Solar Photovoltaics: Principles, Technologies and Materials
Prof. Ashish Garg
Department of Material Science & Engineering
Indian Institute of Technology, Kanpur

Lecture – 33
Generation II Technologies: A-Si Solar cells

So, welcome again to a new lecture of Solar Photovoltaics: Principles, Technologies and Materials.

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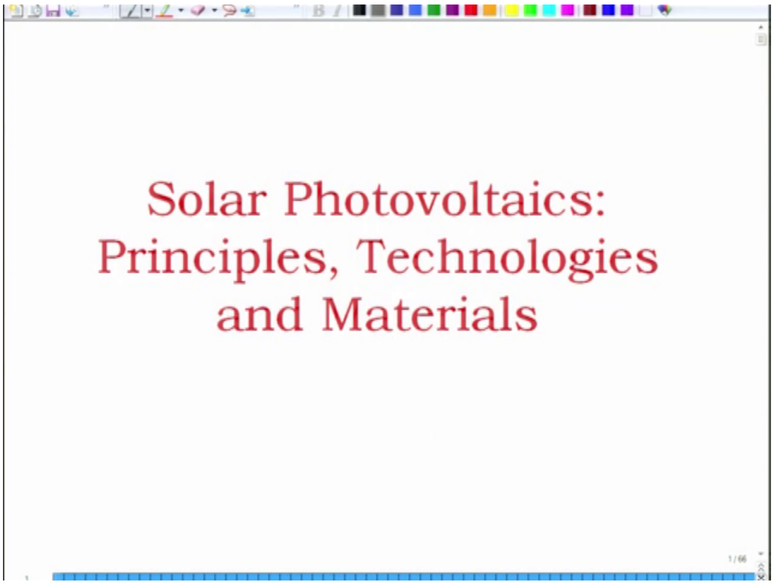

Solar Photovoltaics: Principles, Technologies and Materials

So, we have been talking about we have initiated our discussion on thin film Solar Cells. After finishing the Gen I solar cells which are primarily based on bulk materials that is silicon gallium arsenide and we will continue with our discussion on the thin film solar cells. So, just a brief recap very very brief recap

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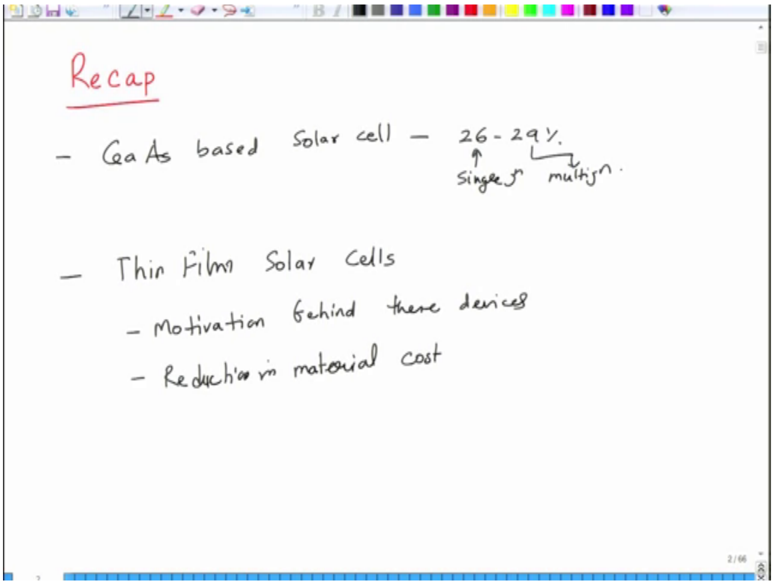

Recap

- GaAs based Solar cell – 26 - 29 %
  - Single J^n multi J^n.
- Thin Film Solar Cells
  - Motivation behind these devices
  - Reduction in material cost

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In the last lecture we talked about gallium arsenide based solar cells. We looked at their design and what are the considerations that are involved in making them better. They have efficiency between 26 to 29 percent. So, this is for single junction and this is for multi junction. Then we move down to thin film solar cells and we were just talking about the motivation behind and these devices and the primary motivation is reduction in material cost by reducing its amount.

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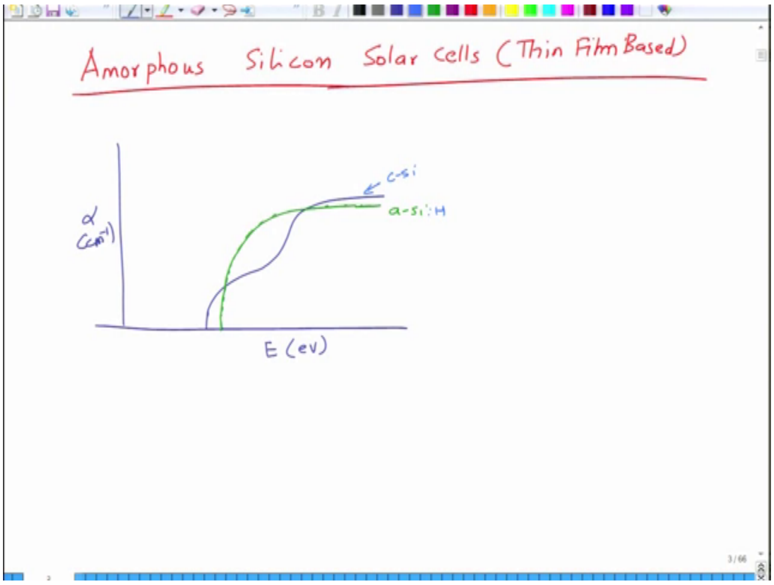

Amorphous Silicon Solar Cells (Thin Film Based)

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Now, let us move to the technical contents of. So, we begin our discussion with the amorphous silicon in solar cells. Amorphous silicon is not a technology of the day, but it is important to see what it was when it was being used. So, we have amorphous silicon solar cells which are basically thin film based ok. So, amorphous silicon basically has to plot the difference between absorption coefficient as a function of energy.

If your crystalline silicon has band gap of something like that and it is this is it is; let us say the coefficient. Now amorphous silicon has a coefficient which is which is significantly higher. So, this is you can say is amorphous silicon and this is you can say is crystalline silicon and this is generally hydrogenated to passivate the bonds, but this is what. So, amorphous silicon offers you much higher absorbance as compared to bulk silicon.

So, if you look at the design of these solar cells, it is very simple. It is not a it is instead of p-n junction it is like a P-I-N kind of junction.

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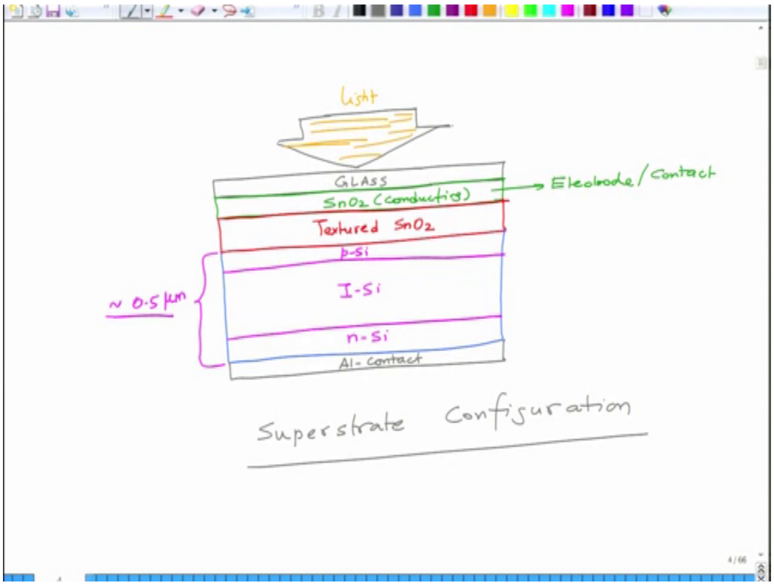

So, if you have you have a glass substrate so, you begin with a glass substrate. So, this is your glass substrate all right. This is glass and the light comes from here. So, this is where the light comes from light. Next to it is we have a tin oxide layer. This is conducting.

So, this makes a electrode or we say contact ok. Next to this tin oxide, we have what we call as textured tin oxide and then we have what we call as a silicon in three different forms. So, we have the first layer of silicon somewhere here, then we have second layer in between and third at the bottom. The first layer is generally called as p silicon, this is I silicon and this is n silicon

So, we make a p-n junction, but in between p-n junction, we put a intrinsic silicon layer like the depletion region white depletion region. So, p-n junctions job is to provide the built in field ok. The band bending because the moment you have p and n Fermi levels have to align as a result you will have band bending. I silicon is the region where most of the light absorption and carrier generation takes place and this whole thickness of this stack is about 0.5 micron about all right. And then we have on this side aluminium contact.

So, what we do here is we basically we have a glass substrate on that we deposit tin oxide first. On tin oxide we deposit some other oxide layer in this case it happens to be tin oxide, but it could be some other oxide. Then we have p type silicon layer, then we have intrinsic silicon, then we have n type silicon layer and then we have aluminum back contact and the light comes from the substrate side. So, instead of gallium arsenide and silicon where the light was coming from the top, here the light is coming from the backside of the substrates.

So, this is basically what we call is a super straight configuration super straight configuration. Light can also come from the other side if you have a transparent electrode on top and that is the possibility. Instead of if you replace this aluminium contact by a transparent electrode, then the light can come from the top and then you replace this transparent electrode on glass with a non transparent electrode. So, that is also a possibility in.

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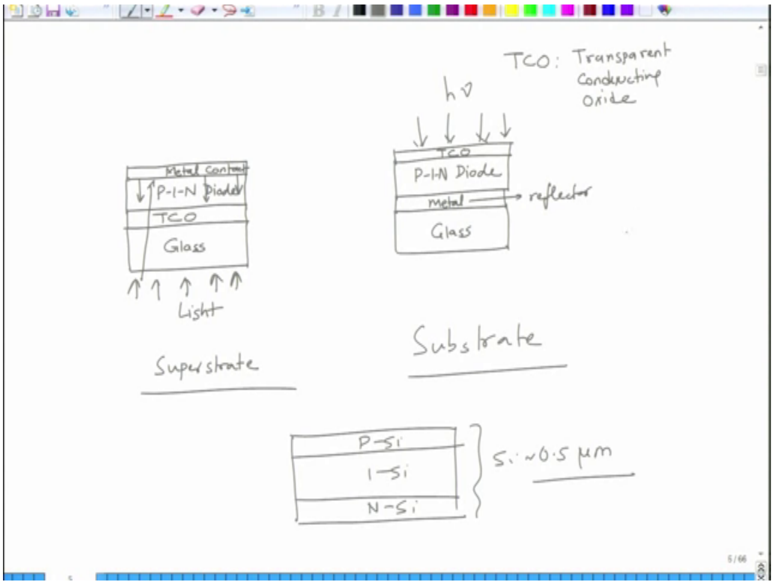

So, generally and there are so you can have two configurations. The first configuration can be the substrate followed by a transparent conducting oxide followed by the photodiode which is the P-I-N diode followed by a metal ok. So, this is glass this is TCO a transparent conducting oxide, this is P-I-N diode and then you have a metal contact which also acts as a reflector. So, light comes from this side; this is light.

So, light goes in it gets absorbed on the way and it also gets reflected from the back metal contact. So, this configuration is super straight configuration that is what we saw in the slide. And others configuration is you have a substrate glass. On top of this you have a metal which is a reflector, then we have a P-I-N diode and then we have a TCO. TCO is Transparent Conducting Oxide and in this case the light comes from this side and this is called as substrate configuration the typical configuration that we have in solar cells in the silicon solar cells in gallium arsenide solar cells.

So, there is this is what is it is and that the P-I-N diode is basically this is what is P-I-N P I N and this is all silicon P silicon, I silicon, N silicon, but it is in thin film form about half a micron thick roughly. So, as I said there are various configurations which are possible here and this can also be used to make multi junction solar cells because silicon makes a solid solution with germanium.

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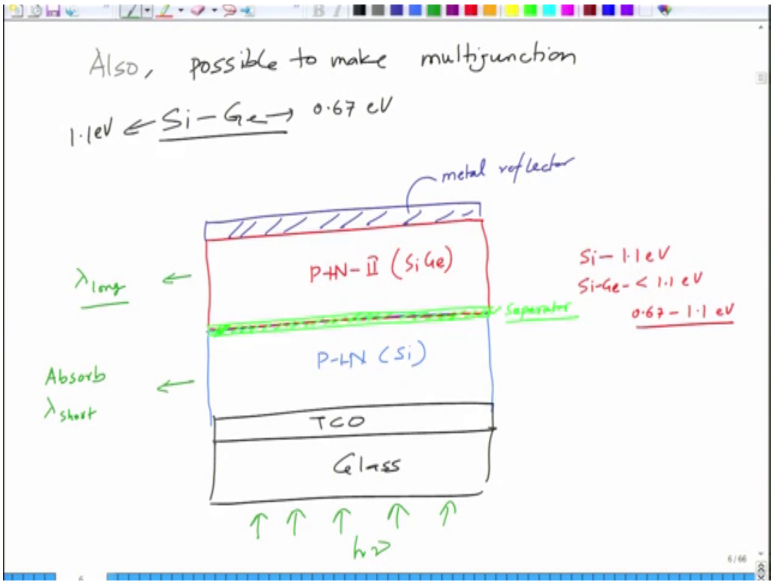

Also, possible to make multijunction

1.1eV ← Si–Ge → 0.67 eV

So, if I go to next page also possible to make multi junction because silicon makes a nice allowable germanium solid solution and silicon band gap is 1.1 eV, germanium band gap is about 0.67 eV and the band gap can be tuned. So, the way you do it is you have a glass substrate

So, you have glass, then you put a TCO, then you put a P-I-N. This is the first P-I-N that you put of silicon and then you put a intermediate layer. You can put an intermediate layer or else you can put on the P-I-N. This another P-I-N is basically this is P-I-N II so, whose band gap is lower than the P-I-N I and this P-I-N II is essentially silicon germanium alloy. And so, silicon germanium this silicon has a band gap of 1.1 eV and silicon germanium has a band gap which is lower than 1.1 eV between 0.67 to 1.1 eV depending upon the composition

And then on the top we put a metal deflector and which is also a contact. As I said in between it is possible to put a layer also which will alter the design which is a different layer in. So, you can isolate the two cells. It is possible to do that, but it depends upon the type of the design of the solar cell. So, it could be a separator which can be possibly put in between. Now this solar cell basically allows you to absorb. So, you since band gap of this layer is higher light comes from here. So, this is light.

So, this allows you to absorb lambda short wavelengths and in this case you absorb lambda long wavelengths. So, this is a so silicon amorphous silicon design allows you to make a multi junction solar cell width or a bilayer or tri layer structure depending upon how much how many stacks you want to make. So, and generally these as we will see later on also we look into the reasons.

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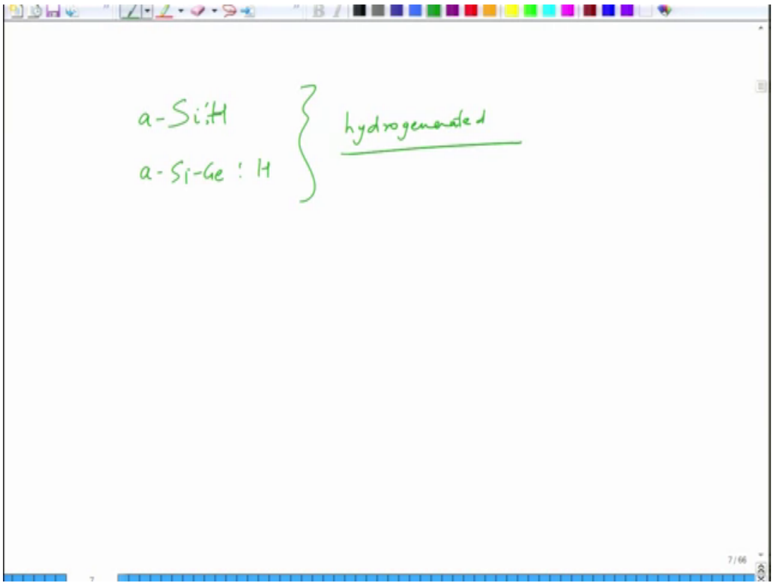

The silicon and silicon germanium silicon amorphous silicon is always denoted by letter H in front and similarity amorphous silicon germanium will have a letter H in front and this basically it is it means that is hydrogenated.

So, it has been exposed to hydrogen and we will look at the reasons of why this is done. This is basically done to reduce the dangling bond density in the in the solar cells. And these solar cells are generally made by so, these are thin film solar cells. So, there is there are certain deposition methods which are used to deposit thin films. So, generally these are made by using CVD or Chemical Vapour Deposition methods.

This chemical vapour deposition methods are basically so, I mean I will just give you a schematic. You have a chamber in which you have a heated substrate. So, this is a heated substrate let us say and this is a chamber which is under vacuum or some protected atmosphere. So, you have reactants which come from this side which are basically precursors ok. These precursors when they arrive here, they react and leave.

So, silicon we will get deposited here. So, silicon we will come down and this may have you know silicon along with the dopant along without the dopant and so on of. So, appropriate react precursors have to be chosen. So, when they react with each other that a chemical reactions occur which allows the silicon to be deposited on the substrate.

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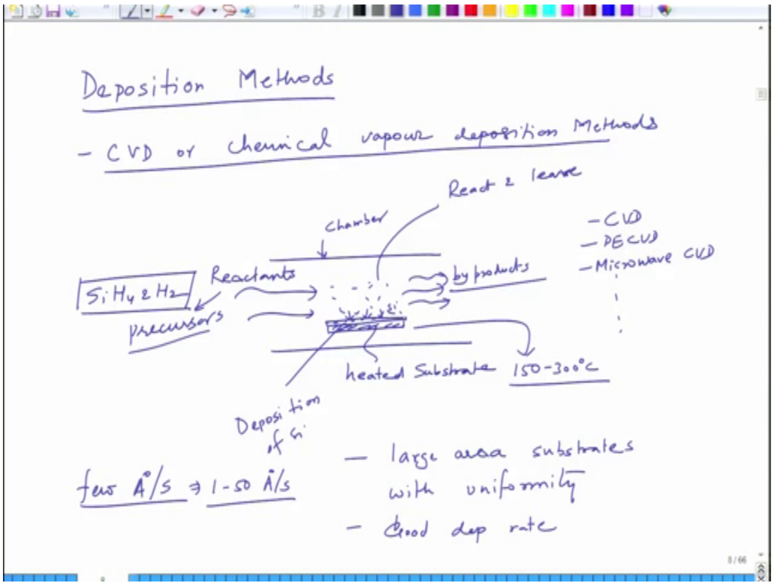

Deposition Methods

- CVD or chemical vapour deposition Methods

- CVD
- PECVD
- Microwave CVD

few Å/s → 1-50 Å/s

- large area substrates with uniformity
- Good dep rate

So, you have deposition of silicon and that and the products by products will be taken out. So, these are by products which are undesirable right reaction products.

So, silicon will be deposited everything else will go out and this happens. So, this is called as chemical vapour deposition because chemicals come into the chamber. They are in vapour form over a heated substrate where they react with each other and the chemical reaction takes place such that the silicon is deposited on top of the substrate and the by products go out of the system. This allows you to deposit large area thin film.

So, large area substrates can be deposited with uniformity and they have reasonably good deposition rate. So, they are not very slow processes. So, the deposition rates of the order of few angstroms per second can be deposited. So, you are looking at a you are looking; so, depending upon the type of CVD process CVD can be plain CVD. It could not be plasma assisted CVD, it could be you know microwave CVD. So, there are various things that you can do with CVD process.

So, for example, during the reaction chain to accelerate the reaction you can create certain you can create microwave most frequently of rf atmosphere. So, wherever you can create electric fields so also so, possibilities are there. So, there are different types of

CVD s. They give you the position rates anywhere between 1 to 50 angstrom per second and they give you a good quality P-I-N junction on the glass substrate.

So, essentially the precursors in this case happen to be generally in case of silicon it happens to be SiH 4 and hydrogen as a carrier gas. So, these are two precursors which are generally used in case of a for example, RF PVD RF CVD. Substrate temperature is of the order of 150 to 300 degree centigrade or maybe 400 degree centigrade depending upon the type of CVD.

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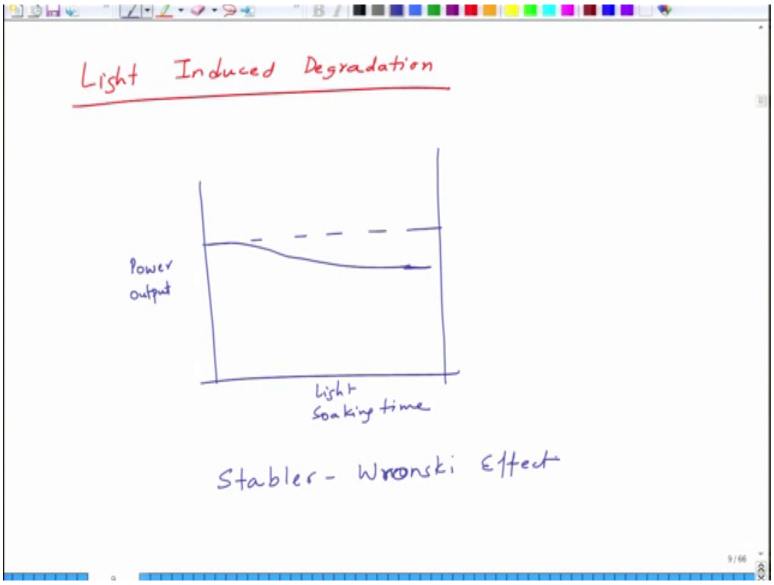

So, these silicon solar amorphous silicon solar cells have one issue which is called as when they are so, they have a issue called as light induced degradation. What happens is that so, if you look at the power output as a function of light soaking time, now let us say this is the stabilized power output and this tends to reduce as a function of light exposure before it stabilizes further ok. So, the reduction there is a reduction in power density that comes out of the solar cell as a function of time and this is main this is due to a effect called as Stabler-Wronski effect ok.

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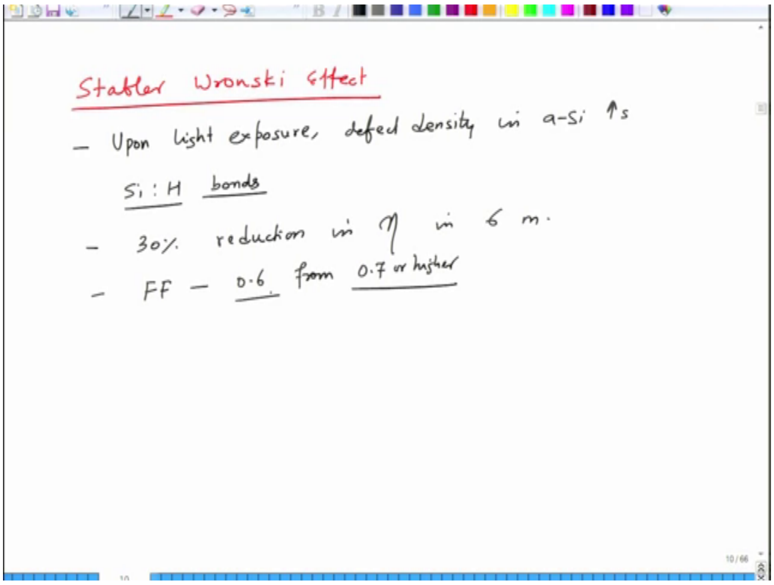

Stabler Wronski effect

- Upon light exposure, defect density in a-Si ↑s
  Si : H bonds
- 30% reduction in η in 6 m.
- FF — 0.6 from 0.7 or higher

So, essentially what happens in this effect is in this Stabler and so as so, upon light exposure defect density in amorphous silicon increases and basically what happens is that it damages the silicon hydrogen bonds after amorphous silicon is always hydrogenated to passivation for passivation because you know amorphous means. So, I will come to that in a little while and this leads to reduction in efficiency of up to 30 percent in 30 percent reduction in about 6 months and the fill factor goes down from 0.6, 0.6 from 0.7 or higher.

So, initial value may be 0.7 or higher then the after degradation it goes down to about 0.6.

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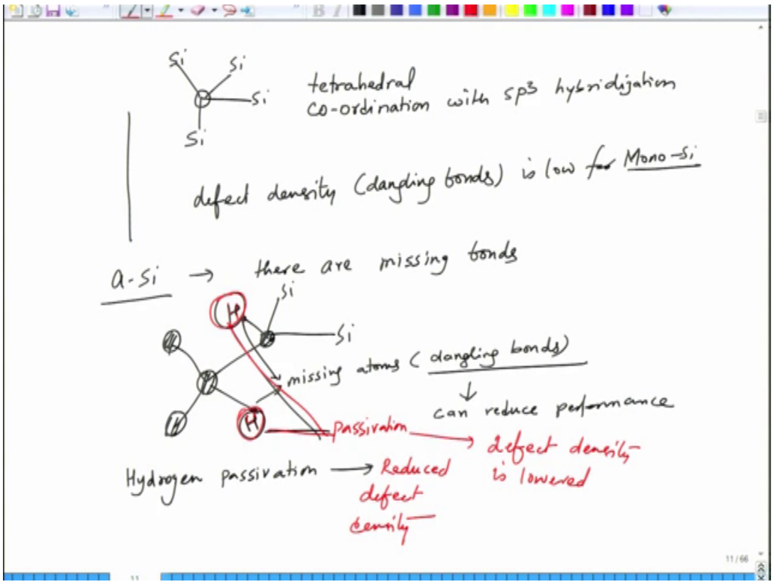

tetrahedral co-ordination with sp^3 hybridization

defect density (dangling bonds) is low for Mono-Si

a-Si → there are missing bonds

missing atoms (dangling bonds)
↓
can reduce performance

passivation → defect density is lowered

Hydrogen passivation → Reduced defect density

So, what is this thing about silicon, you see silicon has you know normal silicon has this tetrahedral buoyant. So, you have each silicon atom coordinated by four silicon atoms ok. It has tetrahedral coordination with SP 3 hybridization right just like diamond it is a diamond cubic structure.

So, in case of mono crystalline of poly crystalline solid each silicon atoms has four neighbours as a result, there are no dangling bonds there may be some dangling bonds at the surfaces and at the cracks etcetera, but by enlarge the defect density is lower. So, defect density in terms of dangling bonds is low for mono silicon right or crystalline silicon. However, for amorphous silicon there are since you do not have a crystalline network all the bonds are not satisfied.

So, silicon needs a tetrahedral coordination, but it is incomplete at many places. So, there are missing bonds. So, you can have situations where you have this silicon atom; it has one bond, it has another bond whenever silicon, but this bond is missing. Similarly this silicon atom it has one bond here it has one bond here, but this bond is missing. So, these missing bonds these are basically a missing atoms you can say missing atoms and these are nothing, but dangling bonds these dang dangling bonds can reduce performance because they act as traps. They will absorb the charge carriers

So, what we do in silicon is that, we do hydrogen passivation by exposing silicon to hydrogen. So, that is why extra hydrogen is put in during manufacturing. So, hydrogen passivation what it does is that it creates these hydrogen bonds. So, it bonds these hydrogen. So, this leads to what we call as so, these hydrogen atoms at these places they lead to passivation and as a result they reduce the defect density is. So, hydrogen passivation basically reduces defect density and this improves the performance.

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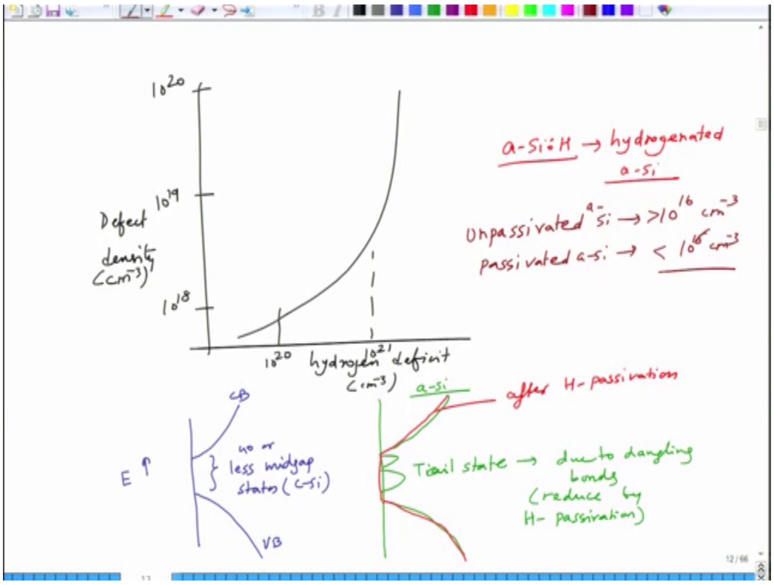

So, if you plot for example, the defect density as a function of a hydrogen deficit, the defect density as a function of hydrogen deficit it tends to increase like this. So, this is a sort of a logarithmic plot. So, somewhere here it would be 10 power 20 per cc and this would be about I do not know 10 to the power 21 and these defect densities would be of the order of 10 to the power 18, 10 to the power 19 and then 20 per CC. So, this is how it tends to int to. So, at height when the hydrogen did so and this is on a logarithmic scale.

So, for one order of magnitude there is a huge increase in the defect density if you have less hydrogen in the system. So, this is what hydrogen then hydrogen passivation does. So, in case of so, if you put it in terms of band diagram for crystalline silicon, the band diagram is like this. So, this is conduction band, this is valence band all right and this is energy. There are no mid gap states or less mid gap states

So, this is less mid gap states no or less mid gap states in c silicon, but when you do the same for amorphous silicon in amorphous silicon. So, of course, in amorphous silicon what happens to is that this is so, of course, bands are not very well defined. But let us say these are the bands in amorphous silicon. There are these tail states in these systems.

So, these are tail states. So, this is for amorphous silicon and these tail states are nothing, but due to dangling bonds and this is they reduce by hydrogen passivation.

And so, so, you can say that if this is before passivation after passivation, it is going to look like this. So, this is after passivation is what. So, this is what is this going to look like after hydrogen passivation. So, that is why amorphous silicon is always noted as amorphous silicon H. This is hydrogenated amorphous silicon with lower defect density.

So, in case of unpassivated so, you have unpassivated this is coated hydro unpassivated or unhydrogenated silicon will have densities, which is larger than 10 to over 16 per centimeter cube. Whereas passivated silicon amorphous silicon will have will have a lower than 10 to the power 15 or 16 per cm much lower.

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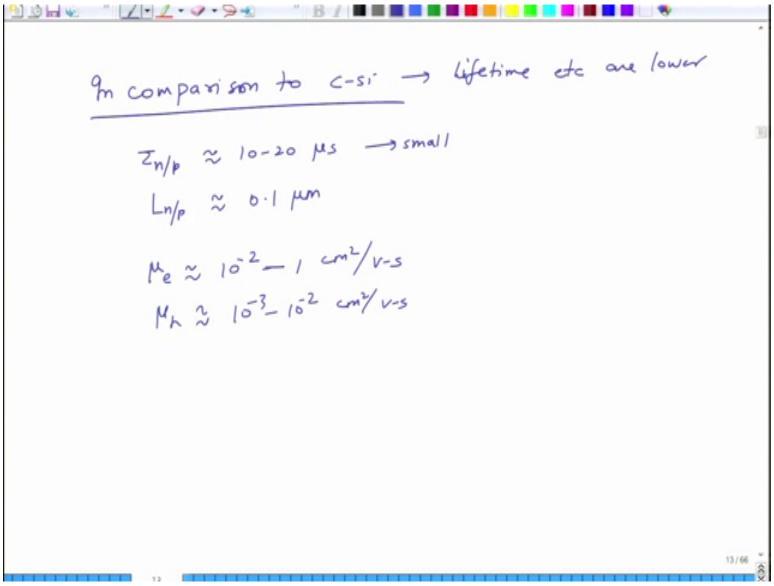

In comparison to c-si → lifetime etc are lower

$\tau_{n/p} \approx 10-20\ \mu s$ → small

$L_{n/p} \approx 0.1\ \mu m$

$\mu_e \approx 10^{-2} - 1\ cm^2/V\text{-}s$

$\mu_h \approx 10^{-3} - 10^{-2}\ cm^2/V\text{-}s$

So,, but; however, since amorphous silicon has its amorphous and there are generally in comparison to C silicon the tau n and p are roughly 10 to 20 microseconds very small as compared to so small as compared to C silicon. The we can say lifetimes etcetera are lower.

So, this is diffusion lengths are of the order of 0.1 micron. Mobilities are also very low electronic mobility is of the order of minus 2 to plus 1 10 to the power minus 2 to 10 to 1 centimeter square per volt second and hole mobility is 10 to the power minus 3 to minus

2 centimeter square per volt second. So, these are the issues in case of so, the methods that is generally employed.

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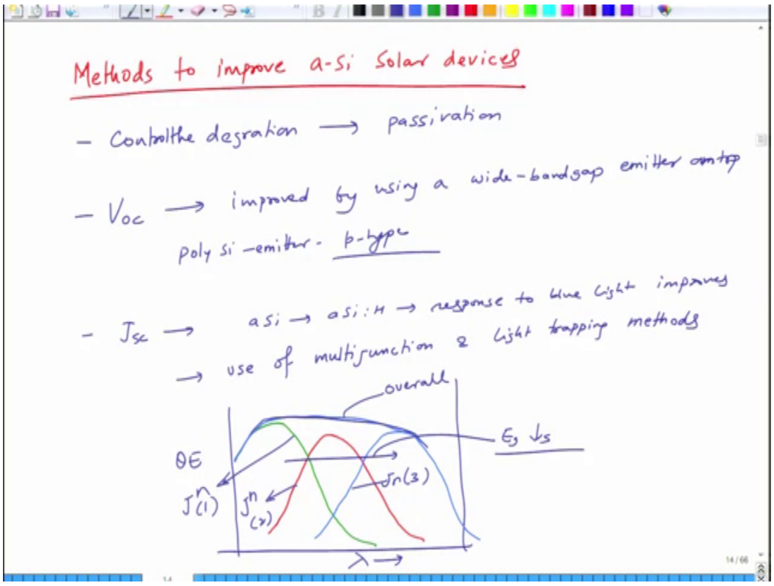

Methods to improve a-Si Solar devices

- Controlthe degration → passivation
- V_{oc} → improved by using a wide-bandgap emitter on top

  poly si -emitter - p-type
- J_{sc} → a si → a si:H → response to blue light improves

  → use of multijunction & light trapping methods

So, basically the methods to improve amorphous silicon solar devices one is to control control the degradation. So, basically you do passivation right which means you put in more hydrogen within the system and improve deposition all right. So, improved processing and passivation will lead to less degradation V oc is generally improved by using a wide band gap emitter on top on top.

And if you use polysilicon emitter, it is basically p-type. J sc is generally improved by hydrogenation. So, if you convert a silicon to a silicon H, the response to blue light improves. So, more blue light is absorbed if you put in hydrogen in the system and then of course, you can use of multi junction and light trapping methods ok.

So, this is how one can improve these solar cells. This is where we finish our. So, for example, there is one thing you can do for multi junction is if you use a multi junction design; if you look at the quantum efficiency of solar cell ah; if you engineer a bandgap in such a manner so that you are able to use higher band gap in the top layer. So, that they give you certain quantum efficiency. You are able to use the intermediate band gap in the middle layer. So, they give you quantum efficiency in this region and then you are able to use shorter band gap in this region, then they give you quantum efficiency the overall quantum efficiency could be something like this

So, this could be sorry. So, this could be the overall quantum. So, this is overall. This is junction 1, this is junction 2, this is junction 3 and you can see the band gap will and this will be E g decreases. So, your lap this is your lambda. So, higher wavelengths absorbed by smaller band gap, lower wavelengths shorter wavelengths are absorbed by longer higher band gap and that is how you can make a multi junction design with silicon. So, amorphous silicon solar cells by using germanium as a material to make solid solutions.

So, amorphous silicon solar cells have efficiencies of the order of let me give you the numbers. So, amorphous silicon solar cells have efficiencies of the order of 10 percent ok. So, this is what we have done about amorphous silicon solar cell in this lecture. We will do the remaining part in the next lecture. Very little is remaining and we will discuss other concurrent technologies in the next lecture.

So, thank you very much.