Electronic Materials, Devices and Fabrication
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Lecture - 28
Process and Device Evaluation

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Last few classes, we have been looking at the various steps that are involve in IC fabrication we saw that we could broadly divide them into four main types one was layering where layering means; you are trying to grow a thin film on top of your wafer, then we have doping. So, doping is the addition selected impurities to your wafer, in order to create a P-type region or n-type region doping of course, important, if you want to create devices like say a pn junction or a transistor. the 3rd on was lithography. So, lithography is important because of this is used, in order to define the dimensions of the device. And also to part of the various devices the ultimately a form part of an integrated circuit and we also have the last 1; it was heat treatment which comes along with all the other three processes. So, we could broadly divide the various steps in IC fabrication into these four kind of categories and we saw each of them in detail.

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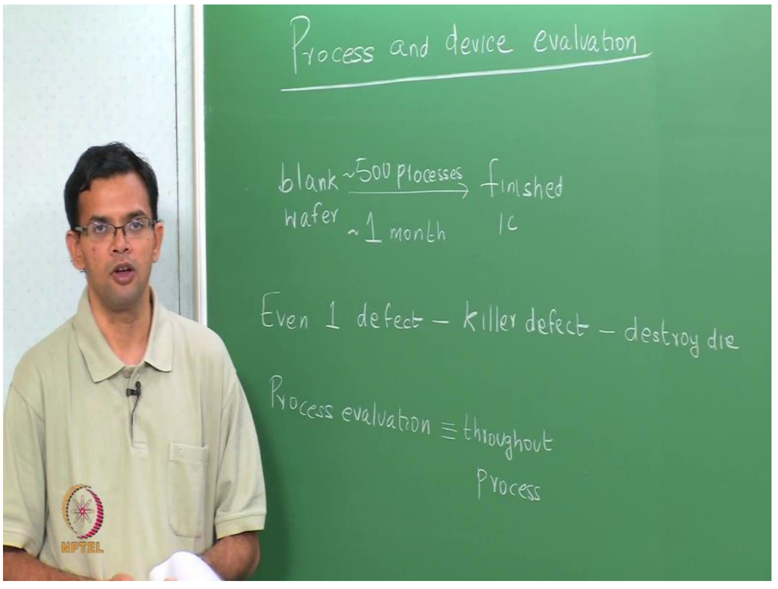

Today, we are going to look the evaluation of the IC fabrication process. So, we are going to look at both process and device evaluation. So, process evaluation is something very critical and we think about it; a typical IC fabrication process starts with a blank wafer at the end of the process the blank wafer goes through various fabrication processes. You can think of these in terms of assembly line at the end of this you get the finished integrated circuit. So, usually this is a die and the given wafer can have many dies for example, a typical 12 inch wafer can have 500 dies each die represent 1 finished integrated circuit. So, starting from the blank wafer to the finished circuit there are usually 500 odd processes.

So, these processes could be the layering or doping or lithography or heat treatment whether, typically around 500 processes the whole thing can take approximately a 1 month. So, even if any of the processes even 1 of them is wrong and hikes a defect, that defects can ultimately destroy the finished integrated circuit .So, even 1 defect and those kind of defects which will ultimately destroy the electrical functionality of the die or called killer defect. So, even 1 killer defect can essentially destroy the die. So, because of this your device or process evaluation is very important and it is usually done at each and every stage of the processes, to make sure the finished with a wafers are getting exact treatment that are intended to get.

So, process evaluation is done throughout and this is sort of obvious; because if you have approximately 500 processes and we do not do evaluation and the end product is bad it is very hard to go back and pinpoint whichever the process is essentially bad. So, process evaluation is done throughout, after each and every step is carried out. Typically process evaluation is done on different kind of wafers.

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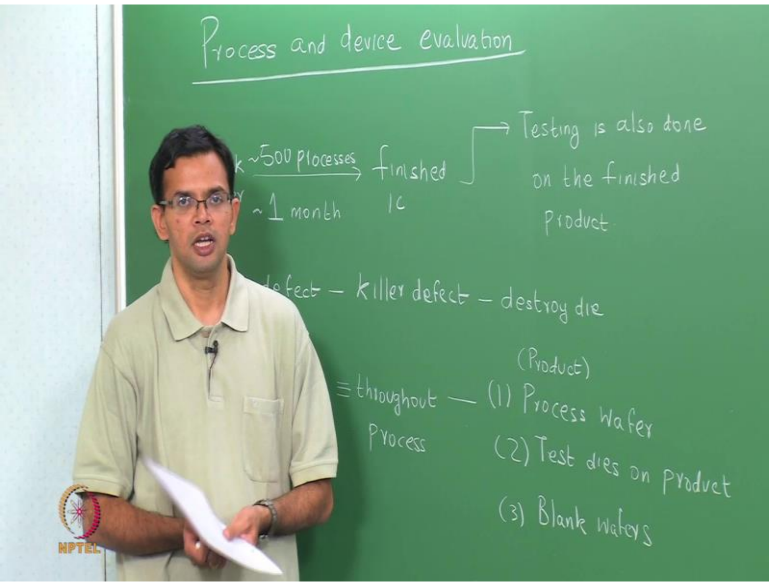

So, the first-one is the wafer the other name for this is your product wafer. So, you can do evaluation directly on the product wafer, sometime within the product wafer certain dies called test dies are also fabricated and then, evaluation is done on these test dies. So, that the entire wafer is not evaluated, but only certain dies or certain section of the wafer is evaluated. So, it can be done on test dies on product apart from that, you can also have something called blank wafers which can also used for monitoring. So, these are the kind of wafers where evaluation is carried out during the process, when the process is done and you get the finished integrated circuit electrical testing is also done on the finished product; to understand this process evaluation bit more, we can divide the various processes that take place during IC fabrication into 2 main types.

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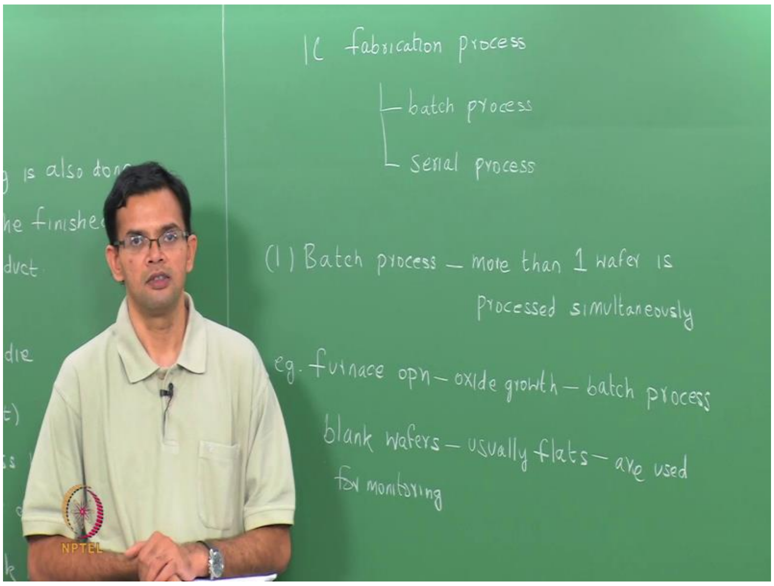

So, if you look at the IC fabrication process it can either be a batch process or it can be a serial process. So, this is 1 way of classifying the processes a batch process is 1, where more than 1 wafer is processed at the same time. So, you have more than 1 wafer. So, it could be usually a bunch of wafers, that a processed together. A typical example, of batch process is furnace operation for example, we have looked at the layering process in 1 of the processes we looked at during layering was oxide growth. In the case of oxide growth the sample is heated in a furnace and usually either a dry oxygen, which is just pure oxygen or wet ox which is steam which is used. In order to form an grow an oxide layer on the silicon wafer.

So, this is a typical example of a batch process, where multiple wafer are processed at the same time. So, that they see the same environment. So, an oxide growth is an example of for batch process, not all of these processes is product wafers. So, along with a product wafer some blank wafer or test wafers are also used and these test wafers can then be evaluated; because they receive a same treatment as that of product wafer when measuring the test wafers we can get an idea how the film is grown on the product wafers. So, here is the blank wafer and these are usually flats, flats means; these are just bear wafers with nothing else on them.

So, blank wafers are used for monitoring. So, typical oxide furnace can have anywhere between 100 to an 100 and 5 wafers. So, out of these 4 or 5 of wafers are used for monitoring. The rest of the wafer, some of those are product wafers and there also usually wafers or again bear wafers that have put at the edge of the furnace. In order to use for regulating the temperature and also for regulating the flow of gas.

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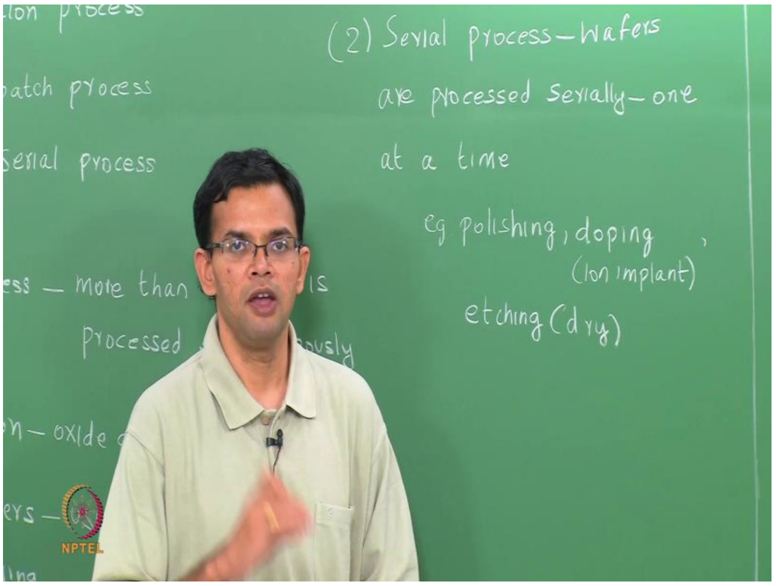

So, furnace operation is example, of a batch process the other type of process is a serial process in this a wafer are processed serially so, 1 at a time. So, an example of a serial process could be polishing, we talk about chemical mechanical polishing, which is part of planarization. So, chemical mechanical polishing could be example of, serial process doping is carried out by ion implantation and not by thermal diffusion that could be an example of serial process. So, I just say ion implantation or etching, again this could be an example of dry etching we also saw dry etching earlier that is an example of serial process. So, in this case the wafers are processed 1 at a time.

So, here again could use blank wafer, in order to monitor the process continuity to make sure that there is no variation from 1 wafer to the other, but actually a each wafer process differently. So, here evaluation is not only carried out on the blank wafers, but also carried out on the process wafer to make sure the process is running smoothly.

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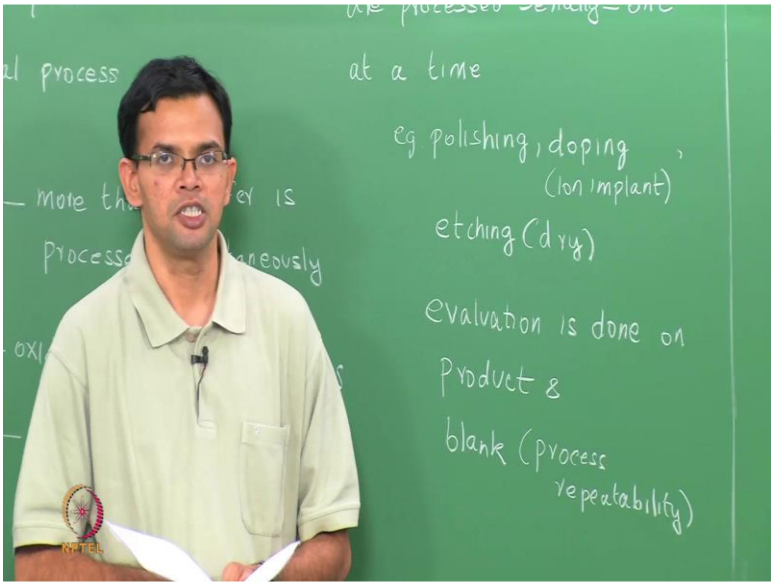

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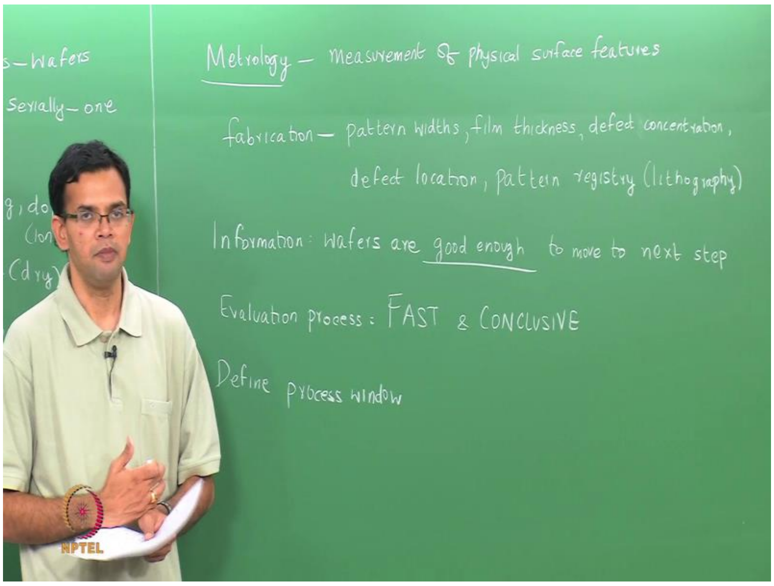

On the product and also blank wafers and blank wafers are used in order to make sure the process repeatability. So, far we have seen what process and device evaluation is and how it is carried out, whether you have a batch process or whether you have a serial process. So, let us look more closely at the evaluation process itself we usually define process evaluation is a part of metrology, where metrology is nothing but, the measurement of physical surface features. So, if you look at the fabrication some important parameters that need to be measure and again if we look at physical surface features, it could be pattern widths especially in metrology the depth. So, we have films of different thicknesses film depth or film thickness, the presence of any defects or contamination.

So, defect concentration the location of these defects also important, because a defect is located on the metal line it could cost a short and a short could basically lead to destruction of the IC defect making it a killer defect. So, defect concentration, defect locations are all important parameter that need to be measure. Another parameter is your pattern registry. So, this refers to the fact again we saw lithography, we have multiple mass and all of these mass is to be align on top of each other. So, that the final device is formed. So, this alignment is refer to pattern registry. So, these are some of the important parameters that need to be evaluated, at almost each and every step of the IC device fabrication.

What metrology should tell us; whether the wafers that pass through a given step are good enough in order to move on to the next step. The information we are looking for is whether, the wafers are good enough let me underline that to move to the next step. So, if you think of a fabrication process with more than 500 steps and I am in a step 10 the metrology should tell me, whether the wafer can be move from step 10 to step 11 or whether they have some defects that treat to be addressed and fixed, before the wafers can move to next step. So, we are looking for evaluation process which has to be fast is important because, we saw that a typical IC fabrication can take up to a month. And if you now, add in process and device evaluation we want to be fast or it will again increase the overall time of fabrication, this is not good because we know time equals money in any factory.

So, that if you increase the process time we will also increase the cost of the product. So, we want an evaluation process that is fast and we will also want, evaluation product that is conclusive. So, it should be able to tell you that your wafers are good and they are good to move on to the next step or they are bad. And then, they need to go and get some sort of defect treatment before they move to the next step or they should be scrapped or deleted from the based on process and device evaluation, we usually define something called a process window. So, a process window defines the acceptable range parameters for that particular process.

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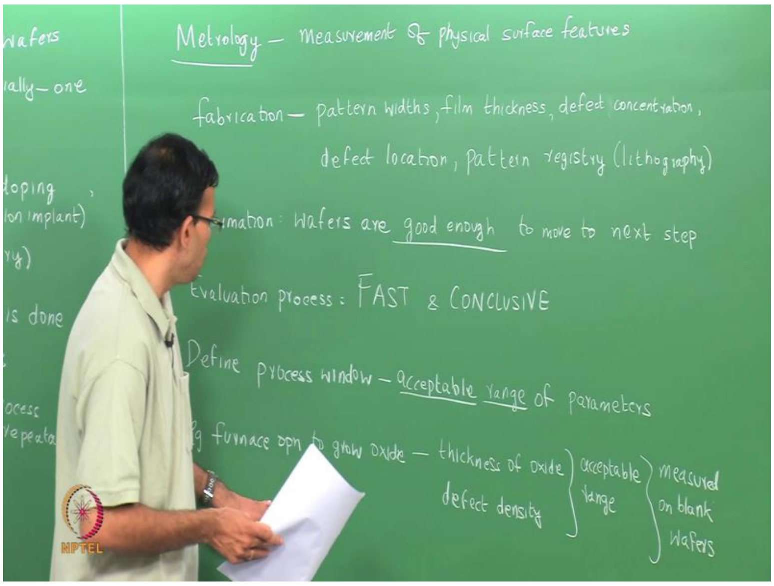

So, to given an example let us go back to the batch process we saw earlier, which is a furnace operation to grow on oxide. So, if you think about oxide growth the important process parameter is the thickness of the oxide layer, any furnace operation can also cause defects in your sample. So, a defect density is another parameter. So, these 2 are the process parameter and then based upon the final device there is usually a range of thickness value and also a maximum amount of defect that is permissible within the wafer. So, there is acceptable range for both thickness and defect level and because a furnace operation is a batch process, when more than 1 wafer processed at a time. These can be measured on the blank wafers or flat wafers whatever is measured on those is transported directly to your product wafers.

So, the measurement on the blank wafers is good then it means; the measurement in the product wafer is also good and then these wafers can then move to the next step. So, this is 1 of the advantages having batch process because the measurements are not carried out directly on the product, but on the blank wafers. To draw back of course, if there is a problem with a process which causes either a thickness shift or high level of density because it is a batch process to essentially effect more than 1 wafer which means that the wafer has to be scrapped when we say scrapped those wafers are contempt and destroyed. You not only destroy 1 product wafer, but you will destroy multiples of product wafers.

So, we think about furnace operation which says 125 wafer typically, 100 wafers of product. So, that in the furnace operation goes bad we would essentially scrapped 100 product wafers again lead to increase cost. So, that is the 1 drawback which we have a batch process. So, so far we looked a defining a process window, we will now look at some of the process evaluation types and then we will at each of those in detail. So, what are some of the process evaluation or measurements that are carried out?

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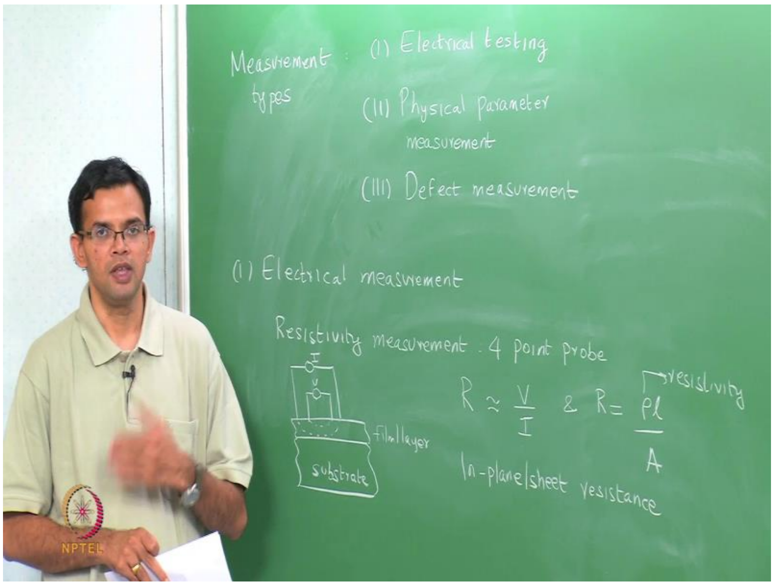

The first kind of measurement of course, it is electrical measurement or electrical testing this is important, because at the end we are manufacturing an electronic device. So, the electrical characteristics of the device are very important. So, electrical testing is carried out, not only during the process, but on the finished integrated circuit is formed electrical testing is also carried out to make sure that the device or the chip functions the way it the way it supposed to function.

You also have measurements, of physical parameters and we just saw an example of this for example, if you look at the oxide, the thickness of the oxide would be an example of physical parameter. The third type of measurement is carried out is the defect measure not all 3 are carried out for each and every process in the IC fabrication steam. For usually, defect measurement carried out for all processes electrical testing carried out only a select location, with certain portion of the device are define for example, if you do doping, you want to measure dopant concentration you can get that by electrical testing process we will see that in minute. Similarly, physical parameter measurement is usually carried out when you doing some sort of layering we are growing a layer or when you are trying to remove a layer by say etching or when you are doing lithography when you trying to define the pattern.

So, combination of these measurements is usually made at various steps processes the combination again depends in the fact that, the measurement has to be fast and has to tell us whether the wafers are good enough to move to the next step. Let us first look electrical measures. So, the simplest example of electrical measurements is of course, measurement of resistance. So, resistance is more commonly resistivity measurement 1 way to measure resistance is, by using a 4 point probe. So, this consists a 4 probe, 2 probes for measuring the voltage, 2 probes for sourcing the current. So, the resistance is nothing, but voltage over current.

So, we give an example of 4 point measurement consider a wafer substrate, usually have a thin film or a layer on the top we want to measure the resistance or the resistivity of the layer. So, there are 2 probes 1 from measuring voltage and 2 probes for sourcing the current. So, in this particular case the resistance of the film of the layer is approximately given by V over I. There is usually some constant term that is given in the front which depends upon the geometry of the 4 point probe arrangement where the typical resistance is V over I and from the resistance, can also calculate the resistivity you know the length of the probes and the cross sectional area. So, the probe here is the resistivity.

So, 4 point probe is usually used for measuring the resistance of the film or the layer it is also called in plane resistance or sheet resistance. And this process works, if the resistivity of the film or the layer is lower than the resistivity of the substrate. So, this means most of the current passes through the film and does not pass through the substrate. So, 4 point probe is usually used for measuring say resistivity of thin films that they deposited for example, you can have a metal film that deposited on silicon metal usually highs a much lower resistivity or an resistance compared to the silicon.

So, the current flows, through the film similarly if you dope specific layer of the substrate. So, that you have a dope layer with a lower resistance that, again can be measured using 4 point probe. Let us look some of the other electrical measurement, we can also use electrical measurement for measuring the concentration depth profile for dopants.

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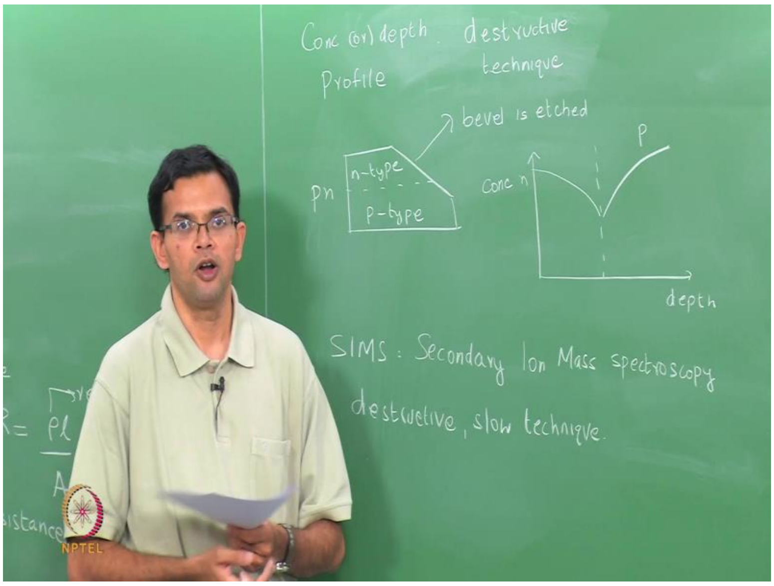

So, the concentration or depth profile this is usually done in conjunction with doping for example, if you have P-type material and you dope a certain region that is n-type. We can measure the n-type region also the depth of the pn junction, by looking at the electrical resistivity; this is again usually done by creating a bevel on the surface. So, that this is usually, a destructive technique. So, we start of P-type material we have dope certain region of this material n-type up to a certain depth.

So, that you now have a pn junction we can find the depth of the pn junction by etching a bevel this is again usually, done by using lithography in order to expose a certain portion of the wafer, which is done etched through and then measuring the resistance as a function of length along with bevel. As you move along with bevel length you also moving down in thickness. So, you can measure with the resistance and relate that to the concentration. So, I will directly plot the concentration. So, near your surface you have a n-type region as you go closer to pn junction we know the electrons and holes recombine forming a depletion region and the concentration dopes, beyond the pn junction once again, the concentration increases because now you have your P-type material.

So, forming these bevels and again looking at resistance we can use this in order to calculate the depth profile of doping. And another technique for measuring doping is called SIMS which is secondary ion mass spectrometer or mass spectroscopy. So, this is again a technique, from measuring the concentration of dopings it is much more accurate when the bevel technique. Because you directly measure the concentration, but it is again a destructive technique and it is slot slower. So, technique like SIMS which is secondary ion mass spectroscopy can be used as a offline technique for say, qualifying a new tool a new dopant tool that is coming to the fab rather than, using it as an inline technique for process or device evaluation.

So, usually technique based on resistances is much more quicker, and then technique based concepts. So, these are some examples of techniques that are used that are based upon electrical measurement. We now, look at some techniques that are based on physical measure that is film thickness, film widths and heights so, on.

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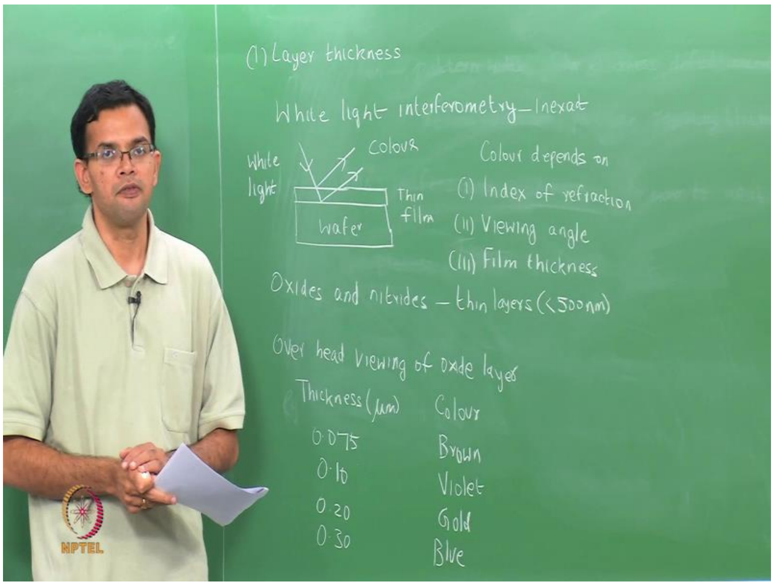

So, we look at physical measurement method and the most important of those is the layer thickness usually, in the case of IC fabrication 1 of the process is lowering. So, in lowering we grow a thin layer of another material, on the top of the wafer and it is important to know the thickness of that layer. So, 1 simple method which in order to measure thickness of these thin films is the fact that, these films are colored and we looking at the color this approximately possible to calculate the thickness of the film. This idea is essentially called white light interferometry.

So, consider a wafer with a thin film at the top. So, this could be a film of oxide layer or an nitride layer. So, white light where to form where to fall on the film, some of the light will be reflected from the top surface of the film, some of it will penetrate through and then get reflected from the wafer. These 2 lights that come out from different depths can essentially interfere and depending upon the thickness, some of the wavelengths will undergo destructive interference; some of the wavelength will undergo constructive interference.

So, even though you have a white light that consumes your output essentially has some color. So, by looking at the color of the film it is possible to approximately calculate the thickness. So, this is the basic idea, behind white light interferometry mainly used for films like oxides and nitrides, where there is no absorption in visible region, but the band gap is usually in the UV region and measuring the thin layers typically lesser than 500 nanometers.

The color in the case of white light interferometry depends upon the film. So, depends upon the index of refraction depends upon viewing angle. So, whether you give the film from top or from the side will matter because it will change, the distance of the path length of the light through the film and also film thickness to give some values, consider an oxide overhead viewing. So, your angle you are looking right down. So, that the angle is 90 degree. So, consider an overhead viewing of an oxide layer.

So, depending upon thickness we will write the thickness in micrometer, we can have different value of color. So, we have thickness 75 nanometer 0.075 the color can be brown, 0.1 it is violet, 0.2 it is gold, 0.3 is blue and so on. So, as your thickness increases the whole thing will again side. So, white light interferometry is an approximate technique, it is not very exact, but this a approximate technique for estimating thickness of the full based on white light interferometry, There is an another technique, from measuring thickness. So, this is called spectrophotometer. Once again, this is based on same principle, except that a monochromatic light resource.

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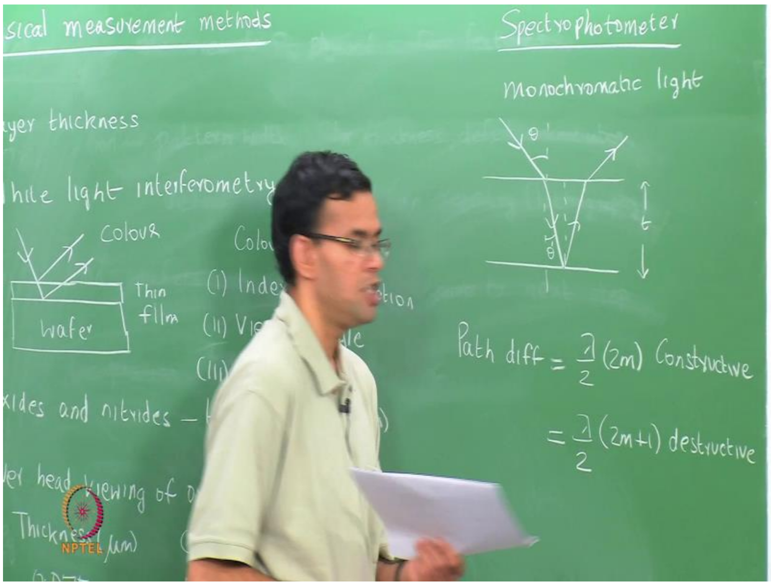

So, here you have example of the film, some thickness t, light falls on this some angle theta, lights get refracted where it gets reflected from the bottom surface and once again refraction, this angle is theta. So, t is the thickness of the film, your path difference for constructive interference, is an integral multiple of the wavelength this is for constructive, for the destructive interference it is an odd multiple. So, we changing the wavelength of the light this is possible to produce fringes of light and dark bands and from knowing the fringes and from measuring the value of m it is possible to calculate thickness.

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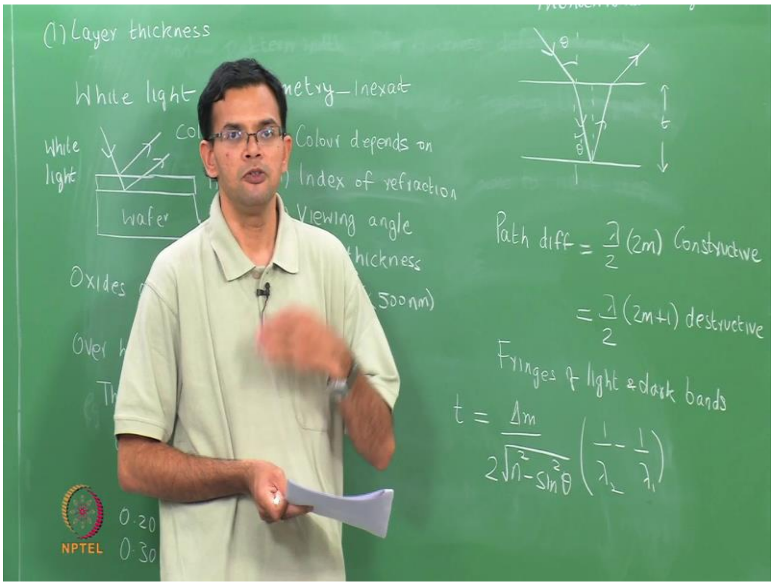

So, thickness t nothing but, delta m for 2 for 2 fringes divided by 2 square root of n square minus sine square theta, n is the refractive index of your material 1 over lambda 2 minus lambda. So, delta m is number of fringes between 2 wavelength lambda 1 and lambda 2; where you have, constructive interference, n is the refractive index and t is the thickness of the film. So, this takes the idea white light interferometry, but using a monochromatic light gives you much more, accurate measurement of thickness.

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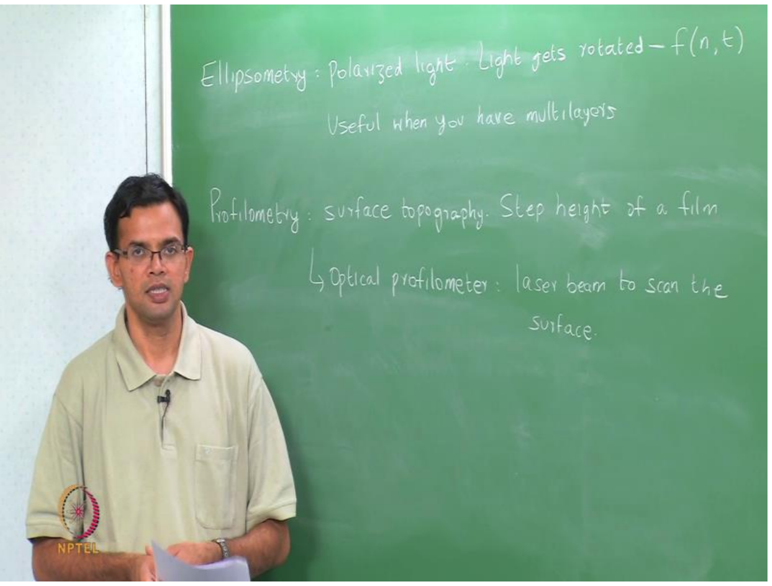

There are some other ways of measuring thickness 1 more technique is the Ellipsometry technique, this uses polarized light instead of normal unpolarized light. So, that when light passes through a thin film and gets reflected it also gets rotated. So, changing the polarization and this change in polarization is a function of both refractive index n and thickness t. So, once again, measuring the change in polarization this is possible to calculate the thickness. So, Ellipsometry is especially useful if you have stacks of different film of different thicknesses. So, that putting in values of the stack, we can calculate the individual thicknesses.

So, this is useful when you have multi layers for example, you can have an oxide layer on top of an nitride and so, on. Another way of measuring thickness called profile metric. So, in this case you measure the surface topography. So, there is a style that moves across the surface. So, that if you have a film that is deposited on the surface you will essentially have a step and by measuring the step height, you can calculate the film thickness. And offshoot of the profilometric technique is the optical profilometer, where instead of a chillers now have a laser beam that is scans the surface in this laser, beam will get reflected of a step.

In based upon the reflection we can calculate the step height, whether you have elipson meter elipson metric or whether, you have profilometri especially optical profilometri or you have an interferon metric all of these are really past techniques, that can be used in order to measures a film thickness. So, 1 of these techniques usually integrated along with process evaluation in order to measure the film thickness. The last 1 we want to look at is the measurement of defects or contamination.

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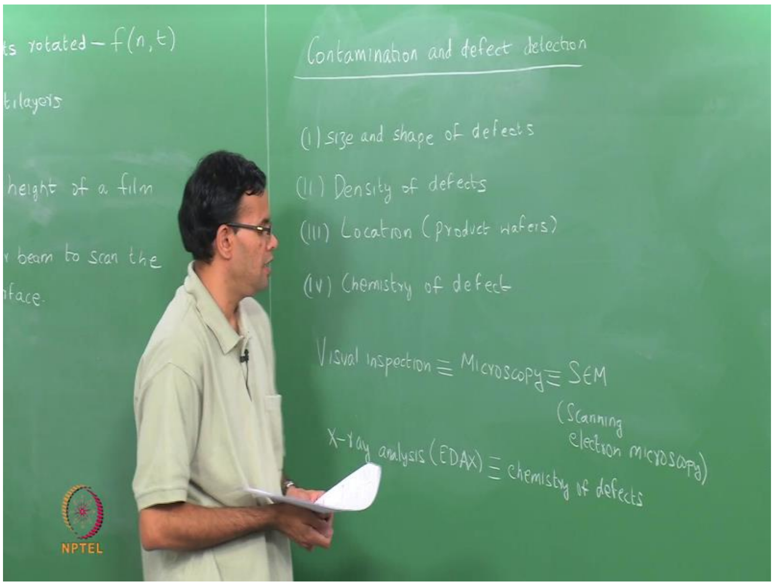

So, when we looked at defects or contaminants or a surface some of the important parameters we like to know, 1 is the size and shape of the defects, the density of the defects. So, how many they are on the surface, the locations of the defects especially, on product wafers because once again you can have defects at certain critical locations which can destroy the die and also, the chemistry or the nature of the defects. So, the simplest way to look at defect density the some sort of a visual inspection.

So, this can be done with a naked I, but now we know the we have devises, whose dimensions or of the order of nanometers. So, typical defects or also of the order of tens of nanometers. So, simple visual inspections with I is not possible. So, usually some sort of microscopy is used and because we have defects of the size of nanometers, usually a scanning electron microscopy or SEM is used. We will not going to the details of an SEM, but an SEM also has an attachment for x-ray analysis this is called E dax; energy diffusive x-ray analysis and this can be use to get information on the chemistry of the defects. So, by using an SEM you not only get information about the size density and location, but later we can also go and gets specific chemical information, about the defects.

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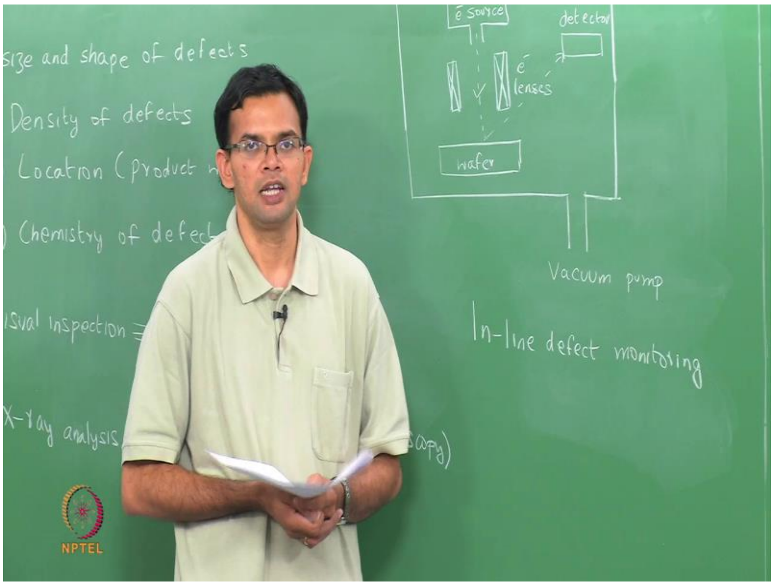

So, a typical SEM arrangement consist of an electron source there are usually lenses in order to focus the beams and scan it on the surface, electron lenses then you have the way. This some sort of a detector which is used for in nature in the whole thing is evacuated. So, the electron beam is scanned on to the wafer surface, where ever you have the defects the images of the defects are collected and these are used the calculate the density and the concentration. Sometimes in the case of pattern wafers, the SEM image of the pattern wafer is compared with a image of the ideal wafer.

So, that we can look for defects during pattern. So, SEM is usually used for defect monitoring in line because, it is a fast technique, but it does not provide any cross sectional information. So, doing cross sectional information TEM or transmission electron microscopy is used, but that is an offline technique. So, today we have looked at 3 main measurement techniques 1 for measuring electrical resistivity, the other for measuring physical parameters typically a thickness of a film, but you can also use it for measuring that dimensions for example, the width and the area of the films and finally, a defect measurements manly using an SEM all of these are used, during the various steps of the process. In order to evaluate the wafers and find out whether these wafers are good or bad for subsequent measurement. So, the next class we are going to look at product yield or process yield, where we see how good a particular IC fabrication process.