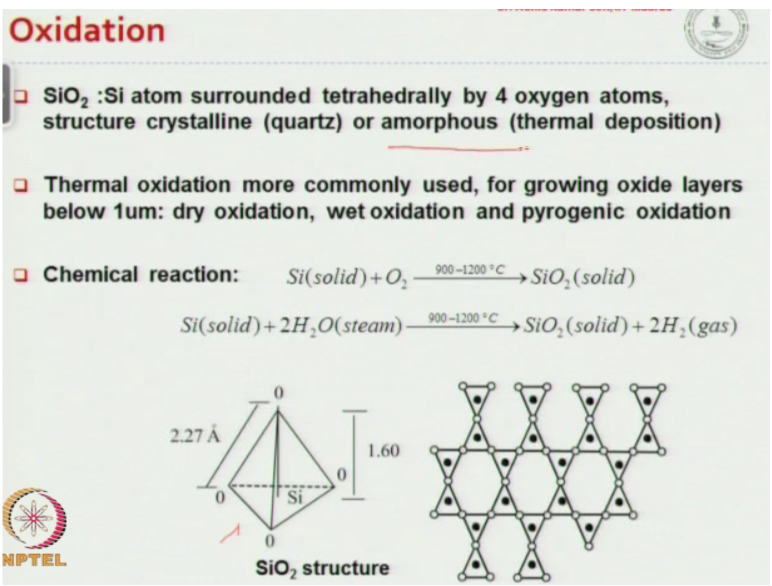

So silicon dioxide if you look at the atomic structure it has you know 4 oxygen atoms in a surrounding the silicon atom as you can see here, and the silicon dioxide has two different types of forms, one is you know a crystalline form in the form of quartz and the other is amorphous

which is the form that we get if we grow oxide using thermal deposition. So thermal oxidation is more commonly used in thermal ovens, oxidation furnaces.

For growing oxidation below 1 micron, we use dry oxidation, wet oxidation or pyrogenic oxidation. If you look at the chemical reaction what happens in a dry reaction is silicon reacts with oxygen at relatively high temperature which is about 900 to 1200 degree centigrade to give silicon dioxide solid okay. Now in steam oxidation or wet oxidation silicon reacts with the steam at high temperature to give silicon dioxide and hydrogen okay.

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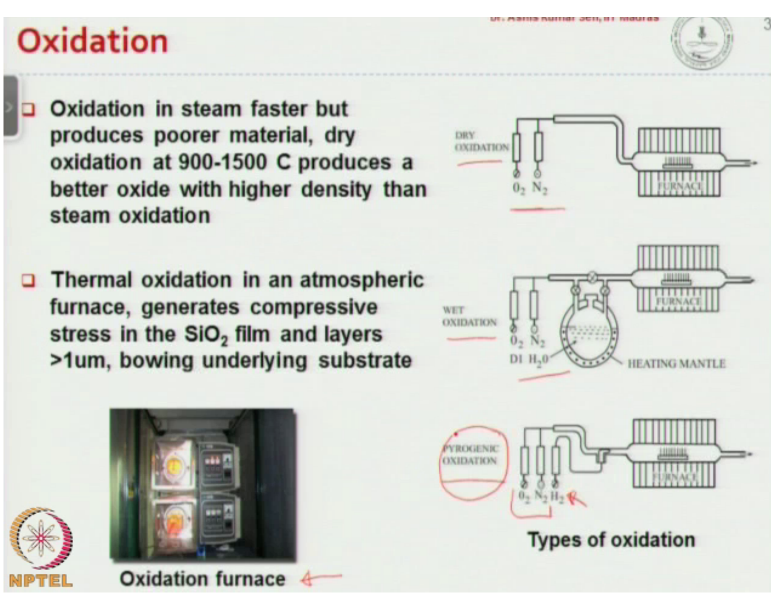

So the difference between wet and dry oxidation is that the wet oxidation is much faster there is difficulty that the you know the quality of the oxide that we produce is poor okay, in oxidation in dry oxidation you know the although it requires it takes more time to grow the oxide layer the quality of the oxide layer is very good with much higher density as compared to the wet oxidation or steam oxidation okay.

So the thermal oxidation is done in oxidation furnace similar to the one that is shown here, so you know what we say here is the high temperature that is maintained inside the oxidation furnace, so typically there will be a boat where we can stack multiple wafers okay, and using a glass stick we can place the boat inside the furnace, so it moves very slowly with time, so we know how much time the boat needs to stay inside the oxidation furnace.

So accordingly, it moves from at one end and it can come out at the other end okay, so this is the typical oxidation furnace that is used to grow oxide layer, so here on the right you see a different oxidation processes, one is the dry oxidation which uses oxygen and nitrogen in the furnace, in wet oxidation we use in addition to oxygen and nitrogen we also use Tim okay, and in pyrogenic oxidation in addition to oxygen and nitrogen we also use hydrogen okay.

So hydrogen can burn itself which that is the reason why it is called as pyrogenic oxidation. Now if we have silicon dioxide layer which is thicker than 1 micron, there may be issues with delamination because the larger thickness the difference between the thermal expansion coefficient of silicon dioxide and the silicon there maybe tendency of that layer to come out from the surface of the silicon if the thickness is higher okay.

So once we oxidized the wafer, the next step is to spin coat our photoresist, which is a photosensitive material on to the surface of the substrate, and you know the way we do it is by using a spin coater okay.

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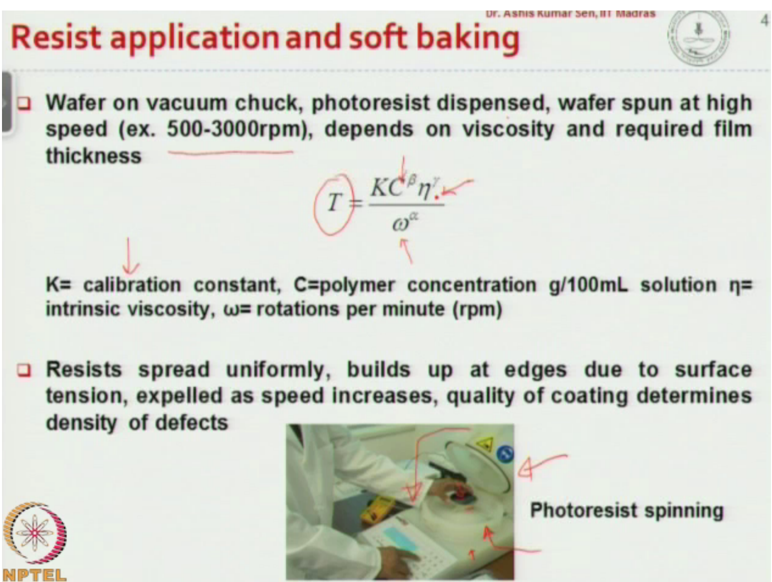

So if you look at here, so typical spin coater is shown here, and a spin coater will have a vacuum chuck, which is connected to a vacuum pump okay, so to create a negative pressure so that it can hold the substrate onto the chuck very tightly, because we are going to spin the substrate. And

then we dispense the photoresist onto the surface, and there is a motor which you drive in rotate the substrate or the chuck holding the substrate at the required RPM okay.

So this is what you see here, this is a typical you know spin coater, and here this is the vacuum chuck and we are placing the wafer on top of this a dispensed photoresist, and this is the lid which is closed to for safety, and then this motor underneath here is will rotate the chuck at the record RPM okay. And there may be different recipes that you can build in onto spin coater such as the acceleration time, you know from zero speed to a fixed speed.

What is the time that it can take to reach that peak speed, and at that peak speed peak RPM how much time it needs to rotate okay, so all those things can be programmed into this spin coater okay? So you know this is the procedure you place the wafer on the vacuum chuck, and dispensed the photoresist and then we spin the wafer or the chuck at high RPM typically 500 to 3000 RPM is used in spin coaters, and depending on the viscosity and the required film thickness we can adjust the speed.

So this is the thickness of the photoresist, which is dependent on the concentration of the polymer okay the photoresist, and the viscosity and it is inversely proportional to the rotational speed, so higher the speed we end up getting lower thickness, higher the concentration of the photoresist we end up getting higher thickness, and higher the viscosity we get higher thickness, and K is a calibration constant which can be determined from experiments okay.

And alpha, beta, gamma are also the exponents of concentration sorry speed concentration and viscosity which can be determined from experiments. Now when we spin you know we dispensed photoresist and when we spin the wafer, the photoresist stood due to centrifugal force it will go towards the edge okay, but that would be always an S effect where more of the photoresist will be around the edge of the wafer, so this is what we initially observed.

But then as the speed increases typically in a spinning process it may be 2 step process or sometimes maybe as high as you know 5 different steps we can have, so you know as the speed increases this photoresist which is around the edge of the wafer it gets displaced okay, so at low

speed the thicker SU-8 around the edges form what is called the buildup edge okay, and this is because of the surface tension high surface tension of the photoresist.

And it is very important to maintain a good quality coating on the substrate, because a good quality coating would lead to a good quality you know surface on a substrate and the further processing of the wafer okay.

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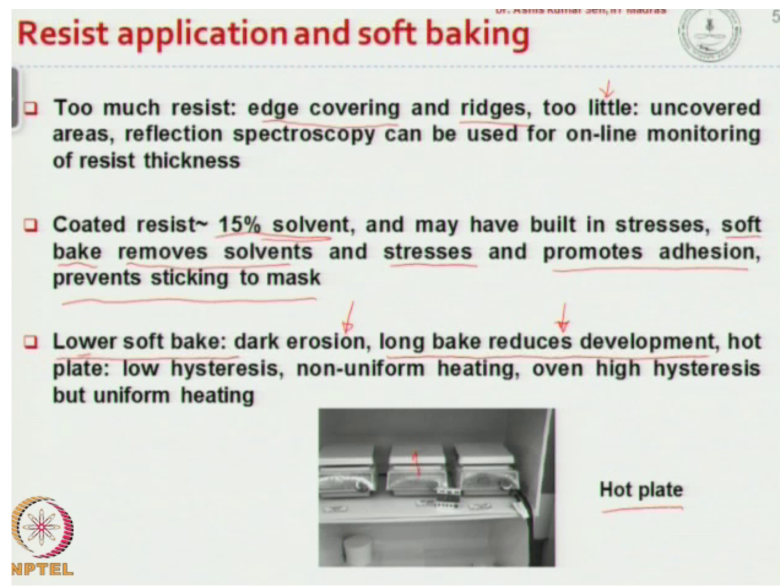

Now if you have you know too much resist that we dispense onto the substrate, if the quantity is more than what we require then you would have you know the edges of the wafer will be covered with SU-8 okay, so you will have a particular more material around the edges of the wafer. And in some cases you would also form ridges in the photoresist surface. On the other hand, if you have too little.

Then what you require then some of the areas of the photoresist of the wafer will not be covered by the photoresist, and while you are spinning the photoresist onto a wafer there are techniques like reflection spectroscopy which can be used for monitoring the thickness of the photoresist while you are spinning it.

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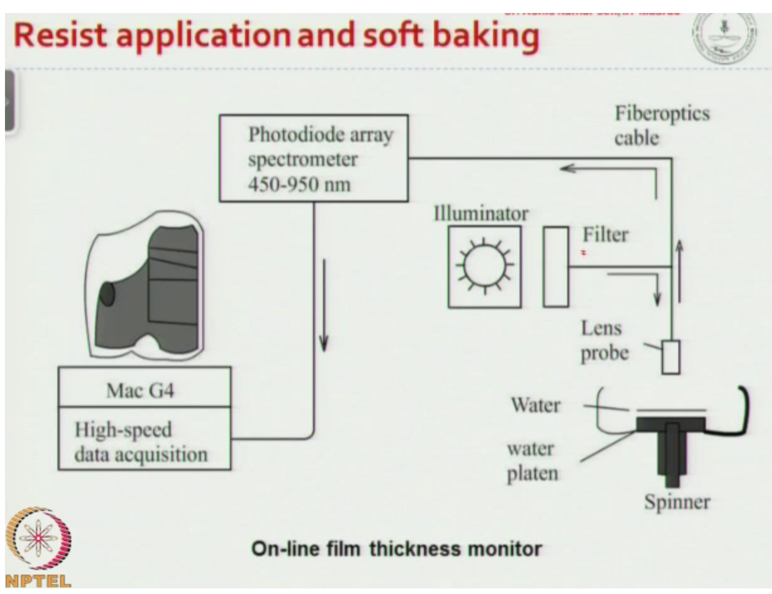

So this is what you can see here, this is the reflection spectroscopy technique which can be used for on-line monitoring while you are spinning the photoresist, so you have an illuminator light which comes through a filter, and lens probe, and it heats the wafer and the reflection light comes in and using a photodiode spectrometer we measure the intensity of the light, so depending by comparing the incident intensity of the incident light and the reflected light we can calibrate the thickness of the photoresist.

So with suitable correlations the difference between the incident and reflection intensity of the light we can predict how the thickness of the photoresist layer is. So typically in the resist in order for this photoresist to spin we use solvent typically 15% solvent is used in the resist, and we may have the built in stresses because of you know highly viscous nature of the photoresist, and so what we do after spinning is to take the wafer through a process called soft baking okay.

So the soft baking process it does two things, it removes the solvent the 15% solvent that typically we use in order for the viscous photoresist to spin is removed by the soft bake process, and also the stresses are removed using the soft bake. And the soft baking additionally promotes adhesion between the photoresist and the wafer, and because we do a baking process the photoresist dries the solvent gets removed.

And so that is the reason we do not have to worry about sticking of the mask on to the photoresist when we do the UV exposure okay. So the baking process does mainly three different things okay, remove the solvent, reduce the stress, improve the adhesion between the substrate and the resist okay and prevents sticking between the mask in the photoresist okay. If you know the baking temperature is very important okay.

If the baking temperature is lower than what is optimal, then you have dark erosion okay, dark erosion meaning some parts of the photoresist are from different points is going to remove, and it will be in the developer solution when you do the development okay, because the baking time is not optimum, so there will be holes inside the photoresist okay because it is not properly baked okay that is known as dark erosion.

On the other hand, if you have longer baking time then what is required, then you know that would reduce the development rate, if you have exposed you have baked you know resist coated wafer for a longer time then that we need the development time will increase, and many times the areas of the photoresist that you want to remove may not get also removed okay. So that is so to get an optimal soft baking time is very important.

Now the way we bake is using hot plate that is one approach, we can also use ovens, the hot plates have a heater at the center of the plate okay, and but one good thing about hot plate is that the hysteresis is low that means the heating and cooling can be achieved pretty quickly you know if you let us say if you increase the temperature to 95 and you want to bring it back to 70 the amount of time that you need is very less okay.

So it has low hysteresis, whereas the heating is non uniform okay because you have a heater at the center there is always a temperature gradient from the center of the wafer to the edge okay, so the heating is not uniform. On the other hand, if you go for oven, the heating will be more or less uniform throughout the surface of the photoresist, but the downside of the oven is that the hysteresis is quite long okay.

If you set a temperature as you know 70 degrees it does not go and reach 70 degrees it goes to you know something higher than 70 goes to 75 comes back to 65 and fluctuate until it gets the steady temperature okay, so that is how we can differentiate between hot plate and oven baking.

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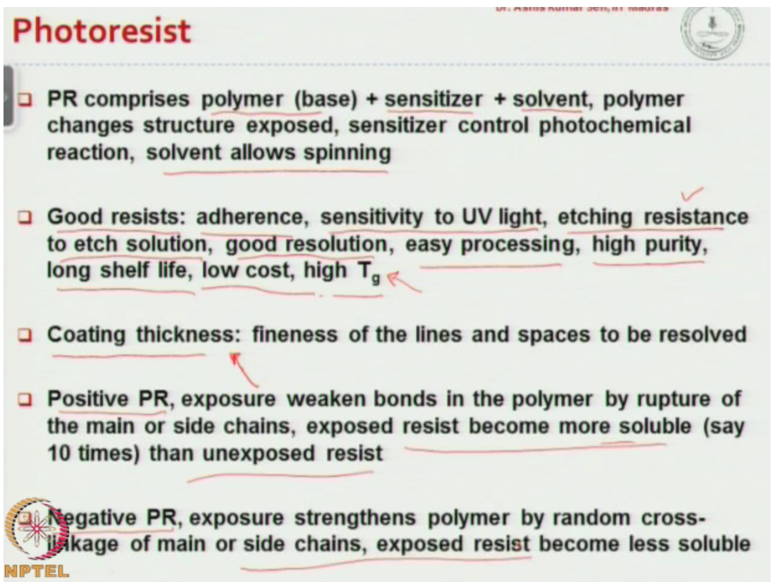

Now what we have in the photoresist in photoresist typically we have three different components, the major component is the polymer which is the base holding the photoresist, and this polymer actually enables the changing of the structure when it is exposed to UV light okay. And then there is a component called sensitizer, which controls the photochemical reaction when UV is exposed onto a photoresist.

And the third component is solvent which we have already discussed that it allows spinning of the photoresist onto the wafer. Now what are the properties of a good resist, good photoresist will stick very well to the wafer, so it has a very good adherence and it would be sensitive to UV light okay. So by you know depending on whether it is negative and positive accordingly it will cross-link or you know links between the bonds are going to break okay.

So it should react with the UV light okay, so the sensitivity to UV light is to be good. The etching resistance to the edge solution, so what do you mean that we use photoresist to create a pattern on the surface of the wafer or surface of an oxidized wafer or surface of a metal in some cases, so we use photoresist as a pattern okay, so when you use photoresist as a pattern and you want to

edge the next layer underneath using etching solution the masking photoresist layer need to have the etching resistance okay to the etching solution that we are using okay.

So it needs to exhibit good etching resistance to the etch solution. Needs to have good resolution to create finer and finer structures, easy processing we can we should be able to process the photoresist in a process easily, the purity needs to be high. The shelf life needs to be high, so you can use it for a longer time. Low cost and high glass transition temperature okay. So these are the properties of a good photoresist.

The coating thickness many time is going to affect the fineness of the lines or the spaces to be resolved, so we would have the precision of the photolithography you know using the photoresist the resolution may be affected by the coating thickness. Because when we talk about photoresist based patterning we are selectively removing photoresist in some portions of the on the surface of the wafer, and that is because of the mass transfer between the photoresist and the developer solution.

If the thickness is high many times thickness is very high and the gap is very low, the mass transfer becomes limited okay, so the resolution of the structure would depend on the thickness of the photoresist okay. So there are two types of photoresist one is positive, the other one is negative, in case of positive photoresist in the exposed areas the bonds will become weak it will be broken, and so the exposed resist become more soluble than unexposed areas okay.

So if you have a positive photoresist coated on to your wafer and we expose UV light through a mask all the exposed areas to UV light will get dissolved in the developer solution okay, whereas if it is a negative photoresist the exposed areas will stay, in the exposed areas the polymers are going to cross link and they are going to stay, in the unexposed areas the photoresist going to dissolved in the developer's solution okay, so that is going to happen in the negative photoresist.

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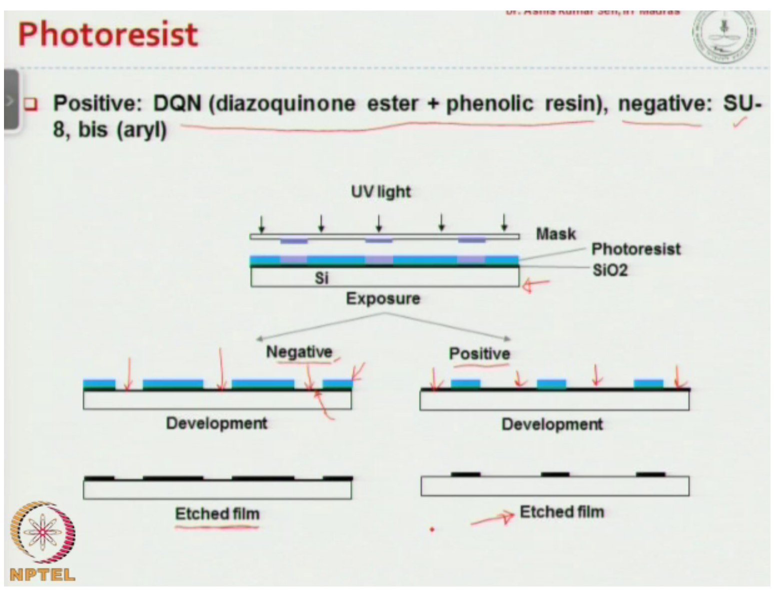

So here are the examples of positive and negative photoresist, you know positive one example is diazoquinone easter +phenolic resin, and one of the widely used negative photoresist is SU-8 okay, so this is what we talked about negative and positive photoresist. Let us say here we have a silicon wafer onto which we have you know put a photoresist layer and we are exposing UV light through the mask, so all those blue lines are APEC, so they can prevent the UV light.

So as you see here the exposed areas, if it were a negative photoresist the exposed areas are going to cross link okay and they are going to survive in the development process, all the unexposed areas are going to dissolve, so here in this unexposed areas where mask is protecting the UV light are going to be removed from the wafer. So then subsequently let us say we have another film underneath, let us say an oxidation layer which is denoted by this black line.

If you can etch so used at once the photoresist is developed we use this layer as a protective mask for etching silicon dioxide, so this is etching film that we get okay starting from here. Now if it were a positive photoresist, in the positive photoresist the exposed areas are going to be dissolved, so in these areas the photoresist are removed, so we get after we do the etching this is the structure of the film that we get okay.

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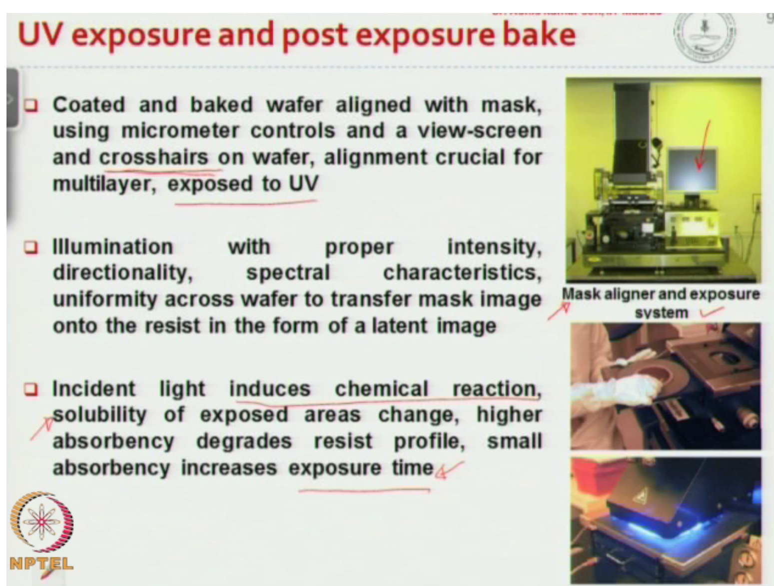

So once we do the you know coating of photoresist, the next step is to bake it so after we did the bake we go for UV exposure through the mask okay. So here you can see you know typical UV mask aligner and UV exposure system, so here you see a typical mask aligner and UV exposure system you know here the coated and baked wafer aligned with a mask and this mask aligner will have the provision in terms of a micrometer and a viewing mechanism to align the mask with the wafer.

And then you know on the mask as I was telling for especially for multilayer you know photolithography, you would have crosshairs on the wafer which will be aligned with the crosshairs in the mask, but for a single layer the crosshair alignment is not going to be important. So once we bring in the mask and the resist coated wafer in physical contact, then we expose the UV.

Now for the UV exposure we have to be very careful in terms of the intensity of the light and the wavelength of the light as well as its uniformity across the wafer okay, so all these parameters are going to affect how the structure is going to look like after development. So immediately after exposure you can actually you know if you have a mask pattern and you do an UV exposure through the mask on to resist coated wafer, after the UV exposure you can actually see the latent image getting transferred to the surface.

So because the entire process is a photochemical reaction that gets initiated when you exposed the UV you know exposed UV light onto the resist, so immediately after the exposed you can actually see a pattern of the mask getting transferred onto the surface. So you know what happens in the exposure is the light the exposed light actually induces a chemical reaction so it is a photochemical reaction, so the solubility of the exposed areas are different as compared to unexposed areas okay.

So the depending on you know the property of the photoresist, if the photoresist is such that the absorbency is going to be higher than it would degrade the resist profile okay. So what is going to happen is if you are beam is going to come straight, then because of the absorbency higher absorbency of the wafer it is going to get penetrated in more into and lateral direction into the photoresist.

So the resist profile if you want to achieve a flat profile instead of a flat profile it may diverse in any direction okay in the lateral direction okay, so that is going to happen if the absorbency of the photoresist is more, whereas if the absorbency is you know less than the exposure time has to be more, so you need to expose it for a longer time for the photochemical reaction to happen in case of photoresist with less you know small absorbency.

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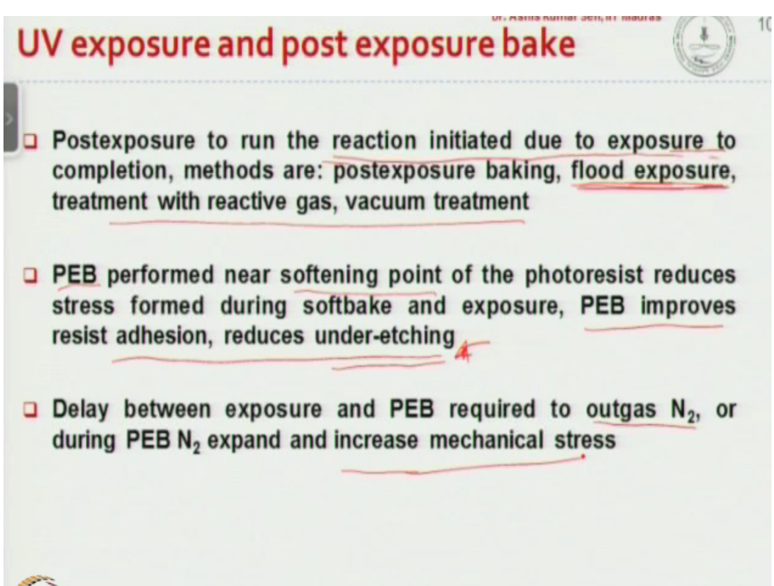

So once we do the UV exposure as I said there is a photochemical reaction that is going to be initiated and you can actually in fact see the pattern getting transferred, now to complete the photochemical reaction that has been initiated what we do is a post exposure bake okay. So we you know we do a post exposure bake to you know complete the reaction initiated during exposure to during the UV exposure.

So there are different methods that are done to achieve post exposure, one is post exposure baking in some cases people use flood exposure, so meaning instead of going for a post exposure bake you can do a complete exposure of UV on to the surface okay, so you just remove the mask and the entire surface is exposed to UV light that is called flood exposure. In some cases, people also go for treatment with reactive gases and vacuum treatment to complete the reaction that has been initiated.

And you know typically the post exposure bake is performed at a higher temperature than the pre bake temperature. And if the post exposure is performed at the you know near to the glass transition temperature of the photoresist okay, then it would reduce the stress that has happened during the soft baking and exposure okay, and so the post exposure will improve the adhesion of the resist on to the surface and would reduce the under etching okay.

So what it means that immediately after spin coating you have done a baking, where there is a chance that the thin film of the photoresist may show a tendency to come out of the wafer okay, and then again you are going for a UV exposure where it would do a photochemical reaction okay that means that there is going to be a change in the internal structure of the bonds in the material, so because of which it may develop some stress inside the photoresist okay.

So if you do a post exposure bake close to the softening point of the photoresist, it is going to reduce the stress and it is going to improve the adhesion between the photoresist and the surface okay. And in some cases it is also going to reduce the under etching okay, so under etching is etching you know in the lateral direction under the layer of the photoresist, so this post exposure bake a softening point is also going to reduce the under etching.

Now another important thing is that you know immediately after doing the exposure we do not do the post exposure bake okay, what happens is during the exposure because of the photochemical reaction nitrogen is released from this photoresist okay, now if we immediately go for post bake the nitrogen will expand and you know try to come out quickly okay, so that would again you know promote delamination between the photoresist layer and the surface.

So there is always after you do you know the UV exposure you do not go for post exposure bake immediately you do a lag, so you wait for some time and then take it to post exposure bake okay. And so you know it helps degas of outgassing of nitrogen and also reduces the mechanical stress.

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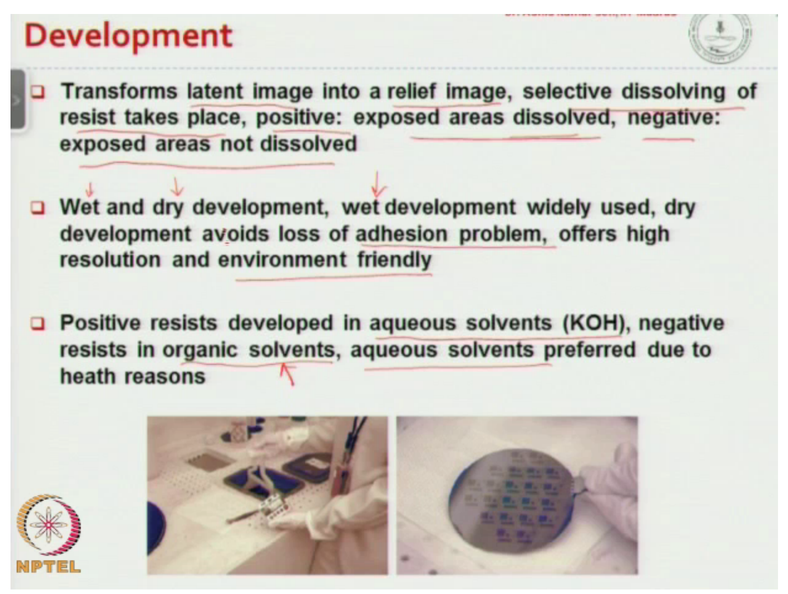

So once we have you know done the post exposure bake then we want to go for development, so we dip the wafer into a developer solution, so the development process actually transforms the latent image into a relief image, so the latent image that we are able to see if you put it in a developer solution depending on the resist pattern on the design of the mask, it is going to remove material in some part of the photoresist so you will be able to get a relief image that you clearly see on the surface of the wafer.

So you know selective dissolving of the resist would take place, as I was telling in the positive photoresist the exposed areas are going to be dissolved, and in the negative exposed areas are not dissolve okay, so that is going to happen. So there are two techniques mainly due to

development, there is wet development and dry development. Wet development is widely used including academia.

However, wet development has certain limitations that you know one is there maybe you know a case where the liquid developer tried to penetrate at the bottom of the photoresist, so there may be chance of under etching okay, there could be chance where the photoresist maybe a little bit overdeveloped so the entire photoresist layer will fall off okay. So these problems are not there in case of dry etching okay, so in dry etching the loss of adhesion problems is not there okay.

However, the dry etching problem process is quite expensive, it requires a more expensive setup okay. And the other downside of wet development is the developer solution that we use is not environmental friendly, whereas dry development where you just use a reactive gas or a plasma to remove material is quite environmental friendly, and the resolution is going to be much better as compared to wet development.

So normally the positive photoresist is developed in aqueous solvents something like a potassium hydroxide, and the negative photoresist are you know developed in organic solvents. So there is a difference between these developer solutions that are used for positive and negative photoresist, and the aqueous solvents are preferred due to health reasons, they are more environmental friendly as compared to the organic solvent.

But the organic solvent are you know cost effective much cheaper as compared to the aqueous solution, so that is why in academia the organic solvents are more widely used.

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Development

- Organics solvents may lead to resists swelling (negative) and loss of resist-substrate adhesion, Dry development overcomes this problem
- De- scumming: unwanted resist removed after development (high AR), patterned areas thinned, high temp baking remove residual solvents, promote adhesion

The downside of organic solvent is going to be you know the resist swelling okay, the swelling of photoresist when it is put in a developer solution, so there could be a problem in terms of the adhesion between the resist and the substrate, so dry development will not have such problem with in terms of adhesion. Now there could be a problem while developing it is called and which is more come by what is called De-scumming okay.

So De-scumming is the process of removal of unwanted photoresist after development okay, and this happens especially for large aspect ratio structures where the thickness of the photoresist is high or the height of the groove is very high as compared to the lateral direction. So the mass transfer becomes limited okay, so it is basically the developer tries to take away remove the photoresist from the wafer.

If the width of the structure is very small the groove is very small then the mass transfer becomes limited, so there is always unwanted photoresist lying on the surface of the wafer okay, which is not able to dissolve in the developer solution, and De-scumming is the process of removal of such unwanted photoresist okay. But the downside of De-scumming is that you know you would be you know etching the entire surface of the wafer more, so the patterned areas are also going to be thin.

We are removing the unwanted resist layer, and at the same time the already patterned layer is going to be thin in that way, and you know after you do the development if you do a high temperature baking that is going to remove the any residual solvents that is going to present on the surface of the wafer, and it would also promote adhesion.

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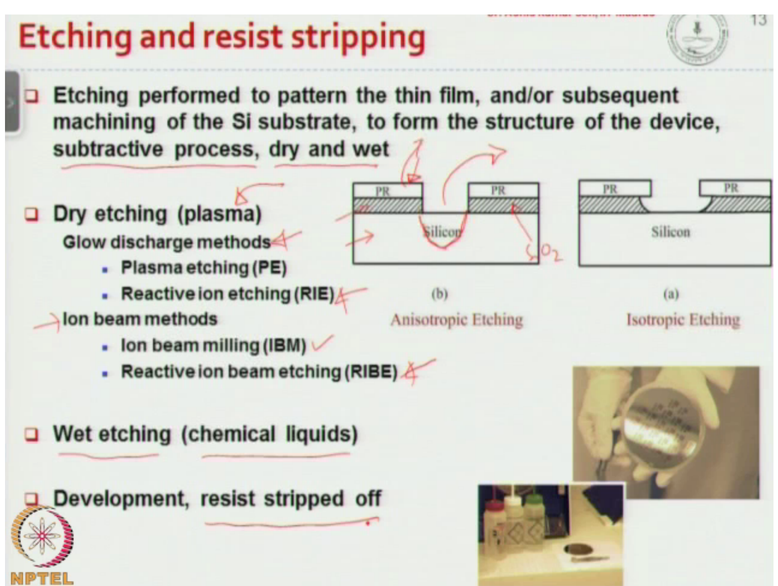

So once we do the development of the photoresist layer, for example as you see here this photoresist layer act as the mask to etch the silicon dioxide laser here okay, this is SO2 layer which you trying to etch. So the etching is performed typically on a patterned thin film okay, and then many times after removing the thin film we also want to etch the silicon itself, so many times we are going to go for a bulk etching of the silicon okay.

So the etching process may involve either etching of this thing film or etching of the bulk of the silicon okay to form the structure of the device. So typically etching is a subtractive process meaning we are removing the material from the you know either in terms of the film or the bulk of the material, we are not actually depositing materials so that is the reason it is a subtractive process, and we have two different you know etching techniques dry and wet etching techniques.

In dry etching is basically based on the plasma, so highly energetic you know ions which interact with the surface that we want to remove okay. So they are mainly categorized as glow discharge method, which is plasma etching or reactive ion etching. And the second one is ion beam

methods, which is ion beam milling, so energetic ions actually collide with the surface to remove the metal, and we also have reactive ion beam etching.

Then we would have wet etching, they are mostly based on some liquids okay chemical liquids that are used for etching, and you know so after we etch after let us stay here in this case we are trying to etch the silicon dioxide layer, so for etching silicon dioxide this photoresist layer acting as a mask okay that means the etchant do not attack photoresist, but only selectively etches the silicon dioxide layer. And once we have etched the silicon dioxide layer our job is finished, so we can remove this photoresist layer, so the resist is stripped off after the etching process.

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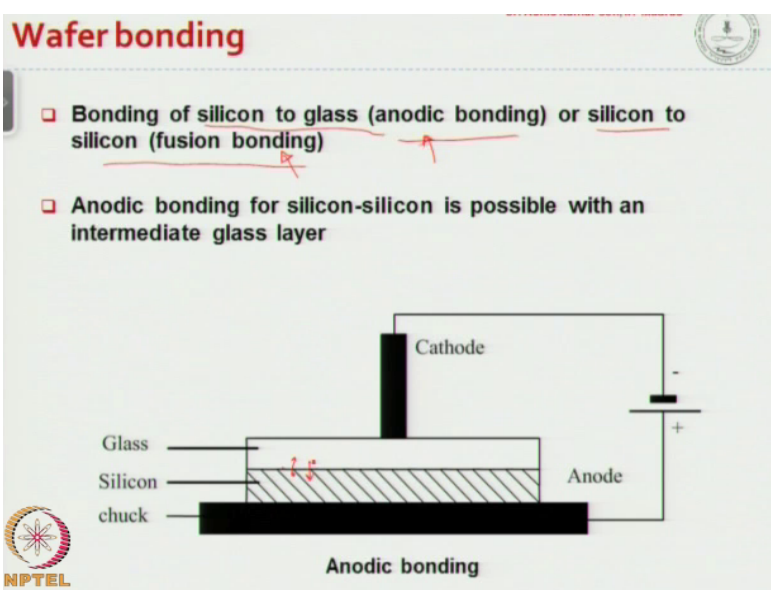

So after the etching let us say we have trying to create a microfluidic channel okay, we have patterned the photoresist, we have done development then we have etched the silicon dioxide, etch the silicon also using bulk micromachining which we will be covering later. And then so we have you know open channel structure okay, but in microfluidics we will need to seal the channel we will need to close the channel, and this is typically done by bonding okay.

So that bonding process would depend on what substrate material that we are dealing with okay, so polymers will have different bonding procedures, silicon will have different bonding procedures. If you talk about silicon's as you see here bonding of both silicon to silicon and

silicon to glass is possible, and silicon to class is typically done by anodic bonding, and silicon to silicon is done by fusion bonding, which uses relativity higher temperature.

So the material in fact goes to melting and that is how the silicon and silicon fuse each other at the interface. And anodic bonding we will go over the bonding process in detail sometime later, anodic bonding uses relatively less temperature as you can see this is the setup, where the silicon is connected to anode and glass is connected to cathode, and by applying a high voltage the atoms or the interface are going to penetrate into each other okay.

So the silicon atom is going to penetrate into glass, and glass atom is going to penetrate into silicon, so you would achieve a bonding between the glass and silicon wafers. We can also use anodic bonding for bonding silicon and silicon, and this is possible if you use an intermediate glass layer.

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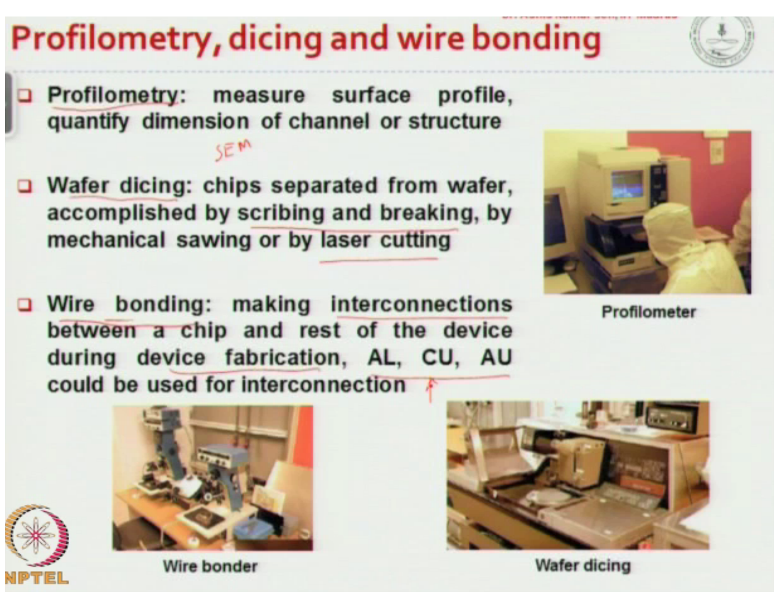

So after we do the bonding the next process will be you know to measure the structure what we have fabricated, in some cases let us see we have made a channel before bonding you can check you know what is the depth, what is the width that you are measuring, and you can compare that with your original design okay, and this is typically done using a profilometer okay, profilometer is one approach that you can use to measure the dimension of the fabricated structure okay for example a microchannel.

We can also use you know scanning electron microscopy SEM to image and determine the different sizes okay. So we go for profilometry to characterize the dimensions of the device, alternatively we can also use things like SEM okay. Once we have done the bonding, the next step would be you know wafer dicing okay, because when you do a fabrication on a typical a single silicon wafer, we may have you know many devices printed okay.

So in order to separate the devices from each other, we would have two dice the silicon wafer, and this is done using a special you know silicon dicing machine okay. And you know so first scribe the wafer and then break it, you know silicon is a very complicated material depending on the crystal plane and the crystal structure and orientation we would have to scribe it accordingly and break it to dice okay.

Alternatively, it is also done by laser cutting okay, so both mechanical sawing and laser cutting are used for dicing of wafers. The next step are typically would to do what is called wire bonding okay, so in micro devices including you know microfluidic device we would have you know many times fluid integrated with electrical electrodes okay.

So in order to establish electrical connection between you know different parts of the electrical network on the chip or you know the electrical connection between the electrodes on the chip and the external electrodes would need to make electrical connection okay. Since the dimensions that we are talking about are very small, we may not be able to always use solder for example okay, so at such small dimensions with small precision requirements we use what is called the wire bonding okay.

So this is used for making interconnections between chip and the rest of the device during device fabrication, the different materials that are used aluminum, copper, gold they are most widely used in the wire bonder.

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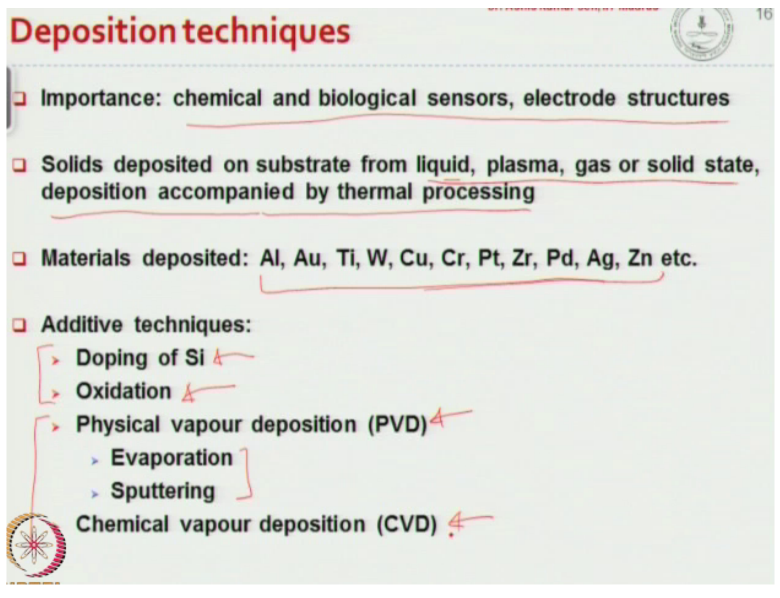

So that gives a broad overview of the photolithography process. Now let us talk about the deposition technique, the first step where we talk about you know two things. One is the doping okay, which is used to increase the conductivity of the silicon wafer especially for electrical applications we need to control the conductivity of the semiconductor itself okay, so since we are talking about silicon based microfabrication let us try to understand what doping method is.

And then we will also discuss oxidation as part of the additive techniques. So the deposition techniques are you know have importance in micro devices, especially when we are talking about chemical and biochemical sensors in microfluidic devices as well, because we are talking about you know putting you know conducting materials on the surface of the wafer either using deposition technique, for example using evaporation or sputtering.

So you know this is required to make enable electrical connection between the chip and the external wall okay. So to deposit materials or metals on the substrate it can be deposited from different sources from liquids, plasma, gas are in some cases from solids okay. And these deposition techniques are actually done in at high temperature, so they need a thermal processing to undergo to achieve the deposition.

Here are some of the materials that are used for deposition on micro devices, and we will be talking about different additive techniques, we will be talking about doping of the silicon and the

oxidation process the detail of it. So after we cover these two, we will also talk about the deposition of different selected metals that are you know presented here, so we will be talking about two important techniques here.

We will be talking about physical vapour deposition namely the evaporation and sputtering, and we will also talk about chemical vapour deposition okay. So let us first talk about the doping of silicon.

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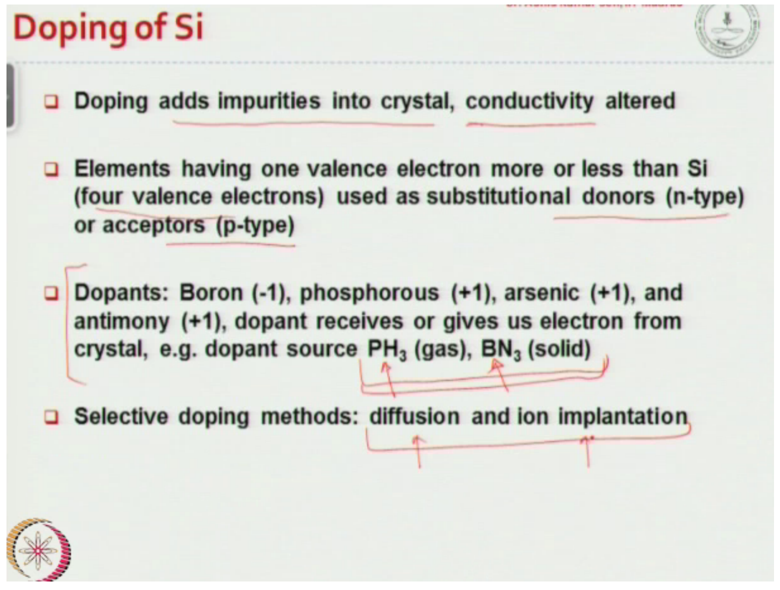

So as I was saying, what does doping do? Doping basically, you know modifies the impurity level in a semiconductor like silicon substrate okay, so the conductivity gets modified okay. So the doping as you see here you know it adds impurities into crystal, so the electrical conductivity gets modified, so what we do typically is we add elements that have you know one valence electron more or less than that of silicon.

So silicon has four valence electron and we add the metals that have either one more or less as compared to silicon okay, so the one that has got one less is known as n-type, and the one that has got one more is called p-type okay. So these are you know some of the dopants that are used boron, phosphorus, arsenic, antimony so the dopant would receive or give electron from the crystal. So some of the you know important sources that are used for doping this is PH 3 which is phosphine and BN 3 boron okay.

So these two are important 2 you know sources, one is the phosphine is a gas and boron is a solid that are used for doping the silicon okay. And we have mainly two important methods that are used for doping, one is the diffusion and the second one is ion implantation.

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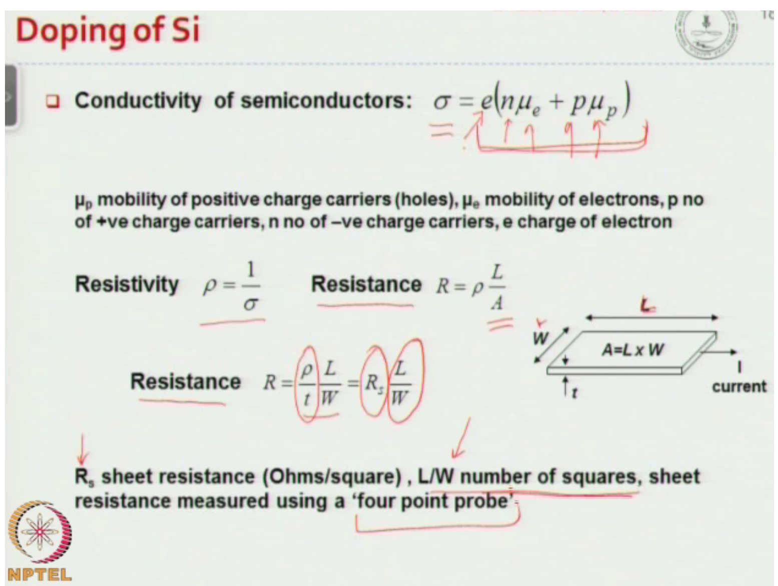

So if you look at doping we are basically trying to improve the electrical conductivity, and which is given by this expression here, sigma is the conductivity which is you know e here proportional to e is the charge of an electron and n is the number of negative charge carriers, mu e is the mobility of electron, mu p is the mobility of protons, and the p is the number of positive charge carriers okay. So the conductivity can be defined in terms of these parameters.

The resistivity is defined as 1/conductivity as you see here, and the resistance R=resistivity*length/area of cross section okay. So you know if you see this typical conductor here, which has thickness t, width W and length L, and current I is flowing perpendicular to the cross section W*t, so you can write the resistance R is going to be resistivity*L/area, area is W*t. So here we can define the resistivity/thickness as something called sheet resistance okay*L/W.

So this sheet resistance the unit is Ohms/square okay, so this is sheet resistance which has unit Ohms/square, and L/W is the number of squares we have, so the L of the substrate could be very high, so then W if you divide L*equal number of W's okay then you can find how many number

of squares we have okay L/W stands for number of squares, and Rs is this the sheet resistance which can be measured using different techniques including the 4-point probe technique. So this is the basic of the conductivity and the resistance of the typical conductor.

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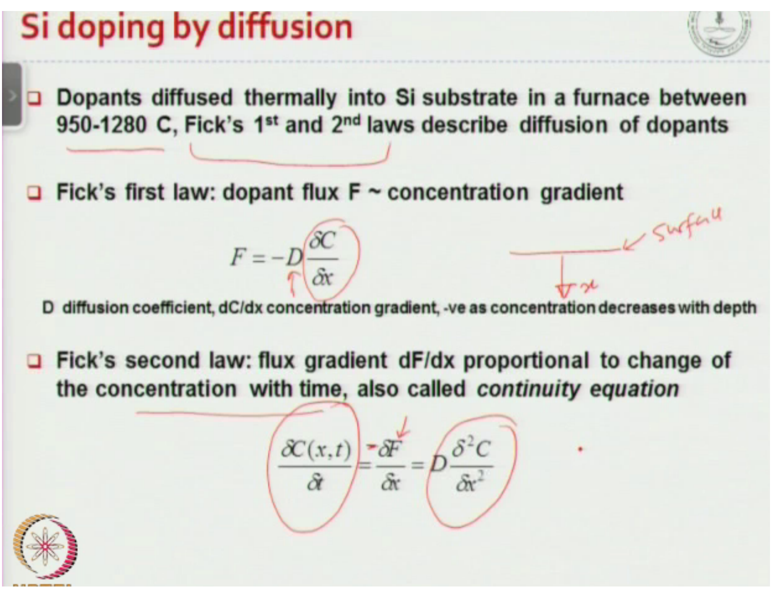

So next talk about that doping by diffusion okay, so the diffusion of dopants occurs between the silicon substrate and you know the gas present in the furnace, which is typically at a temperature 950 to 1280 centigrade, and this diffusion is governed by the Fick's first and second law. And if you look at the Fick's first class law, which says that the dopant flux is proportional to the concentration gradient okay.

So F is negative of D is the diffusion coefficient*del C/del x is the concentration gradient, here x is *the substrate okay, so this is x, this is let us see this is the surface x is *the substrate okay. And the Fick's second law tells that the flux gradient del F/del x is proportional to the change of concentration with time, so this is the concentration change with time, the gradient del F/del x is proportional to the change of concentration over time.

So there is a negative sign here because the flux would reduce with increase in the x. So again if you here if you use the expression for F from the Fick's first law this is the equation you get okay. Now to solve this equation we need boundary conditions okay, so we need 2 boundary conditions here.

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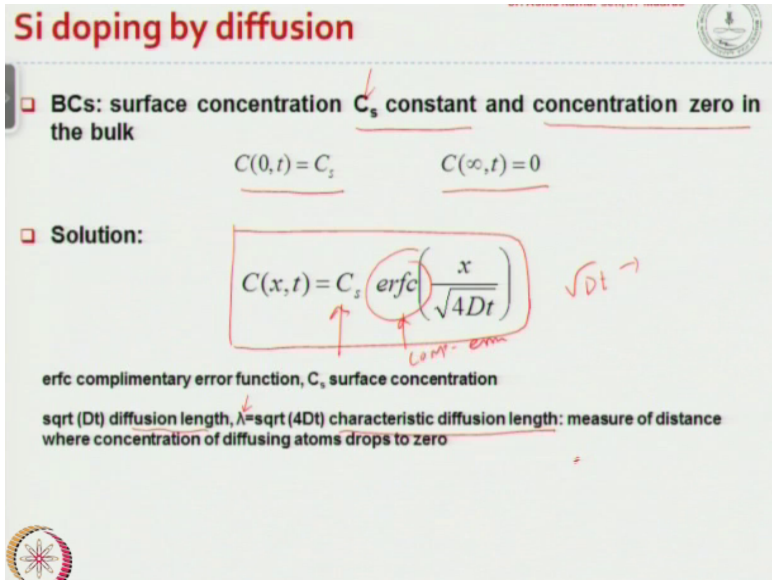

So these are 2 boundary conditions, the concentration of at the surface Cs is constant, we assume that there is infinite supply of the source, so that the surface concentration is going to remain constant, and the concentration is going to reduce to 0 in bulk okay, so C 0, t=Cs and C infinity, t is going to be 0. So using these 2 boundary condition, we can find the expression for how the concentration is going to vary with x that means how the concentration is going to change with the depth into the substrate.

So it follows an error function (()) (55:03) this is the complementary error function, and Cs is the surface concentration, and we have square root of Dt, square root of Dt is the diffusion length okay, and lambda=square root of 4Dt if you define lambda=square root of 4Dt that will be known as the characteristic diffusion length that means if the measure of distance where the diffusion of the concentration is going to reduce to 0 okay.

So it will be a Cs at the surface very higher at the surface is going to reduce to 0 at a distance which is square root of 4Dt okay, so this is assuming that the surface concentration remains constant. So next we look at if the concentration is you know limited, then how the concentration profile is going to look like, so we will continue on that with that let us stop here.