Solar Photovoltaics:
Fundamental Technology and Applications

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Lecture-15
The Film Solar Cells – Parameters and Characteristics

Welcome everyone to our solar photovoltaics course. If you remember in the last lecture we have started learning about the amorphous thin film silicon solar cell, not only the amorphous silicon solar cell. But other thin film solar cell technologies like CDT or 6 base silicon solar cell. And we have shown that what are the techniques to grow this kind of thin film solar cell like some of the techniques which we learnt is physical vapor depositions method and in chemical vapor deposition method.

In physical vapor depositions method we have see that there are 3, 4 methods which includes their one of the very common methods which is used not only in the second generation but also in organic photovoltaics and in perovskite photovoltaics is the thermal depositions. Then we have learnt about how to do a sputtering and molecular beam epitaxy or MB. And also in the chemical vapor depositions we have seen that the there are different methods for chemical vapor depositions.

It can be plasma enhanced, it can be hot wire CBD but the ultimate the process is same in almost all the cases. We need have a reactive gases which will fall on the substrate and the substrates need to absorb it and finally we need to that the gases from the substrate. Now all of this methods leads to the formations of the thin film on the substrate. Now the next job is to make a solar cell out of that, today we will learn about different kinds of thin film solar cells.

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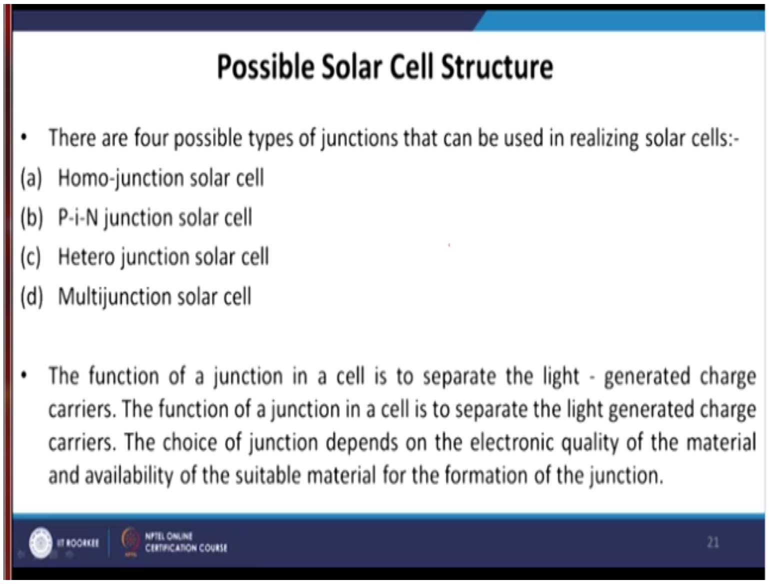

Possible Solar Cell Structure

- There are four possible types of junctions that can be used in realizing solar cells:-

(a) Homo-junction solar cell
(b) P-i-N junction solar cell
(c) Hetero junction solar cell
(d) Multijunction solar cell

- The function of a junction in a cell is to separate the light - generated charge carriers. The function of a junction in a cell is to separate the light generated charge carriers. The choice of junction depends on the electronic quality of the material and availability of the suitable material for the formation of the junction.

There are 4 possible types of junction that can be used in realizing solar cell, it can be a homo junction solar cell, it can be P-i-N junction solar cell, it can be hetero junction solar cell or it can be multijunction solar cell. Now we will learn about this 4 different type but just a point to mention here when we say that PIN junction solar cell, so basically we mean that a p-type and intrinsic layer and then n-type layer.

Later on we will discuss about the perovskite solar cell we will see that this pin or nip geometry plays a very significant role in determining the optical properties of the perovskite solar cell. In perovskite solar cell a very important electrical properties is the hysteresis. So we will see that whether we make a pin junction geometry or an nip geometry base solar cell the hysteresis is change significantly.

The function of a junction in a cell least to separate the light generated charge carriers. So when the light falls on the junction, so excitons of the bound electron hole pairs created and they finally get separated. The function of a junction in a cell is to separate the light generated charge carriers. The choice of the junction depends on the electronic quality of the material and availability of the suitable material for the formation of the junction.

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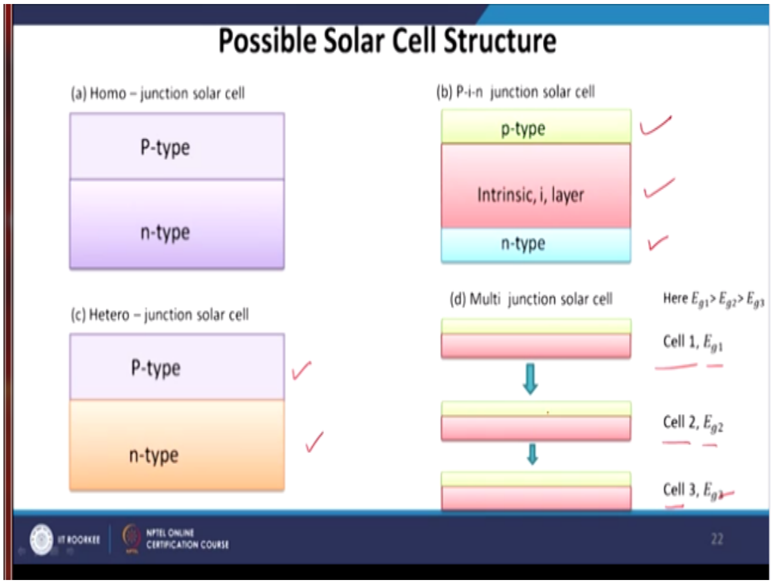

Possible Solar Cell Structure

(a) Homo – junction solar cell

P-type

n-type

(b) P-i-n junction solar cell

p-type

Intrinsic, i, layer

n-type

(c) Hetero – junction solar cell

P-type

n-type

(d) Multi junction solar cell

Here $E_{g1} > E_{g2} > E_{g3}$

Cell 1, E_{g1}

Cell 2, E_{g2}

Cell 3, E_{g3}

Now look that homo junction solar cell, in a homo junction solar cell you have a p-type layer and a simple n-type layer or a standard solar cell. A pin junction solar cell you have a p-type layer, you have an n-type layer and in between you have an intrinsic or i-layer. Now as I said that you can also have an n-type layer intrinsic layer and p-type layer. Then hetero junction solar cell it can be p-type layer and n-type layer but it can alternate.

And then there are multi junction solar cell which is actually a combination of 3, 4 cells, cell 1, cell 2, cell 3 with a different band gap Eg1, Eg2 and Eg3. And we have to make sure about the band gap matching that is Eg1 greater than Eg2 greater than Eg3 and we can connect them in a series are in parallel to make a multi junction solar cell.

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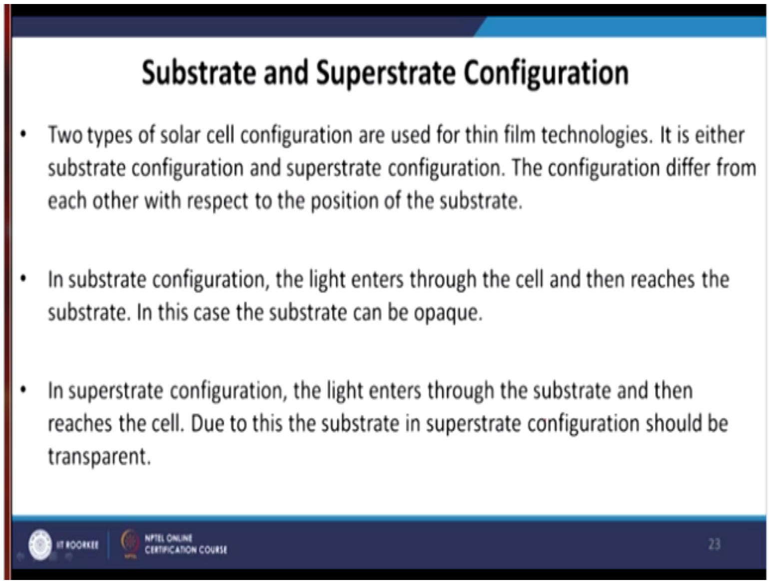

Substrate and Superstrate Configuration

- Two types of solar cell configuration are used for thin film technologies. It is either substrate configuration and superstrate configuration. The configuration differ from each other with respect to the position of the substrate.
- In substrate configuration, the light enters through the cell and then reaches the substrate. In this case the substrate can be opaque.
- In superstrate configuration, the light enters through the substrate and then reaches the cell. Due to this the substrate in superstrate configuration should be transparent.

Now the substrate and superstrate configuration, 2 types of solar cell configuration are used in the thin film technologies. It is either substrate configuration or superstrate configuration, the configuration differ from each other with respect to the position of the substrate. In substrate configuration the light enters through the cell and then reaches the substrate, in this case the substrate can be opaque.

In superstrate configuration the light enters through the substrate and then reaches the cell. Due to this the substrate in superstrate configuration should be transparent. So there are 2 different methods of the operation in superstrate configuration the substrate should be transparent because light falls on enters through the substrate and then it is reaches on the cell. Whereas in substrate configuration the substrate can be opaque because light enters through the cell and finally reaches on the substrate.

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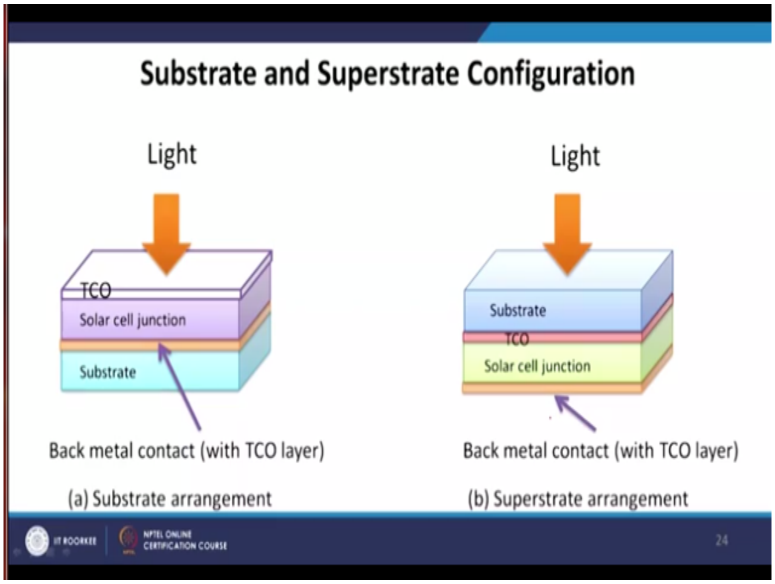
Substrate and Superstrate Configuration

(a) Substrate arrangement

(b) Superstrate arrangement

For example you can see in this figure here, so we have a substrate then the solar cell junction and then the transparent conductive oxide. So light falls on the top, so even if the substrate is something like a very opaque layer, so that does not matter a lot because light falls from the top. So only matters the top surface has to be transparent and it falls on the solar cell junctions which creates exciton and separate the excitons.

Whereas in superstrate arrangement you see that the substrate is on the top, so and then there is a TCO and then there is a solar cell junctions. So here the substrate has to be transfer it because now the light falls on the substrate and then it passes though the TCO and goes to the solar cell junctions. And in both of this cases in here the back metal contact is here, so basically the solar cell junction is sandwiched between the TCO layer and the back metal contact and in the bottom we put the substrate.

Here we put that TCO solar cell junction in between TCO and the back metal contact but the substrate is on the top. Sometimes it is also called like forward geometry or reverse geometry.

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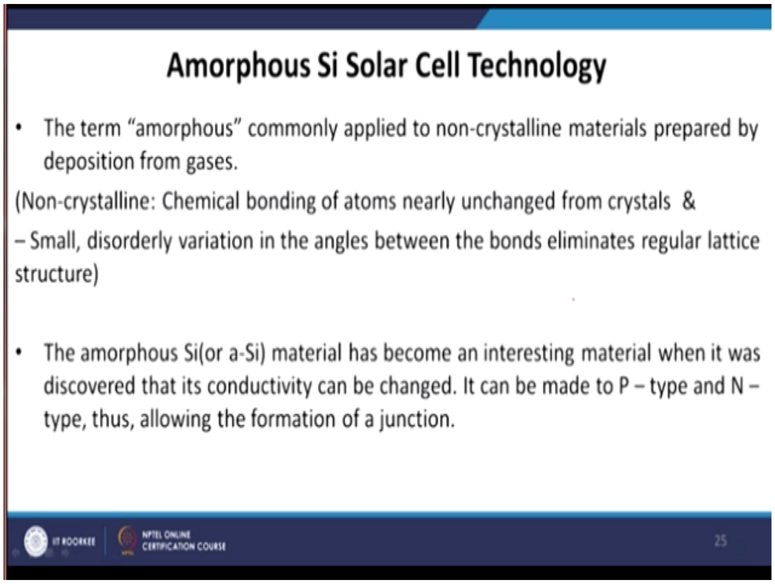

Amorphous Si Solar Cell Technology

- The term "amorphous" commonly applied to non-crystalline materials prepared by deposition from gases.

(Non-crystalline: Chemical bonding of atoms nearly unchanged from crystals &

– Small, disorderly variation in the angles between the bonds eliminates regular lattice structure)

- The amorphous Si(or a-Si) material has become an interesting material when it was discovered that its conductivity can be changed. It can be made to P – type and N – type, thus, allowing the formation of a junction.

Now the term amorphous commonly apply to non crystalline materials prepared by the deposition from gases. So we are pretty much sure about what is an amorphous material or what is an crystalline material. And usually how do we material characterization wise how do we know some material is amorphous or some materials are crystalline. We use an experimental technique called XRD X-ray diffraction.

So from the XRD peak analysis or looking at the nature of the peak we can comment on whether a material is crystalline or whether a material is amorphous even we can know what is the degree of crystallinity. Non crystalline just a chemical bonding of atoms nearly unchanged from crystals and small disorderly variations in the angles between the bonds eliminates regular lattice structure.

The amorphous silicon material has become an interesting material when it was discovered that it is conductivity can be changed. So in amorphous material or in amorphous silicon you can change the conductivity that we cannot do in the case of crystalline silicon. It can be made to p-type and n-type thus allowing the formation of a junction. So we can even make optoelectronic devices like solar cell with the varied conductivity.

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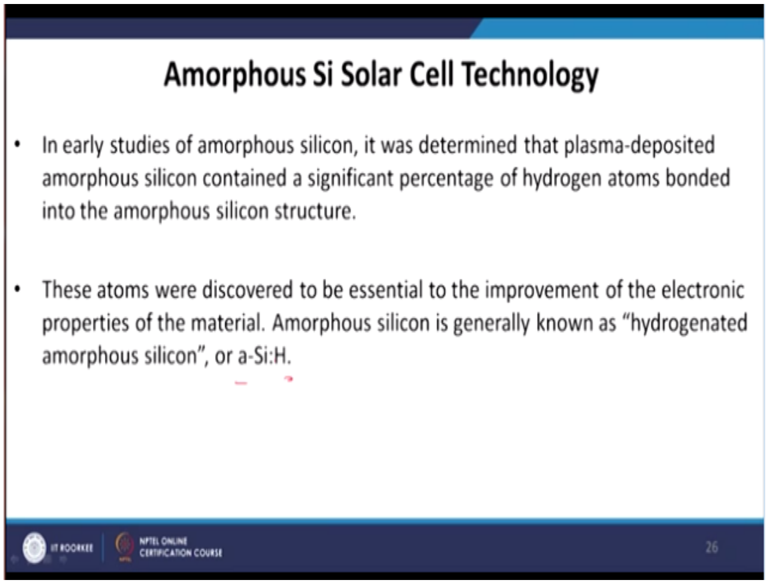

Amorphous Si Solar Cell Technology

- In early studies of amorphous silicon, it was determined that plasma-deposited amorphous silicon contained a significant percentage of hydrogen atoms bonded into the amorphous silicon structure.
- These atoms were discovered to be essential to the improvement of the electronic properties of the material. Amorphous silicon is generally known as "hydrogenated amorphous silicon", or a-Si:H.

In early studies of amorphous silicon it was determined that plasma deposited amorphous silicon contains a significant percentage of hydrogen atoms bonded in the amorphous silicon substrate. These atoms where discovered to be essential to the improvement of the electronic properties of the material. Amorphous silicon is generally known as hydrogenated amorphous silicon or a-Si-H, a stands for amorphous and this is hydrogenated silicon.

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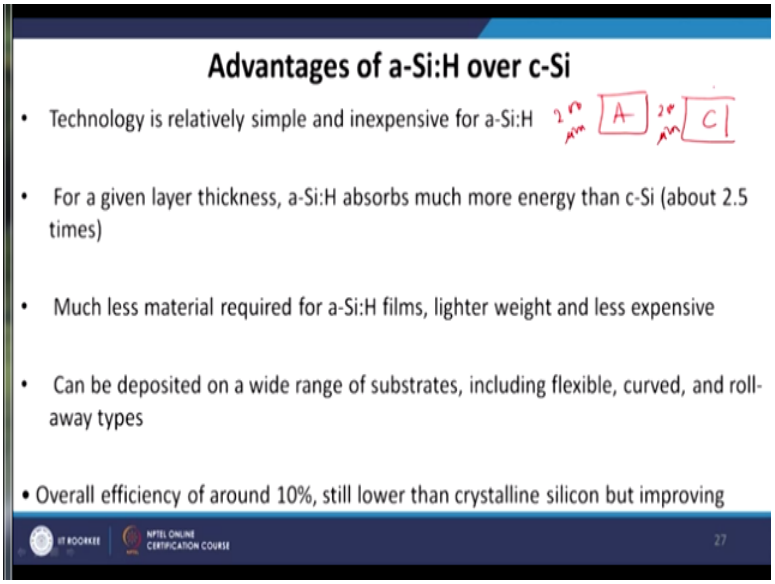

Advantages of a-Si:H over c-Si

- Technology is relatively simple and inexpensive for a-Si:H
- For a given layer thickness, a-Si:H absorbs much more energy than c-Si (about 2.5 times)
- Much less material required for a-Si:H films, lighter weight and less expensive
- Can be deposited on a wide range of substrates, including flexible, curved, and roll-away types
- Overall efficiency of around 10%, still lower than crystalline silicon but improving

Now what are the some common advantage of the amorphous silicon solar cell over crystalline silicon solar cell. The first technology is relatively simple and inexpensive for a amorphous silicon, so here we do not need use like big furnace or arc furnace, (()) (07:44) reduction techniques, Siemens method like that. Here we can only use physical vapor depositions or chemical vapor deposition technique to grow the thin films or amorphous silicon on a substrate.

Foe a given layer thickness is amorphous silicon absorbs much more energy than a crystalline silicon about 2.5 times, this is a very important parameters. Now how good a material will absorb that depends upon on it is absorption coefficient or molar absorption coefficient. Now for a given thickness that means if I have 2 different example one is an amorphous silicon and another is a crystalline silicon.

So this is an amorphous and let us say this is a crystalline silicon, now both of them you consider 200 micrometer although for amorphous silicon it is pretty high, so 200 micron. So what it means that the light absorptions by the amorphous silicon solar cell is much higher than the crystalline silicon solar cells is almost 2.5 times. So that means we do not need make 200 micron thick amorphous film even if we wanted to get same absorption for a desired thickness of a crystalline silicon.

Now here we need much less material required for the amorphous silicon films they are lighter weight and they are also less expensive, it can be deposited on a wide range of substrate including flexible, curved and roll to roll substrate. Now let us say we wanted to install our solar cell on some kind of gadgets or on the rooftop which is not every plot but have some different kind of weird geometry like a triangular geometry or like periodic function.

So in that case we cannot put a very rigid substrate or rigid crystalline silicon on it. We need to make the solar cell on some flexible substrate or let us say we need to charge our battery or charge our mobile phone using our solar cell and I need to paint my solar cell on top of my bag. So obviously if I use crystalline silicon solar cell I cannot do that because that is the very rigid substrate.

So the only way it is possible if the substrate become flexible let us say it is a polymer base substrate, so that we can easily attach to any flexible or foldable material. So this opportunity or this advantage amorphous silicon cell provide to us, it can be fabricated on a flexible substrate.

An example of a flexible substrate is polyethylene trioxide coated glass substrate or PET coated ITO substrate and it can be fabricated on a curve surface.

And also this flexible substrate we can make on a roll to roll basis, overall efficiency is around 10% which is of course low than the crystalline silicon solar cell. But it is gradually improving, there are lot of people who are now working on the different technologies on the thin film solar cell technologies. And because of the tremendous research activities the day by day the efficiency is always increasing.

Now one of the key aspect of the material is the crystal structure, now in mono crystalline silicon each atom is covalently bonded with it is neighboring atoms and it is covalent bond is same.

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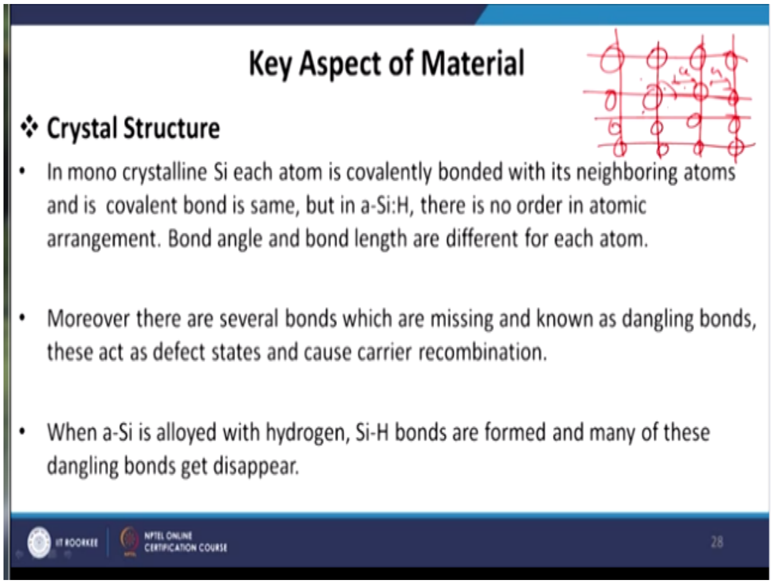

Key Aspect of Material

❖ Crystal Structure

- In mono crystalline Si each atom is covalently bonded with its neighboring atoms and is covalent bond is same, but in a-Si:H, there is no order in atomic arrangement. Bond angle and bond length are different for each atom.
- Moreover there are several bonds which are missing and known as dangling bonds, these act as defect states and cause carrier recombination.
- When a-Si is alloyed with hydrogen, Si-H bonds are formed and many of these dangling bonds get disappear.

But in amorphous silicon there is no order in atomic arrangement bond angle and bond length are different for each atom. If you remember like you know how does a crystalline silicon arrange to it with each other let us we draw some silicon atom, this circle is a silicon atom let us say and they are all bonded with each other by the Van der Wall force or by covalent bonding. So we know that the silicon which is at the center let us say for this silicon example it has 4 valance electron in it is outer circuit.

So to make a covalent stable bond it will share it is one of the electrons with a neighboring silicon atom. In this way it will share it is 4 valance electron with the 4 valance electrons of the neighboring silicon atoms and we will get total 8 electrons, the most stable nearest neighbor structure. And similarly the nearest neighbor will also get benefited because all of them will now started sharing their valance electron with the other neighboring electrons.

And each of them will get the 8 electron in their outside circuit. In this way every silicon will get a stable structures and what we finally get that every nice periodic arrangement of the silicon atoms. Now this nice periodic or arrangement where the distance between the 2 silicon atoms is always constant throughout the crystal, that is a signature of a crystalline lattice. But in amorphous lattice this crystallinity is destroyed we do not have a particular relation between the inter-atomic spacing or between the bonding angle of this 2 atoms.

Moreover there are several bonds which are missing here and known as the dangling bonds, these are defect states and cause carrier recombination. Now this dangling bonds in the amorphous silicon they are a major source of the trap or the defect states. Now this defect states acts as a source of electron hole recombinations. We do not recover lot of electron hole recombination because that is acts a non radiative source of light distractions in the case of the optoelectronic devices.

When a amorphous silicon is allowed with hydrogen, silicon hydrogen bonds are formed and many of this dangling bonds get appear. Now there are several techniques to treat this defect states or treat this dangling bonds. For example if we treat this amorphous silicon with the hydrogen some dangling bonds can disappear.

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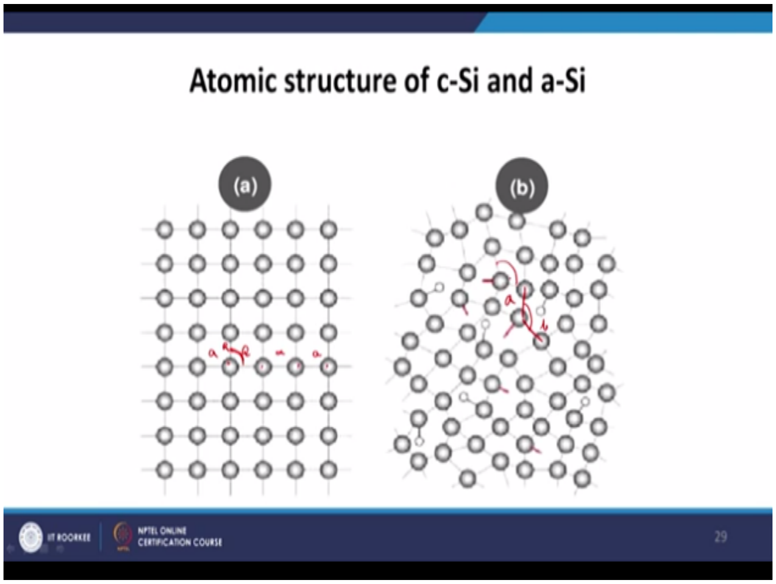

Atomic structure of c-Si and a-Si

Here we are showing the atomic structure of the crystalline silicon and the amorphous silicon. As just we have drawn here you see that the distance between the successive crystal atoms is fixed. If this is a so this will be also be a and the angle between this the 2, 3 atoms the angle is this one that is always fixed throughout the crystal.

Whereas you look at the amorphous silicon here the distance from this atom to this atom and the distance between the this atom to this atom is not same. If this is a then this is b and a is not equal to b and if you look at the angle here is not same as the angle here. So this kind of asymmetry in the crystal lattice parameters and the bond angles actually cause the amorporosity in a materials which also manifested at in terms of the dangling bonds.

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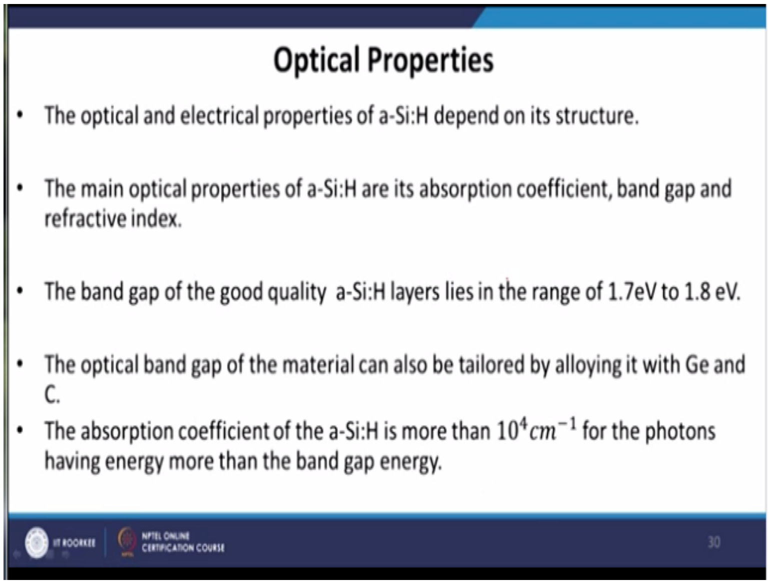

Optical Properties

- The optical and electrical properties of a-Si:H depend on its structure.
- The main optical properties of a-Si:H are its absorption coefficient, band gap and refractive index.
- The band gap of the good quality a-Si:H layers lies in the range of 1.7eV to 1.8 eV.
- The optical band gap of the material can also be tailored by alloying it with Ge and C.
- The absorption coefficient of the a-Si:H is more than $10^4 cm^{-1}$ for the photons having energy more than the band gap energy.

Now because of the change in the crystal structure we know that the structure and properties are related to the each other. Now since the material properties is different their optical properties also different. The optical and electrical properties of the amorphous silicon is way different from a crystalline silicon. The main optical properties of the amorphous silicon hydrogen at the absorption coefficient band gap and reflective index.

Now by absorption coefficient what we mean that the amorphous silicon hydrogenation has a much higher absorption coefficient than a crystalline silicon solar cell. So that is why the same length of the amorphous silicon can absorb almost 2.5 times of the sunlight than a crystalline silicon. Similarly the band gap can be tunable by changing this defect states and the reflective index can also be tuned.

The band gap of a good quality amorphous silicon layers lies in the range of 1.7 electron volt to 1.8 electron volt. The optical band gap of the material can be tailored by alloying it with Germanium and carbon. Now this molecular beam epitaxy techniques also allow us to put different kind of doping inside the material and that changes the band gap significantly. The absorption coefficient of the amorphous silicon is more than 10 to the power 4/centimeter for the photons having energy more than the band gap energy.

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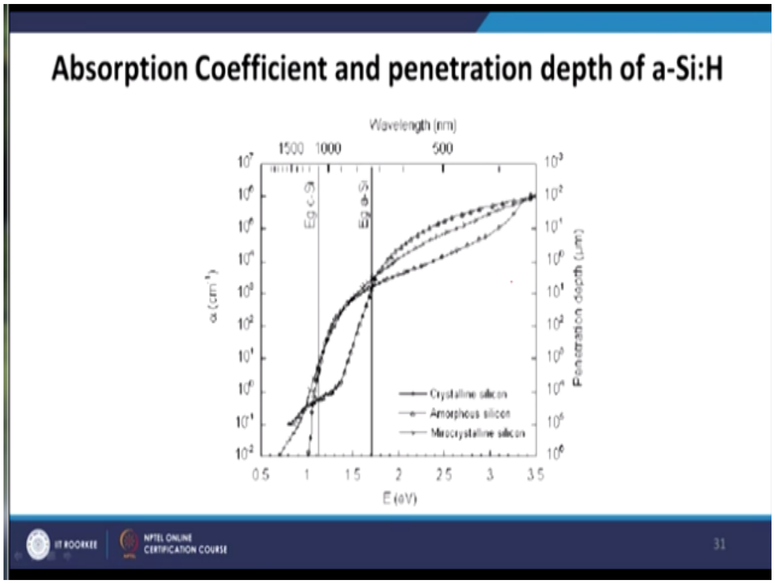

Absorption Coefficient and penetration depth of a-Si:H

Here we are showing the absorption coefficient and penetration depth of amorphous silicon. As you can see here y axis is the absorption coefficient and x axis is the energy in electron volt. So for a crystalline silicon solar cell it is very very straight it does not change but amorphous silicon solar cell it changes significantly.

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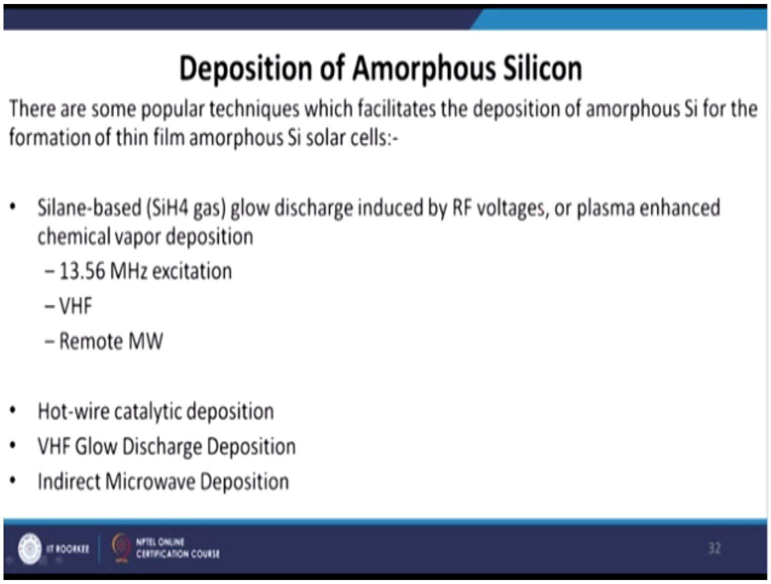

Deposition of Amorphous Silicon

There are some popular techniques which facilitates the deposition of amorphous Si for the formation of thin film amorphous Si solar cells:-

- Silane-based (SiH4 gas) glow discharge induced by RF voltages, or plasma enhanced chemical vapor deposition
  - 13.56 MHz excitation
  - VHF
  - Remote MW
- Hot-wire catalytic deposition
- VHF Glow Discharge Deposition
- Indirect Microwave Deposition

Now the depositions of the amorphous silicon there are some popular techniques which facilitates the depositions of the amorphous silicon for the formation of the thin film amorphous silicon solar cell. Silane based gas glow discharge induced by RF voltage or plasma enhanced chemical vapor depositions are to commonly use techniques to deposit the amorphous silicon.

Now some of the characteristics features are 13.56 megahertz excitations is required for this kind of thing, very high frequency and also we need to remove the molecular weight.

Hot wire catalytic deposition can also be used for the depositions of the amorphous silicon, VHF glow discharge depositions can also be used and indirect microwave depositions can also be used.

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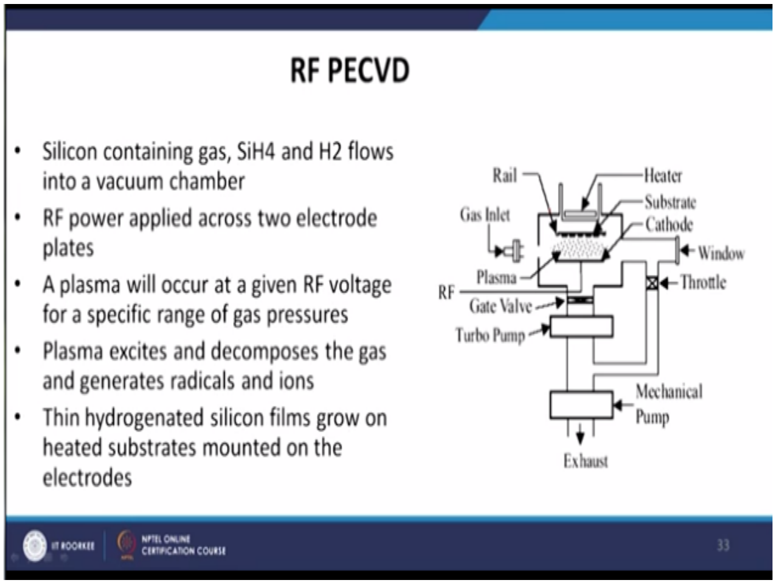

RF PECVD

- Silicon containing gas, SiH4 and H2 flows into a vacuum chamber
- RF power applied across two electrode plates
- A plasma will occur at a given RF voltage for a specific range of gas pressures
- Plasma excites and decomposes the gas and generates radicals and ions
- Thin hydrogenated silicon films grow on heated substrates mounted on the electrodes

Now what is radio frequency PECVD, silicon containing gas, silicon SiH4 and hydrogen flows into a vacuum chamber, you look there is a vacuum chamber here where the silicon containing gas SiH4 and the hydrogen flows inside this vacuum chamber. Radio frequency power applied across the 2 electrode plate, so there are cathode and there is an anode. And we apply the radio frequency power between this 2 electrode.

A plasma will occur for a given RF voltage for a specific range of gas pressure, plasma excites and decompose the gas and generate radicals and ions. Thin hydrogenated silicon films grow on a heated substrate mounted on the electrodes.

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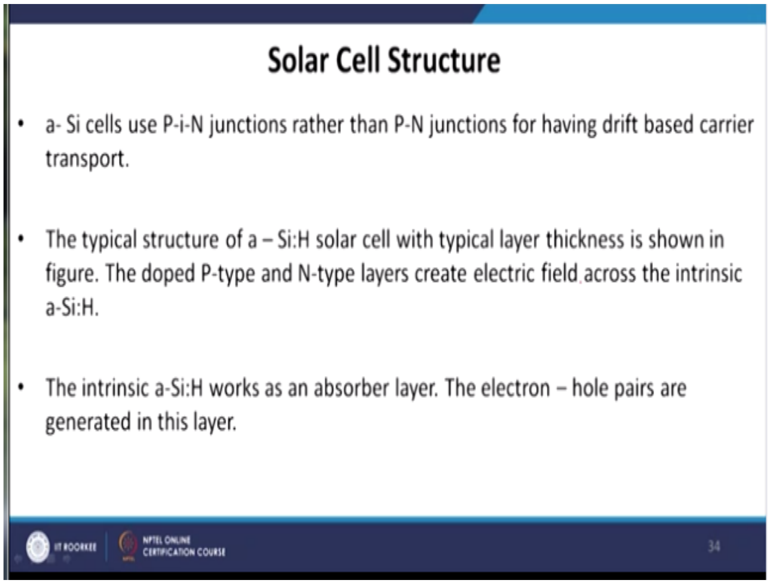

Solar Cell Structure

- a- Si cells use P-i-N junctions rather than P-N junctions for having drift based carrier transport.
- The typical structure of a – Si:H solar cell with typical layer thickness is shown in figure. The doped P-type and N-type layers create electric field across the intrinsic a-Si:H.
- The intrinsic a-Si:H works as an absorber layer. The electron – hole pairs are generated in this layer.

Finally what we get is a pin junction solar cell amorphous solar silicon solar cell use pin junctions rather than p-n junctions for having drift base carrier transport. The typical structure of an amorphous silicon solar cell with typical layer thickness is shown in the figure. The doped p-type and n-type layers create electric field across the intrinsic amorphous layer, the intrinsic amorphous layer works as an absorption layer, the electron hole pairs are generated in this layer.

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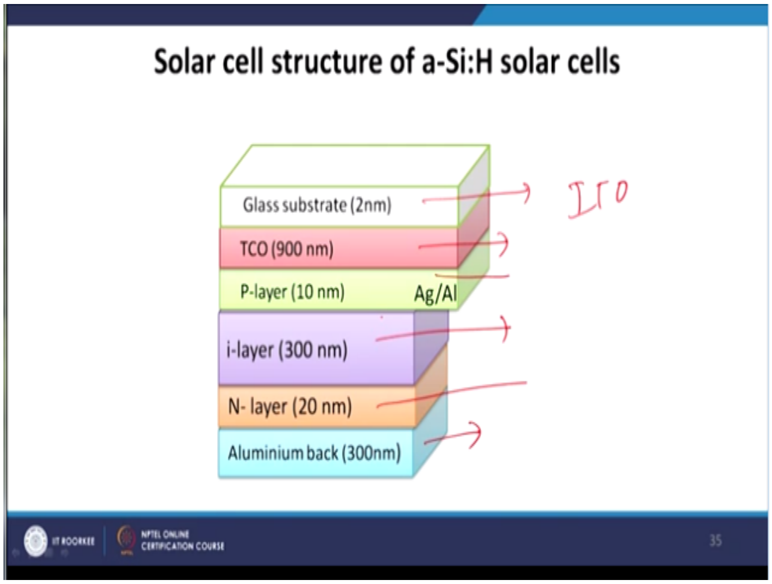

Solar cell structure of a-Si:H solar cells

Here we are showing the schematic diagram or geometry of an amorphous silicon solar cell, you see that there are 2 electrodes one metal electrode other back contact which is an aluminum contact which is such as 300 nanometer and there is this TCO. The transparent conductive oxide, which is have a 900 nanometer which we put usually on a glass substrate for example ITO indium doped tin oxide glass substrate.

In between them there is a pin geometry one is the p-type layer which is AgAl silver or aluminum which is somewhat around like 10 nanometer and then as an n-type layer we use like 20 nanometer thickness. In between the active layer where the material or the electron hole pair get generated that is i-layer which has a thickness of 300 nanometer. So this is the basic diagram of amorphous silicon solar cell.

So as you can understand this is way different from a crystalline silicon solar cell. Here the exciton or the electron hole pair generates in the i-layer only. Now in the inorganic solar cell the word exciton is not use very popularly or it is not very correct to use the word exciton. Because exciton stands for the bound electron hole pair, in organic solar cells or in organic materials the binding energy between the electrons and holes are very very high.

So in that case the word excitons is much more appropriate to use than in the context of the inorganic solar cell. Because here the charge carriers are rather free, so a little bit amount of the electric field can make them move around the solar cell. So today we have learned actually a very important techniques of the second generation solar cell or thin film solar cells which is amorphous silicon solar cell technology.

Here we have learnt about the different growth technique and we have learnt about how to deposit thus amorphous silicon on a substrate. And as well as different components of an amorphous silicon solar cell and how to use this silicon solar cells. Now this is about the second generation solar cell, now in the next lecture we will talk about the third generation solar cell, third generation solar cell actually includes a lot of different varieties of materials.

It include some different kind of organic and inorganic dyes and we can make a solar cell based on that called dye sensitized solar cells, it can be used by the conducting organic polymers. Now it is worthwhile to mention that in 1990 the conductivity in organic polymer was discovered.

After that all this polymers have been use to make optoelectronic devices and that has (()) (19:59) new generations of the optoelectronic device fabrication.

And that is called organic photovoltaics or organic light emitting diodes. Similarly after the discovery of the perovskite materials we have the perovskite based solar cells. And we have the different kind of hybrid solar cells we have tandem solar cells all of this thing. And these all fall under the domain of the third generation solar cell. In our next lecture we will start with the dye sensitize solar cell where we use some dye or sensitize molecule to make a solar cells.

This is a very commonly used techniques and they are for a long time in the literature and we will also demonstrate you how to make a dye sensitize solar cell.

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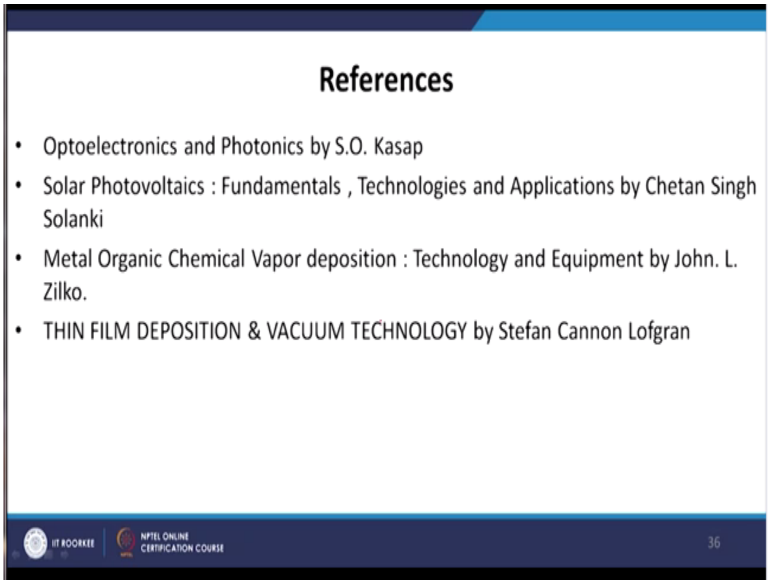

References

- Optoelectronics and Photonics by S.O. Kasap
- Solar Photovoltaics : Fundamentals , Technologies and Applications by Chetan Singh Solanki
- Metal Organic Chemical Vapor deposition : Technology and Equipment by John. L. Zilko.
- THIN FILM DEPOSITION & VACUUM TECHNOLOGY by Stefan Cannon Lofgran

In the meanwhile for the present context for the reference you can look for the optoelectronics and photonics book S.O. Kasap and thus Chetan Solanki’s book on solar photovoltaics. As well as there some other references like metal organic chemical vapor deposition technique if you wanted to know about the MOCVD method in details by John.L.Zilko and thin film deposition techniques by Lofgran, thank you.