Solar Photovoltaics:
Fundamental Technology and Applications
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Lecture-14
Thin Film Solar Cells – Fabrication Techniques

Hello everyone welcome to our course solar photovoltaics, today we will learn about amorphous silicon solar cell. If you remember from the last few lectures we have started with solar photovoltaics. In this context in the last 2 lectures we have discussed about crystalline silicon solar cells, to recapitulate few of the factors which we learnt in our earlier classes are how to make a crystalline silicon.

And starting from crystalline silicon how to make a crystalline silicon base solar cells, what we have showed there the major source of silicon is sand. And silicon is the second largest abundant material on the earth surface. Now this silicon which is usually derived from the sand that is first mixed with the coke or the carbon at high temperature in a arc furnace and further by the Siemens method we make a polycrystalline silicon.

But to get a single crystal silicon we have to further purify it, this metallurgical grade silicon which we usually get by burning the silicon dioxide in the presence of carbon is not that much pure for using in the silicon base solar cell industry. But it is enough for use in the steel and aluminum industry, most of this case this metallurgical silicon has a purity of 98%. Now to make a chip based silicon or a optoelectronics quality silicon what we need to do starting from metallurgical silicon we need to further purify it.

And how can we purify it, so we can purify it in the by blowing it with oxygen or Hcl at high temperatures and we have seen that starting from the metallurgical grade silicon we can get a polycrystalline silicon by Siemens method. Then further by Salkowski's method or CZ method we can get a single crystal silicon and from a single crystal silicon we got it into the piece and get a thin wafer of the silicon.

Now we can do a (()) (02:41) of this silicon wafer but to make a solar cell we need to have a p-n junction. So that is achieved by diffusing some kind of carrier gas which contains the phosphorus as a donor impurity and along with some minor amount of the oxygen. So what will happen this phosphorus will dope on all side of this p-doped semiconductor, now selectively etching the font surface we can get an ideal p-n junction solar cell.

Then finally we dopiest the metal electrode on the top and also some anti reflection, you remember what was the role of this anti reflection coating it was to minimize the reflection loss as minimum as possible. And finally once we get a silicon wafer or silicon solar cell then we assemble those silicon solar cell to get a solar module. We assemble many of the solar module to get a solar panel and we assemble many of the solar panel to get a solar cell RF.

And this RF is usually installed for the practical application, this was the story of a single crystal silicon solar cell. And we have also mentioned that this single crystal solar cell showed very high efficiency as high as sometimes 20 to 24% or even 25% efficiency. But the huge processing cost which comes due to the high temperature and the material processing makes this solar cell very very costly.

Now a technology will only be available for the common people when the cost is also reduced at the same time as per as is quality or as per as is efficiency is concerned. So that part is done by the second generation solar cell, so that we will learn in details today.

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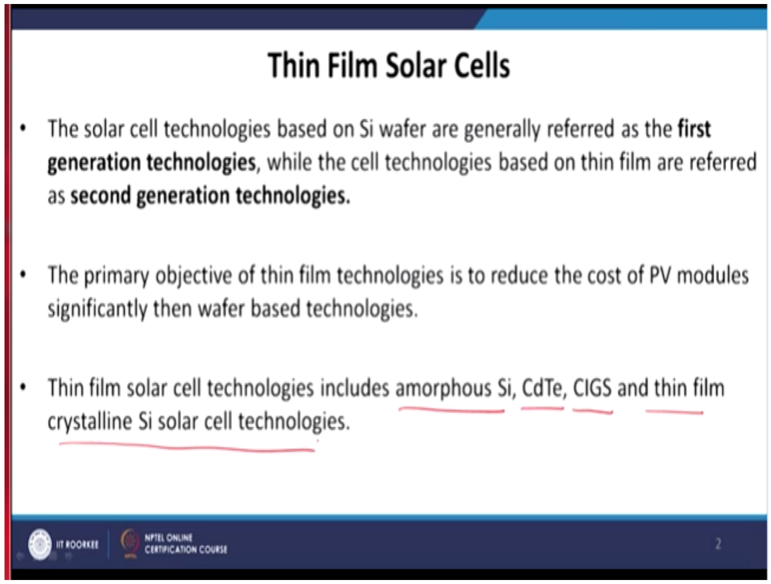

So just as we mentioned the solar cell technology is based on the silicon wafer are generally refer to as the first generation technologies whereas the cell technologies based on thin film are referred to as the second generation solar cell. Now the primary objective of the thin film technologies is to reduce the cost of PV modules significantly than the wafer base technologies, where this high cost is coming.

This high cost is coming in the first generation solar cell from the material processing because it inhales high temperature processing and also the yield is very low. So because of that the cost of production of first generation solar cell is often very high. On the other hand the second generation solar cell or the thin film based solar cells that informs a relatively easier processing method which does not always involve high temperature.

And which makes it little bit or less inexpensive or less expensive in comparison to the first generation solar cell. Thin film solar cell technologies include amorphous silicon and it is include CdTe, CdTe is stands for cadmium telluride, cadmium telluride is a quantum dot. So we can use the quantum dot also to make a solar cell. CIGS, this is a metal base solar cells and thin film crystalline silicon solar cell technologies. So these are all part of the second generation solar cell technologies.

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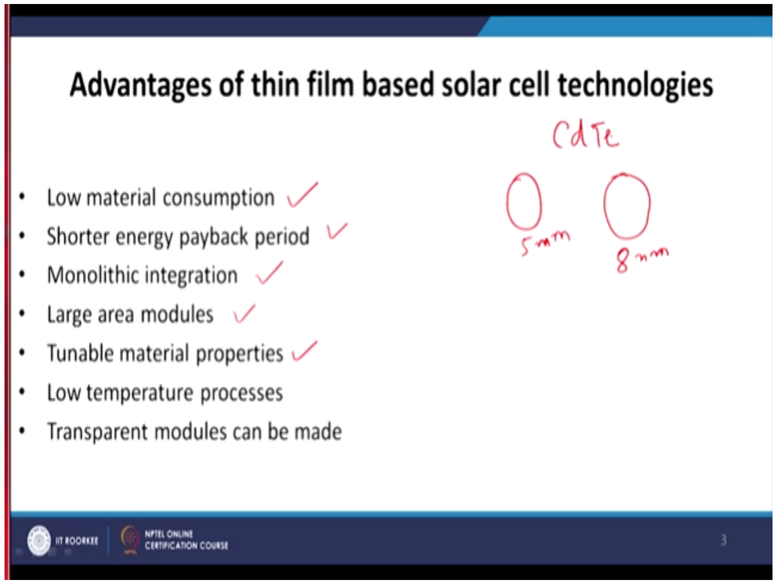

Now some of the basic advantage of the thin film solar cell technologies over the first generations are the following. For first important thing is that low material consumptions, here the amount of materials required to process the silicon solar cell is much less in comparison to the wafer base technologies. Second is shorter energy payback period, so since the amount of heat required here to generate or process this kind of thin film is much less than the first generation solar cell.

The energy payback period is much shorter in comparison to the first generation solar cell. Then it comes monolithic integration, large area module, so we can make a very large area solar cell module out of this solar cell. Material properties can be tunable, this is very very important in many of this material for example we take an example of CdTe cadmium telluride it is a quantum dot.

Now we know that this quantum dot has a bizarre properties, if you change the size or dimension of this quantum dot their optical and electrical properties changes. For example if I took 2 quantum dot like one at like this and another is like that. One has a dimension of 5 nanometer and another has a dimension of let us say 8 nanometer. So these 2 quantum dot even they made of these same material CdTe their emission their optical emission and absorptions will be quite different.

Now we can utilize this CdTe because of the difference in the optical properties to make different kind of optoelectronics device for example solar cell o LED. So the material properties can be tunable here that is one of the very important aspect in the second generation solar cell. Low temperature process, so the processing temperature which involves here is much low in comparison to the wafer base technologies.

And finally transparent modules can be made, so we can make a transparent modules out of this thin film solar cells. So what will be the advantage for that if we can make a transparent module then we can put it in our window, we can put it in our wall. So basically we can make a transparent window or transparent wall and still can get sunlight based energy in the room. So that is one of the big achievement of this thin film based solar cells.

So because of this advantage it take over from the first generation base silicon solar cell very shortly. Now let us learn some of the deposition techniques or some of the thin film growth techniques. One of the very important technique in this context is PVD or physical vapor deposition.

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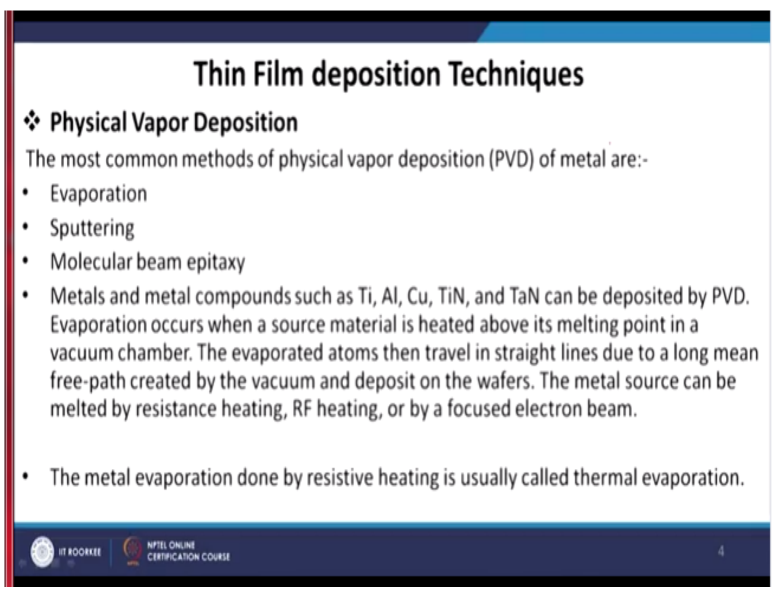

The most common methods of physical vapor depositions or material or metal or evaporation, sputtering, molecular beam epitaxy or MBE. Metals and metal compounds such as titanium, aluminum, copper, titanium nitride and tantalum nitride can be deposited by PVD. So commonly titanium, aluminum or copper we usually deposit by physical vapor depositions.

Now some of the common methods as we mention for the PVD method for metal are evaporations, sputtering and MBE or molecular beam epitaxy. Evaporation occurs when a source material is heated above it is melting point in a vacuum chamber. So we take the material in a vacuum chamber we create ultra high vacuum then we heat the material substrate above it is melting temperature, so that this the atomic gas of the metal start forming and it deposit on the degenerated substrate.

The evaporated atoms then travel in straight line due to a long mean free path created by the vacuum and deposited on the wafers. The metal source can be melted by resistance heating RF heating RF stands for radio frequency, so RF heating or by a focused electron beam. So these are the methods by which we can melt the metal, so what are the methods we can melt the method one is resistive heating.

So there you connect some kind of resistance along with this substrate below the substrate, you pass a very high current. And we know that because of the current there will be heat will produced in the resistance or in the load and because the heat the metal can be melted. Similarly we can use radio frequency based heating method or we can use focused electron beam for heating the metal.

Now finally once the metal got heated and also the chamber is vacuum the (()) (10:44) quite high. So the beam of this metal atoms which is now in a gaseous state can travel inside this vacuum distance and go and deposit on the silicon wafer, so that is the technique behind this evaporation method. The metal evaporation done by resistive heating is usually called thermal evaporations, this method sometimes also called thermal evaporations.

Not only for the thin base solar cell but also for third generation solar cell especially for organic photovoltaics like bulk heterojunction solar cell or perovskite base solar cell when you deposit the metal electrode on top of the active material we use this thermal evaporation method.

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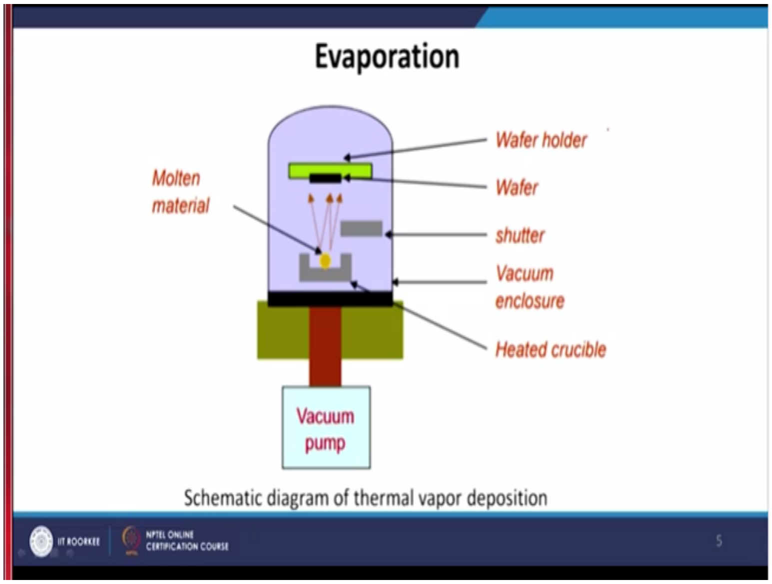

Let us look the diagram of the thermal depositions systems, so the parts or the components of the systems is shown here in this figure. As you can see there this is a big chamber is there, the cylindrical chamber showing here. And the chamber is connected with a vacuum pump, the role of the vacuum pump is to evacuate the air inside the chamber and create vacuum.

Now depending upon the vacuum pump whether it is rub pump or whether it is a turbo pump or whether it is a diffusion pump, the amount of the vacuum created inside the chamber is different. If we wanted to create a normal vacuum something like 10 to the power -2 to 10 to the power -3 pascal, then a rub pump will do our job. But if we wanted to go for ultrahigh vacuum which is very often needed like something like 10 to the power -6 or 10 to the power -7 bar.

In that case we have to use some different kind of vacuum pump, to create that much amount of high vacuum in the system. Now you can see that there is a substrate holder that is shown in the this green color, this is the substrate holder and the wafer on which we want to deposit the metal is kept on the substrate holder. Now it is worthwhile to mention that in the thin film solar cell it is the wafer which we deposit the metal.

But in the case of organic solar cell it is the solar cell itself on which we deposit the metal or in perovskite solar cell, it is the solar cell itself on which we deposit the metal. Now the metal piece or the metal chunk or the metal ware is kept here and then we heat the metal by resistive heating. So the metal melts and then there is a shutter is there so the role of the shutter is that when we want the metal atom beam to go front direction then we remove the shutter.

But when you do not want the deposition we close the shutter, it is acts like a gate and then we have to make sure that this the vacuum enclosure is properly sealed, so there is no leak. Because the deposition is not possible if the pressure is below a certain value of the pressure and also like **in** the pressure is below a certain value what will happen a thin insulating layer of the metal oxide will be deposited on the wafer which we do not want.

So to remove that possibility we have to make sure that the vacuum is enough inside the material usually 10 to the power -6 to 10 to the power -7.

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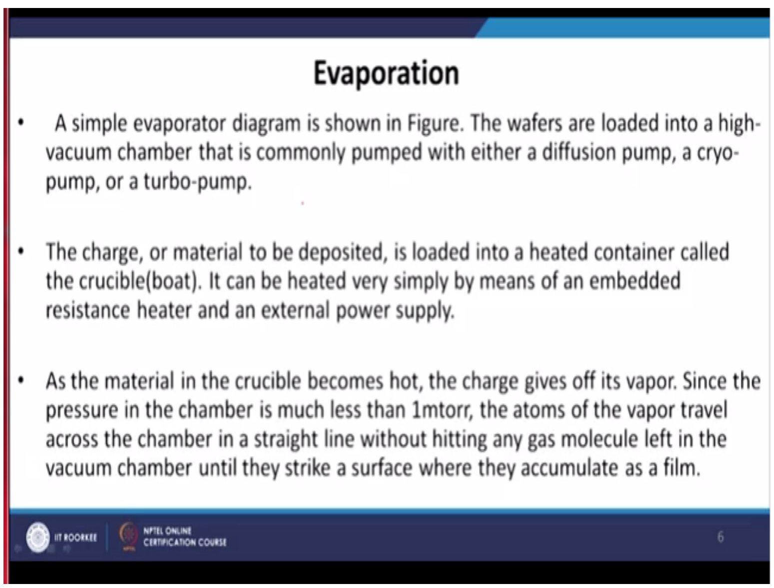

The wafers here are loaded into a high vacuum chamber that is commonly pumped with wither a diffusion pump a cryo pump or a turbo pump. If we use a turbo pump then you can achieve 10 to the power -2 to 10 to the power -3 bar pressure but if we use a diffusion pump or a cryo pump then you can go much lower vapor pressure. The charge or material to be deposited is located into a heat container called the crucible or boat.

Now for different materials or different metals we use different shape of boat or crucible, it can be heated very simply by means of an embedded resistance heater and an external power supply. As the material in the crucible becomes hot the charge gives up it vapor since the pressure in the chamber is much less than 1 mtorr the atoms of the vapor travel across the chamber in a straight line without heating any gas molecule left in the vacuum chamber until they strike the surface where they accumulated as a film. And we can control the growth of the film by some kind of sensor or piezoelectric sensor.

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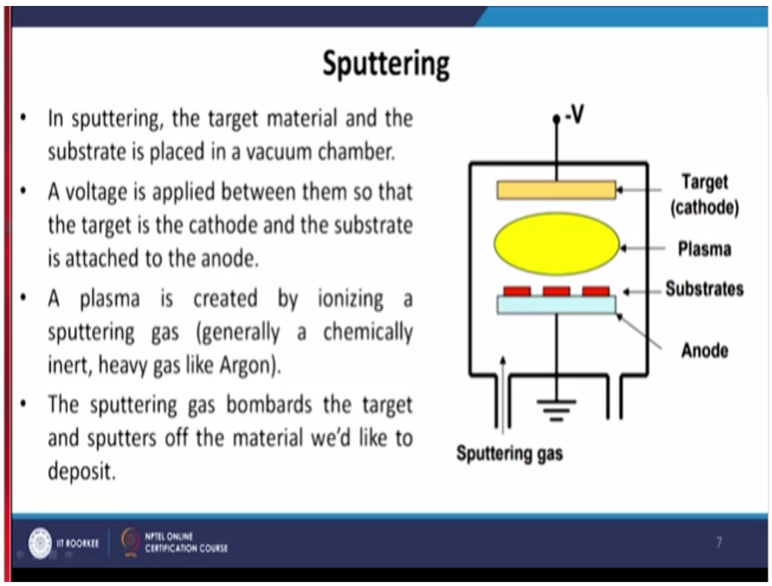

On the other hand in the case of sputtering the target material and the substrate is placed in a vacuum chamber. Here as for example we are showing this is a rectangular chamber where we have put the substrate and the target material inside this vacuum chamber and target we call it as a cathode let us say an substrate which is put on another electrode let us call it as a anode. A voltage is applied between them, so that the target is cathode and the substrate is attached to the anode.

So that means there is a potential difference has been created between the target and the substrate. A plasma is created by ionizing a sputtering gas, generally a chemically inert heavy gas like Argon. So in sputtering we use usually inert gas like Argon and we create plasma inside the chamber. The sputtering gas bombards the target and sputters off the material we would like to deposit.

So what it does like this sputtering gas or the plasma gas, so goes and heats the target and it rips out the atom layer from the target because that is of target which we wanted to deposit on our substrate.

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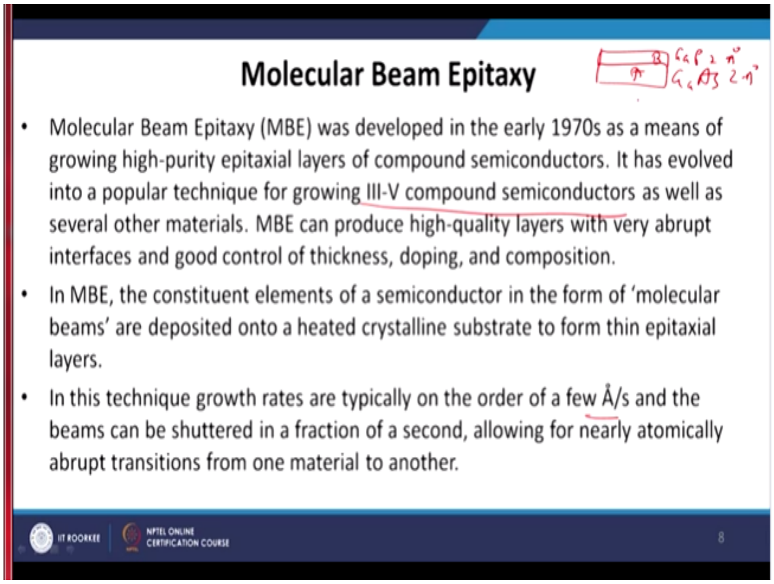

The third method in this context is MBE or molecular beam epitaxy, a very sophisticated technique which is used for the growth of the thin film very control growth of the thin film especially for gallium nitride or gallium arsenic it is used very very commonly. Molecular beam epitaxy or MBE was developed in the 1970s as a means of growing high purity epitaxial layers of compound semiconductors.

So what is compound semiconductors like single layer semiconductor example is like silicon or gallium arsenide but when you have a multiple layer of semiconductors like let us say for some operation I need to have a layer of gallium arsenide and gallium phosphate together. So that is an example of a compound semiconductor to grow a very very control layer of this compound semiconductor we usually use molecular beam epitaxy.

It has evolved into a popular technique for growing III-V compounds semiconductors as well as several other materials. MBE can produce high quality layers with very abrupt interfaces and good control of thickness doping and compositions. Now in MBE method you can control the thickness of the film in nanometer level even you can control the growth of the defect states the doping and the compositions of the material very very precisely.

In MBE the constituent elements of a semiconductor in the form of a molecular beam are deposited on to a heated crystalline substrate to form thin epitaxial layers. In this technique growth rates are typically on the order of few Armstrong/second and the beam can be shuttered in a fraction of a second allowing for nearly automatically abrupt transition from one material to another.

If the growth rate is 1 Armstrong or 2 Armstrong/second, so that means we can imagine that let us say I wanted to make 2 different layers of a semiconductor. One semiconductor gallium arsenic which I need 2 Armstrong layer and on top of that let us say I need gallium phosphate layer which is also 2 Armstrong, material A and material B. Now out of this 3 different methods which we described here one was sputtering another was thermal evaporation and the third was molecular beam epitaxy.

So we have to use molecular beam epitaxy of this precise control and when we need to have an epitaxial growth of the compound semiconductor. Now since the growth rate is 1 or 2 Armstrong/second we can start on a crystalline wafer to grow gallium arsenide and we can grow 2 Armstrong. And rapidly put the shutter on and then change the source or change the target material to go to gallium phosphate then we can alternate this method.

The high precision of the shutter which can be closed or open in a fraction of second and the very very precise growth rate makes this possible very very high precision thin film growth by the molecular beam epitaxy technique.

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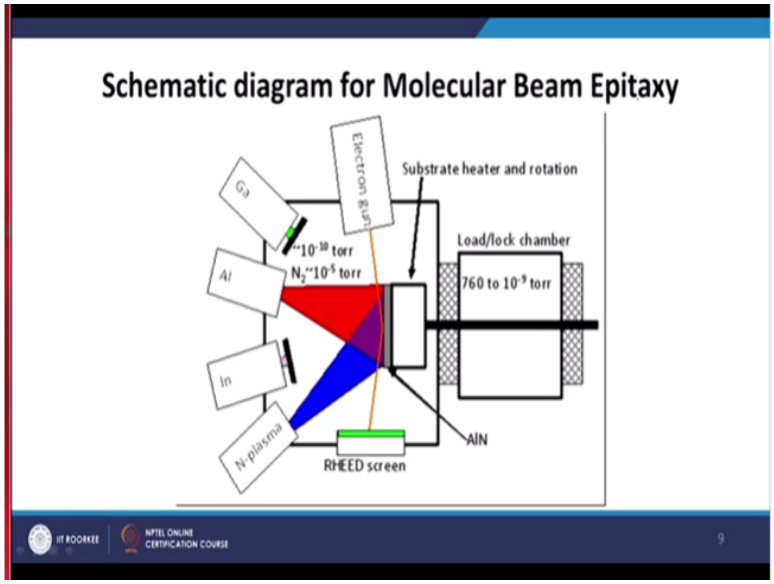

So the schematic diagram for the molecular beam epitaxy is shown in the following figure as you can show that there are different source of metals or different source of semiconductors we can use here like gallium, aluminum, indium here. And the electron gun is coming through here and the plasma goes through here and there is an RHEED screen here. Now the load lock chamber is on the right hand side which is are 10 to the power -9 torr.

Now this is the substrate heater and which can rotate, now either if we choose the gallium or aluminum or indium. So depending upon that which material we can choose it can fall on the substrate and it can deposit this. And the plasma the nitrogen plasma usually they fall on it and then recope the material and try to help to deposit on the substrate. So just like physical vapor depositions we have also chemical depositions or CVD technique.

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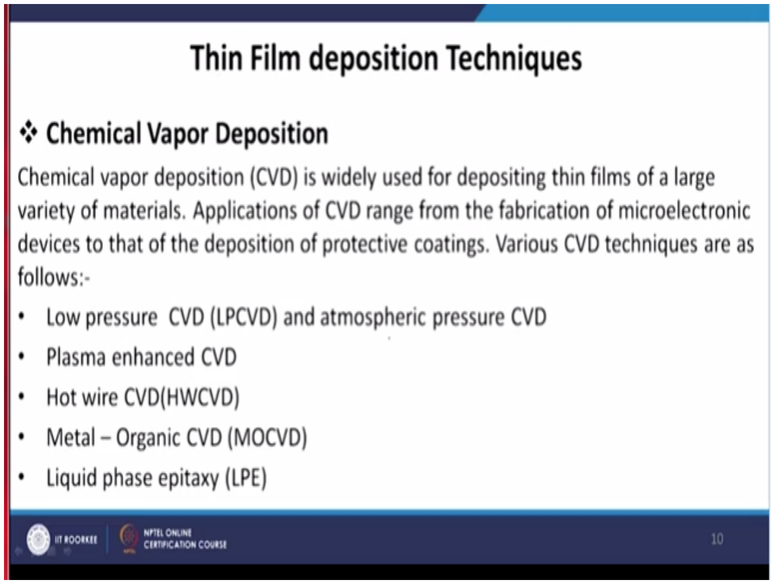

Chemical vapor depositions or CVD is widely used for depositing thin films of a large variety of materials. Application of CVD range from the fabrication of microelectronic devices, so that of the deposition of the protective coatings. So like for making encapsulants for any kind of optoelectronics devices CVD is the best technique. Various CVD techniques are as follows low pressure CVD or LPCVD and atmospheric pressure CVD.

Plasma enhanced CVD, hot wire CVD which is also abbreviated as HWCVD, metal organic CVD MOCVD or liquid phase epitaxy LPE. These are all example of the various chemical vapor deposition techniques, we will discuss few of them in details, the first thing is that low pressure CVD

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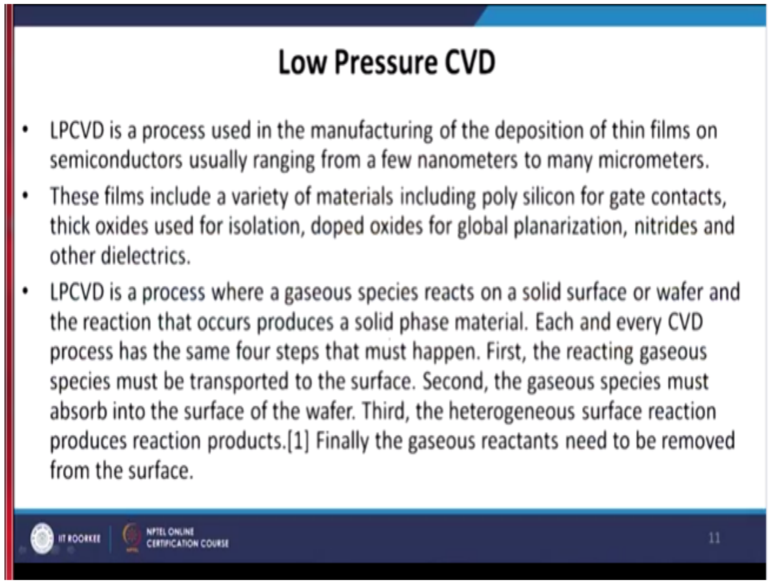

In LPCVD what we use this is used as a manufacturing process of the depositions of the thin films on semiconductor usually ranging from few nanometers to only micrometers. So based on how much thickness we want to get from our target material you choose what kind of CVD method we will use or depending upon what kind of material or what kind of precision we want or our end goal we choose like what kind of CVD methods will be suitable for our job.

So in LPCVD the growth film include a variety of materials including poly silicon for gate contacts, thick oxides used for isolation, doped oxides for global planarization, nitrides and other dielectrics. LPCVD is a process where a gaseous species reacts on a solid surface or wafer and the reaction that occurs produce a solid phase material. Each and every CVD process has the same 4 steps that must happen, so there are 4 steps happen in a CVD method.

In the first stage the reacting gaseous species must be transparent to the surface. So whatever the gas we wanted to react that needs to be transferred to the surface. Second the gaseous species must absorb onto the surface of the wafer, the second process is that once this gaseous species reach the wafer substrate the wafer needs to absorb them. Third the heterogeneous surface reaction produce reaction or the reaction products.

Finally the gaseous reactants need to be removed from the surface, so these 4 methods is common for all kind of CVD method.

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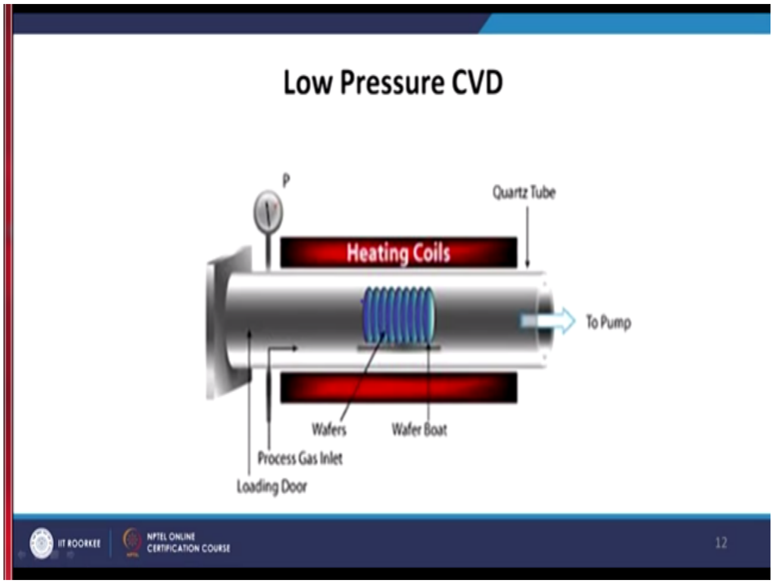

For example here the low pressure CVD technique is shown as you can see there, so there is a chamber ok and then this chamber is very often made of the quartz tube and which is placed inside a heating coils and these are the wafers. And these are the wafer boat and which the wafers are help and whatever we wanted to deposit that comes here, so this is the loading door and this is the process gas inlet and we can control the pressure by a gauze here and this outlet is going to the pump.

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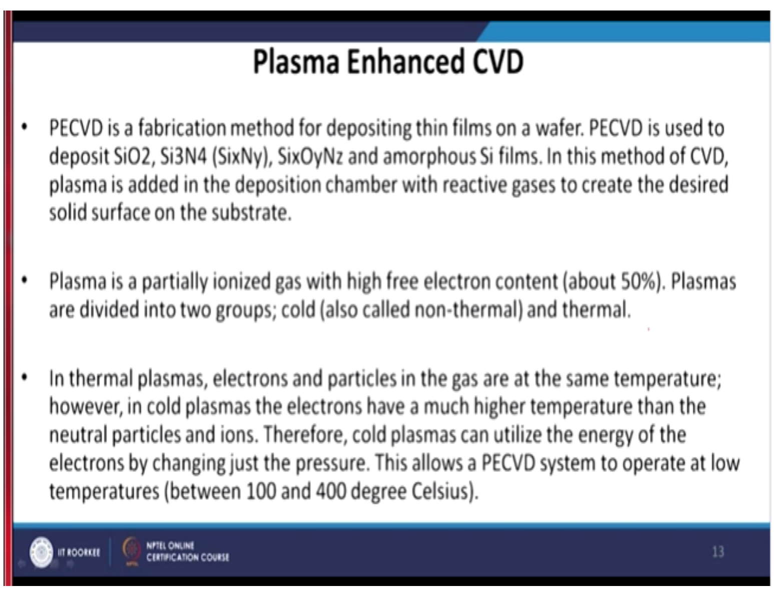

The second method in this context is the plasma enhanced CVD or PECVD which is a very very commonly used CVD technique by the semiconductor industry. PECVD is a fabrication method for depositing thin films on a wafer, PECVD is use to deposit silicon dioxide Si3N4, SiOyNz and amorphous silicon films. In this method of CVD plasma is added in the deposition chamber with reactive gases to create the desired solid surface on the substrate.

So whatever the gas we wanted to absorb on the surface that we call as a reactive gases, so that reactive gases comes through along with the plasma. Inside the chamber plasma and the reactive gases they go and fall on the desired substrate. The plasma now helps this gaseous of the reactive gases to absorb on the substrate. Plasma needs particularly ionized gas with high free electron content above 50%.

Plasmas are divided into 2 groups, cold plasma also called non-thermal plasma and thermal plasma. In thermal plasmas, electrons and particles in the gas are at the same temperature, however in cold plasmas the electron have a much higher temperature than the neutral particles and ions. Therefore cold plasmas can utilize the energy of the electrons by changing just the pressure, this allows a PEVCD system to operate at low temperature between 100 to 400 degree Celsius.

So if we use a cold plasma then we can use a temperature range between 100 to 400 degree Celsius. And in cold plasma what happens the electrons have a much higher energy than the particles and ions. So that the cold plasma can utilize the energy of the electron by exchanging and by just changing the pressure.

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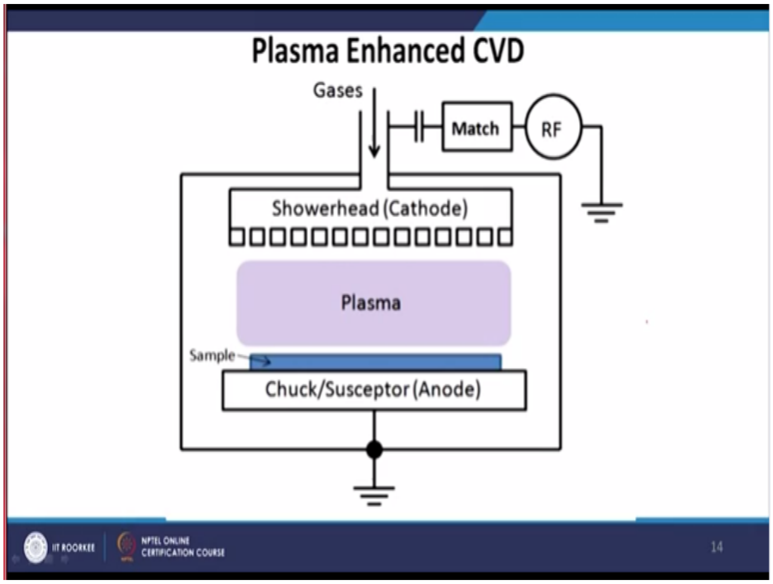

Here we are showing a schematic diagram of the plasma enhanced CVD, you can show that we create the plasma here and this is the cathode which is a showerhead cathode and the susceptor or the chunk is the anode. So these 2 cathode and anode has been connected to a voltage supply, so that we can create a potential difference and the sample substrate on which we want to deposit that is placed on the anode.

Now the plasma that also contains the reactive gases, now the gases comes from this inlet ok and there is a radio frequency which is used here. And then whatever this gas which you wanted to react on the substrate or on the sample substrate that comes through here. Now the plasma helps in this process and it goes and then it deposit or react on the sample substrate.

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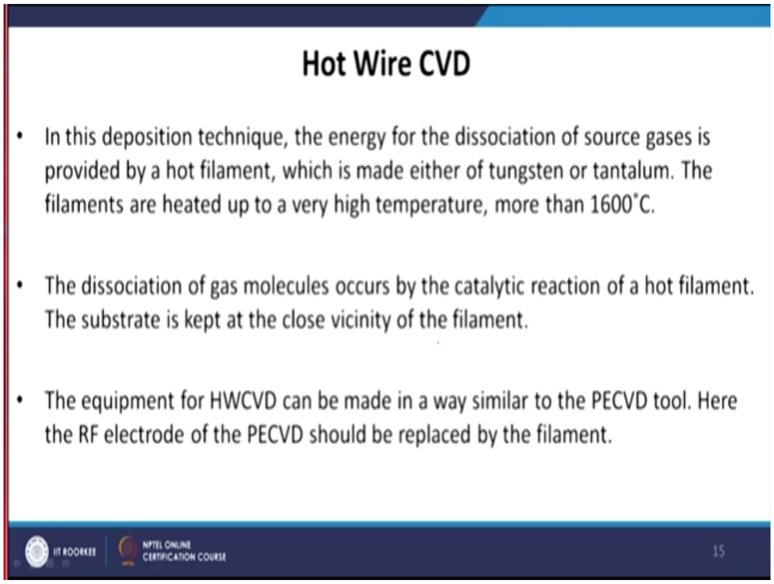

The next method is the hot wire CVD, in this deposition technique the energy from the dissociation of the source gas is provided by a hot filament which is made either of tungsten or tantalum. The filaments are heated up to a very high temperature more than 1600 degree Celsius, the dissociation of the gas molecules occur by the catalytic reaction of a hot filament, the substrate is kept at a close vicinity of the filament.

The equipment for HWCVD can be made in a way similar to the PECVD tool, here the RF electrode of the PECVD should be replaced by the filament.

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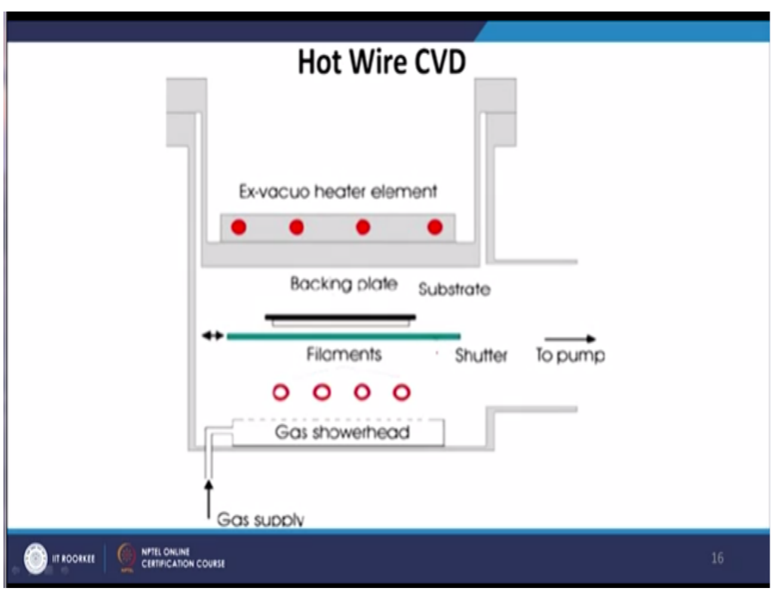

So hot wire CVD is same like PECVD only difference is that instead of the RF we have here the wire coil which actually heats the substrate. You can see here the same thing we put a filaments and which is controlled by a shutter and then we have the gas supply and then we have a cathode and anode and whatever the substrate we wanted to put that comes through and the reactive gases goes through there and react on the substrate and deposit on the substrate.

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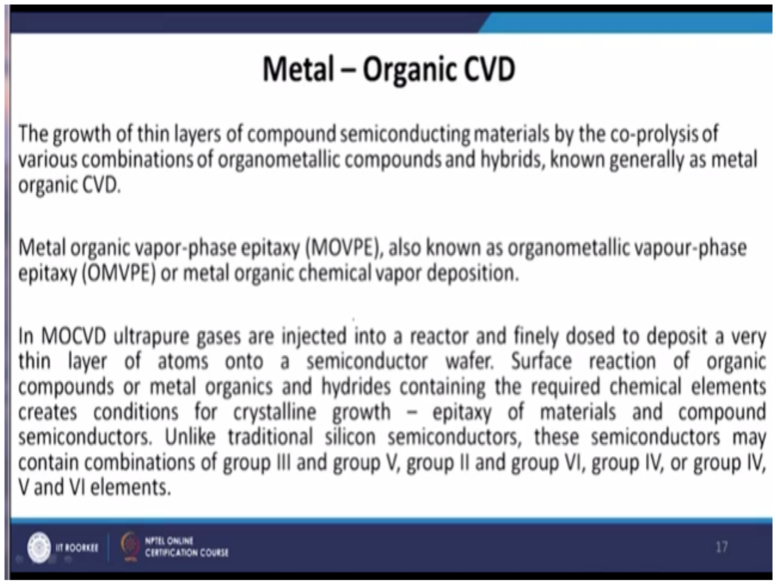

Then metal organic CVD, the growth of thin layers of compound semiconducting materials by the co-prolysis of various combinations of organometallic compounds and hybrids known generally as metal organic CVD. Metal organic vapor phase epitaxy or MOVPE also known as organometallic vapor phase epitaxy OMVPE or metal organic chemical vapor depositions, these are synonyms.

In MOCVD technique the ultra pure gas are injected into the reactor and finally close to deposit a very thin layer of atoms onto a semiconducting wafer. Surface reaction of organic compounds or metal organics and hydride containing the required chemical elements creates condition for crystalline growth epitaxy of materials and compound semiconductors. Unlike traditional silicon semiconductor these semiconductors may contain combination of group III and group V, group II and group VI, group IV or group VI or group V and group VI elements for example like that.

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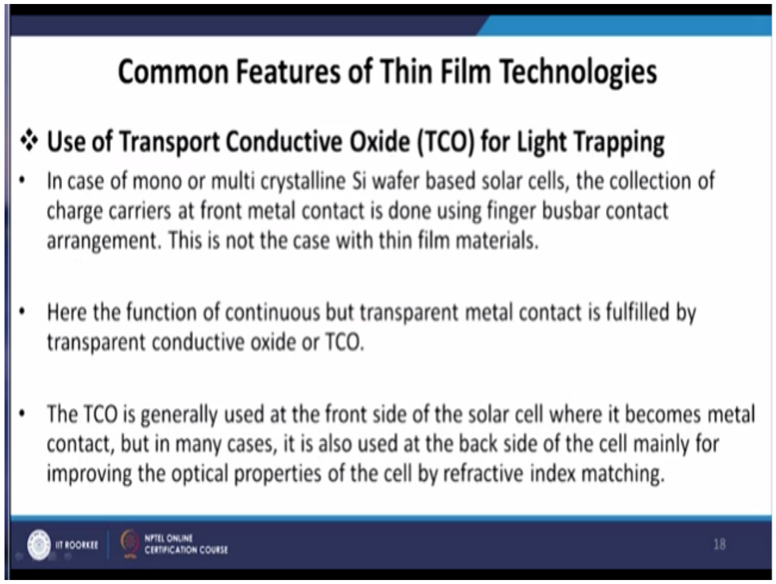

Now some of the common features of the thin film technology is that in the thin film technologies we very often use a transport conductive oxide or TCO for light trapping. Now what is this TCO or the transport conductive oxide, in case of mono or multi crystalline silicon wafer base solar cell, the collection of the charge carriers at front metal contact is done using finger busbar contact arrangement, this is not the case with the thin film technology.

You remember when we have learnt about the single crystal silicon solar cell we have shown that we use a finger kind of electrode in the for making a metal electrode. But in the case of the thin film technology we do not use finger electrode, we used a transparent conductive oxide layers usually an ITO or FTO which is an indium dope tin oxide layer or fluorine doped tin oxide layer. Here the function of the continuous but transparent metal contact is fulfilled by the transparent conductive oxide or TCO.

The TCO is generally used at the front side of the solar cell where it becomes metal contact but in many case it is also used as the back side of the cell mainly for including the optical properties of the cell by refractive index matching.

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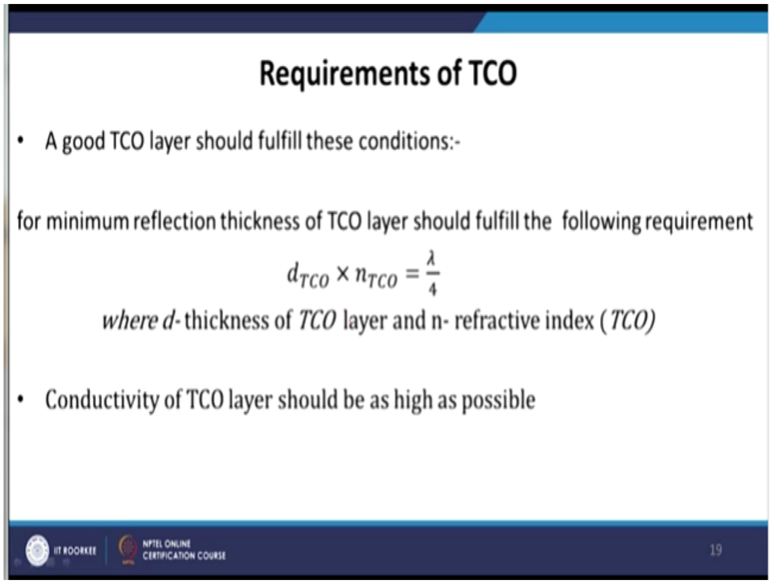

A good TCO layer should fulfill this conditions, for minimum reflection thickness of the TCO should fulfill the following requirement, dTCO into nTCO = lamda/4. So where d is the thickness of the TCO layer and n is the refractive index of the TCO layer. Now the thickness of the TCO layer times the refractive index of the TCO layer should be equal to the lamda/4. Now conductivity of the TCO layer should also be as high as possible, now what are the different types of the TCO.

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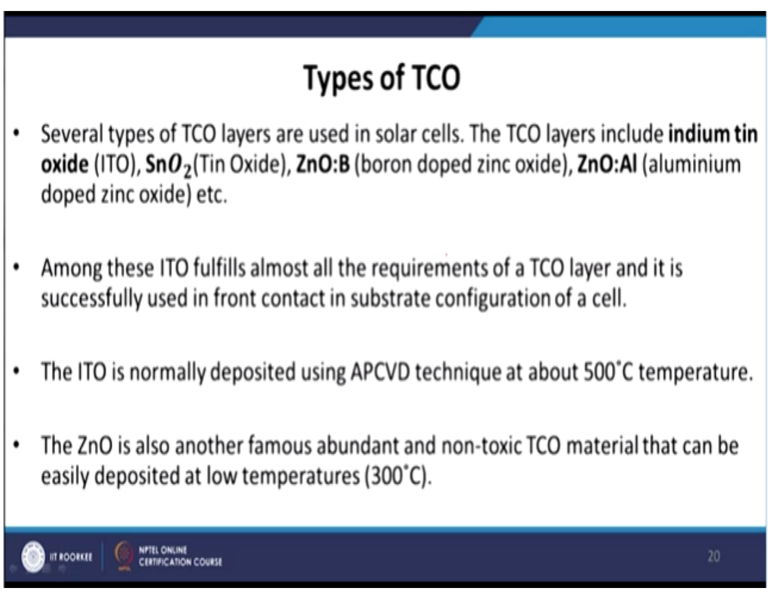

Several types of TCO layers are used in solar cells, the TCO layers include indium tin oxide ITO as we just mentioned SnO2 tin oxide, zinc oxide boron or born doped zinc oxide aluminum doped zinc oxide etc. Among this ITO fulfills almost all the requirements of a TCO layer and it is successfully used in the front contact in substrate configuration of a cell. The ITO is normally deposited using APCVD method at high temperature somewhat around 500 degree Celsius.

The zinc oxide is also another famous abundant and non-toxic TCO material that can be easily deposited at low temperature or 300 degree Celsius.

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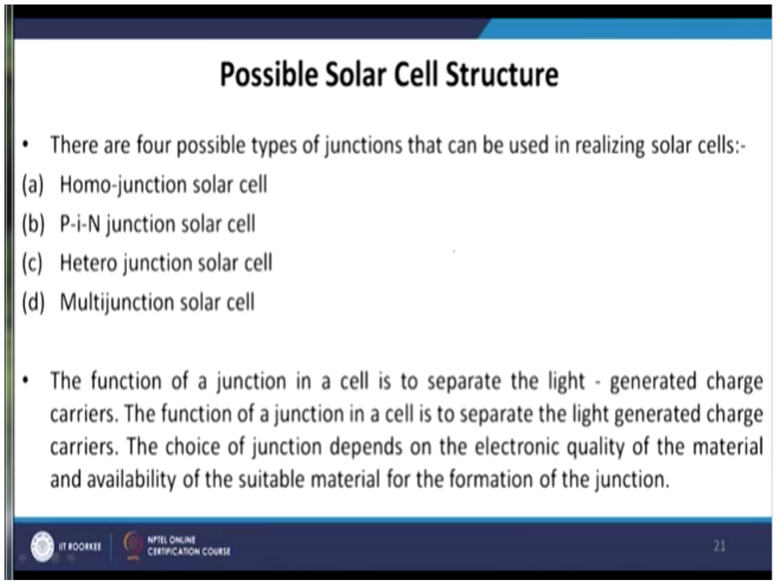

Now possible solar cell structure out of this things are 4 possible solar cells structure can be realized one is HOMO junction, another PIN junction, another is hetero junction solar cell, another is the multijunction solar cells. But today we will learn so far, in the next class we will discuss in details about the different types of the thin film solar cells, thank you.