Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 32
Generation I Technologies: GaAs Solar cells

So, welcome again to this new lecture of the course Solar Photovoltaics: Principles, Technologies and Materials. So, first we will do a brief overview of what we have done in the couple of lectures.

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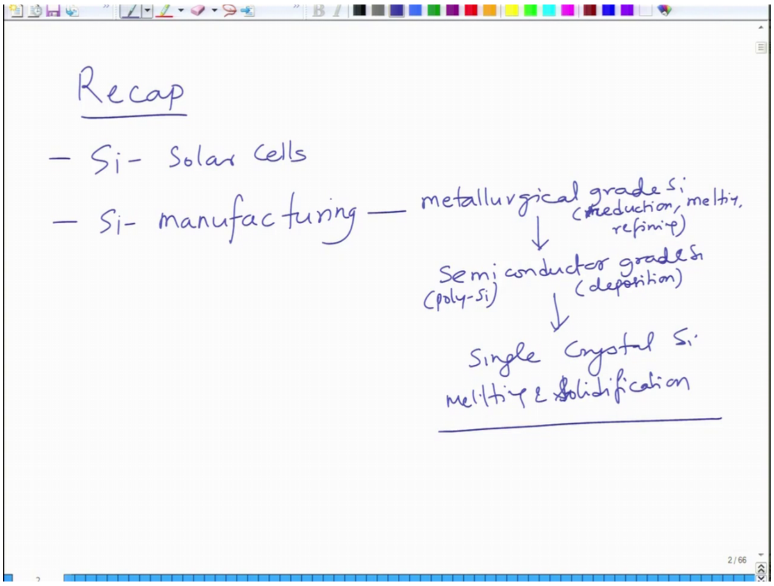

Recap

- Si- Solar Cells
- Si- manufacturing — metallurgical grade Si (reduction, melting, refining)

↓

Semiconductor grade Si (poly-Si) (deposition)

↓

Single Crystal Si
melting & solidification

So, in past few lectures, we looked about silicon solar cells and strategies and the design and the strategies improve them. And then we look looked at silicon manufacturing. So, silicon manufacturing is quite complex and it is very energy intensive process and that is what accounts from most of the cost of silicon.

So, although we have plenty of sand available, silicon has to be converted from silicon oxide to sand which is the TDS process. So, first we get what we call as metallurgical grade silicon, which is then converted to semiconductor grade silicon using Siemens process and then we have a single crystal silicon.

So, this stage is all about reduction, melting, refining. And this is stage is again then about this is more about deposition of silicon S i h c l 3, and this converts into silicon pure pureed form of silicon.

And then we have again, solidification and melting and solidification to form so this semi to form a single crystal silicon. So, this is a stage we have poly silicon, which is polycrystalline in nature and then it is converted to a single crystal. So, as you can see as you go from metallurgical grade to semiconductor to single crystal silicon, the cost keeps increasing and this is what is the major reason, why silicon is expensive.

However, it is still the most common solar cell that you have in the market. So, majority of the solar cells in the market are of silicon, poly silicon as well as single crystal silicon. Poly silicon is more prominent, because poly silicon is cheaper than single crystal silicon as a result it attracts, it is attractive for economical reasons.

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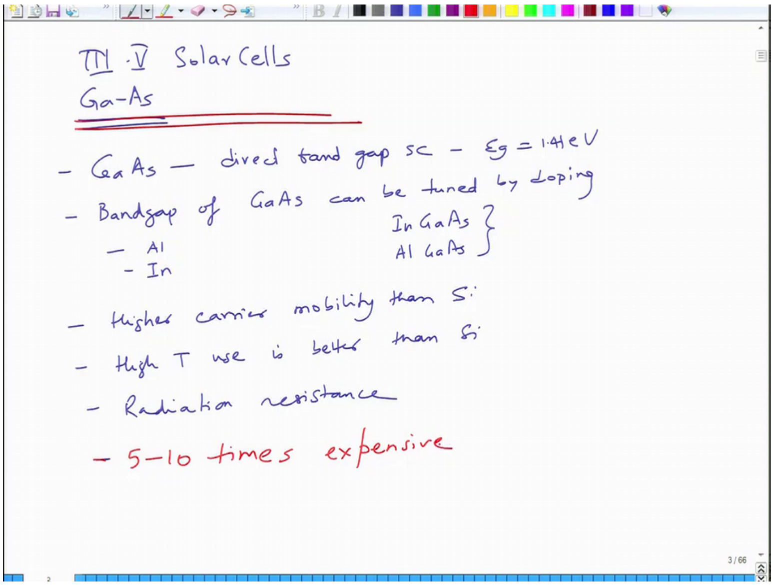

III - V Solar Cells
Ga-As

- GaAs — direct band gap SC — $E_g = 1.41 eV$
- Bandgap of GaAs can be tuned by doping
  - Al
  - In

InGaAs
AlGaAs

- Higher carrier mobility than Si
- High T use is better than Si
- Radiation resistance
- 5-10 times expensive

Now, let us look at other first generation technology that is 3 5 solar cells. 3 5 is basically group 3 and group 5. So, basically we are talking of here a gallium arsenide based solar cells ok. And these gallium arsenide based solar cells are based on as you know gallium arsenide, which is a direct band gap semiconductor of band gap 1.1 e v; sorry 1.41 e v, not 1.1.

And the band gap of gel gallium arsenide can be tuned by by doping and typical dopants that we use are things like aluminium and indium. So, you can have aluminium gallium arsenide ion and indium gallium arsenide and aluminium gallium arsenide, so it is called as In GaAs and AlGaAs. So, these are two commonly used forms of gallium arsenide doped with the name an aluminium.

And basically the gallium, for example aluminium popping leads to increase in the band gap to closer to about 1.8 electron volt so. And it has advantages over silicon for example, it has higher carrier mobility than silicon, and it can be used for high temperature use is better than silicon, then it is more radiation resistant. So, it is good for a space applications. However, it is the backside is it is 5 to 10 times expensive.

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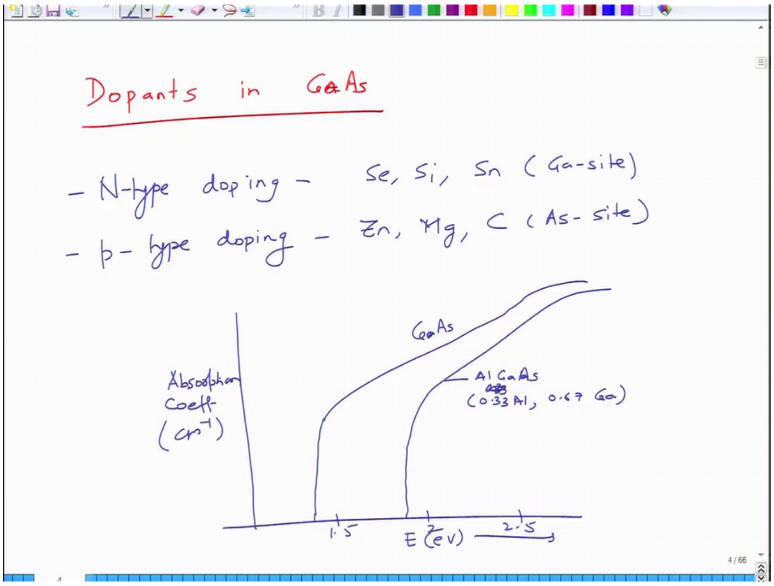

Dopants in GaAs

- N-type doping - Se, Si, Sn (Ga-site)
- p-type doping - Zn, Mg, C (As-site)

The typical dopants in gallium arsenide are so we use for N-type doping, we use selenium, silicon, tin, which cured to gallium site basically. And for P-type doping we generally use zinc, magnesium, carbon these go to arsenic sites.

And the band gap as we said is tuned in this fashion, so we have let us say you have absorption coefficient alpha. Centimetre inverse and then we have let us say E in e v. So, if you think of let us say this is 1.5 to 2.5, then gallium arsenide is slightly lower than 1.5. So, the band gap of gallium arsenide will increase like this, something like that and alumina aluminium gallium arsenide will be somewhere here.

So, this is AlGaAs, and this is gallium arsenide. So, this would be about 33 percent gallium. So, this would be 0.33 aluminium and 0.67 gallium, this increases the band gap of gallium arsenide.

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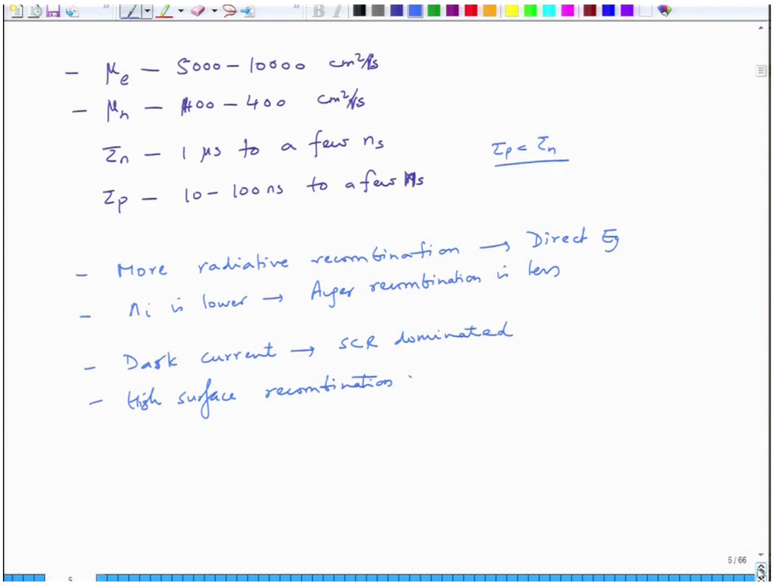

- μ_e — 5000 – 10000 cm^2/Vs
- μ_h — 100 – 400 cm^2/Vs

τ_n — 1 μs to a few ns

τ_p — 10 – 100 ns to a few μs

$\underline{\tau_p < \tau_n}$

- More radiative recombination → Direct E_g
- n_i is lower → Auger recombination is less
- Dark current → SCR dominated
- High surface recombination

So, so carrier mobility is as I said is higher, so mu e in gallium arsenide is about 5000 to 10000 centimetre square per second and mu h is about 400 to 100, 100 to 400 centimetre square per volt second volt second, sorry not second. And the lifetimes of carriers electron lifetime is about 1 microsecond to 10 to power 14 per N a. So, this is nanosecond you can say a few nanoseconds actually, a few nanoseconds and to a few nanoseconds.

And tau p or tau h you can write this is 10 to 100 nanoseconds to a few nanoseconds small n. And so as a result of direct being as a result since it is a direct band gap semiconductor, it has more radiative recombination, since it is a direct band gap semiconductor. And since it has higher band gap, the n i is lower as a result ajar recombination is less is less saviour.

And trap assisted depends upon the quality how you make it and generally tau p is less than tau n for the same doping level. And dark current in this systems is generally SCR dominated, and they also have high surface recombination. So, these are some features of devices based on gallium arsenide solar cells. So, generally gallium arsenide solar cell the design is like this.

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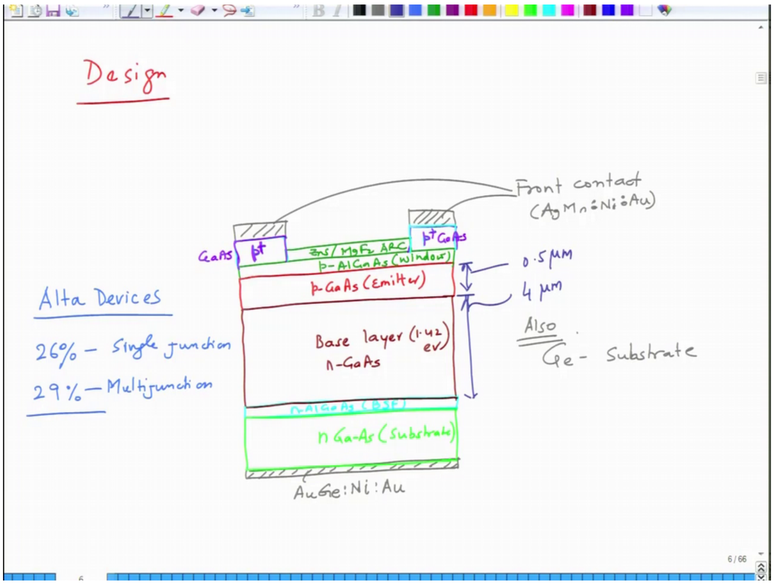

So, we have you can start with the bottom layer. Let us say, so we have n, n gallium arsenide as substrate all right. And then we have the back contact, so let us first make the devices then we will put the contact. And then another layer of is a intermediate layer in between, which is of n aluminium gallium arsenide’s of slightly higher band gap to pre to create a back surface field, which reduces the surface recombination ok. So, basically it is used to slow down the carriers when they move towards the electrode, because it has higher band gap as a result. Carriers will have to face a bit of energy barrier to move to the n n electrode.

And then we have base. So, if I make the base this is the base layer, base layer is made of n gallium arsenide and this has of course, 1.42 e v of band gap. And on top of this we have a ammeter. So, this is ammeter which is p-type gallium arsenide. And then we have on top again a small layer of p-type AlGaAs, which is again to this is called as a window ok, but again it reduces the surface recombination.

And then we have on top layer of zinc sulphide and magnesium dichloride, which is ARC essentially ok, so you can say it is ARC. And then we have Gilbert heavily doped region of so we can say on this sites we have heavily doped region of let us say p plus ok, p plus gallium arsenide, I can write this a p plus gallium arsenide p plus ok.

And then we have on top the front contact, so this is again front contact, which is generally align alumina an alloy of AgMn -Ni -Au ok. And in this case the back contact is made up from the back side, this is a alloy of Au, AuGe alloy with nickel and gold. So, you sort of you put in all these layers together, so that you make a good contact all right.

So, again the work function matching has to be done, so that carriers are not blocked by the electrodes, but again similar concept for the electrode you cannot cover the whole surface with the electrode because of opaque nature of metal. So, as a result you have to optimise the electrode position just like you did in silicon. These also used sometimes germanium as germanium as substrate, germanium can also be used as a substrate, because they have a good lattice match between the two.

And we put n gallium arsenide as a substrate, because of good lattice match, so that dislocations are smaller than number at the so defects are lower as a result the decor in the lower recombination is lower. These solar cells in efficiency, so there is a company called as Alta devices.

So, right now they their solar cells show 26 percent for single junction and gallium arsenide also is used in multi junction devices. And in multi junction they have gone up to about 29 percent. So, they have very high efficiency as compared to silicon ah. So, this is a typical picture of gallium arsenide solar cell, the concepts which are used in silicon are also valid here to improve the performance.

So, design considerations are fairly similar use of ARC surface passivation, use of reducing the surface recombination reducing bulk recombination, so many and so forth. So, these principles are valid.

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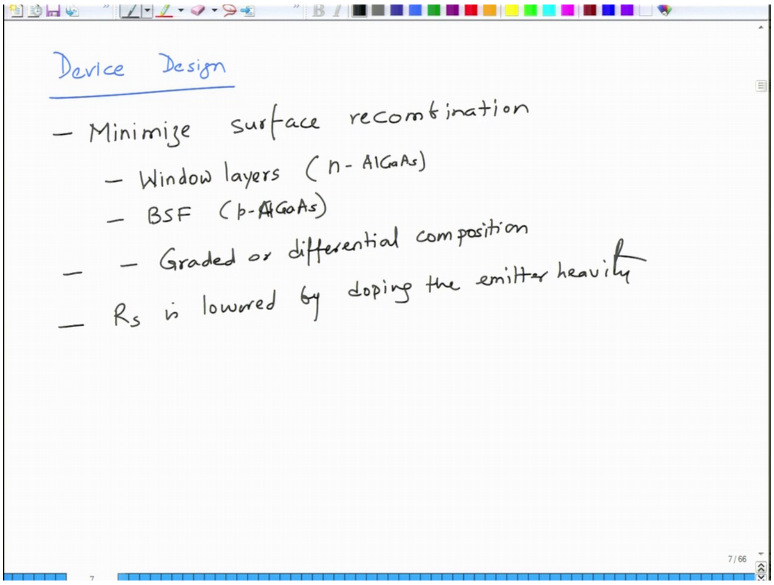

Device Design

- Minimize surface recombination
  - Window layers (n- AlGaAs)
  - BSF (p-AlGaAs)
  - Graded or differential composition
-
- R_s is lowered by doping the emitter heavily

And basically the device design requires 1 to minimise surface recombination and for that people use these window layers. Window layers of for example, you can say n-type aluminium gallium arsenide for instance and you can use back surface field layers, which are p-aluminium aluminium gallium arsenide to reduce the surface recombination.

Often one also uses graded or a differential composition in the semiconductor itself to slow down the carriers. And series resistance is generally lowered by doping the emitter heavily, so that leads to reduce reduction of series resistance in these materials. So, these are certain consideration, which are used for gallium arsenide solar cells. So, in summary what we have covered so far about single crystal.

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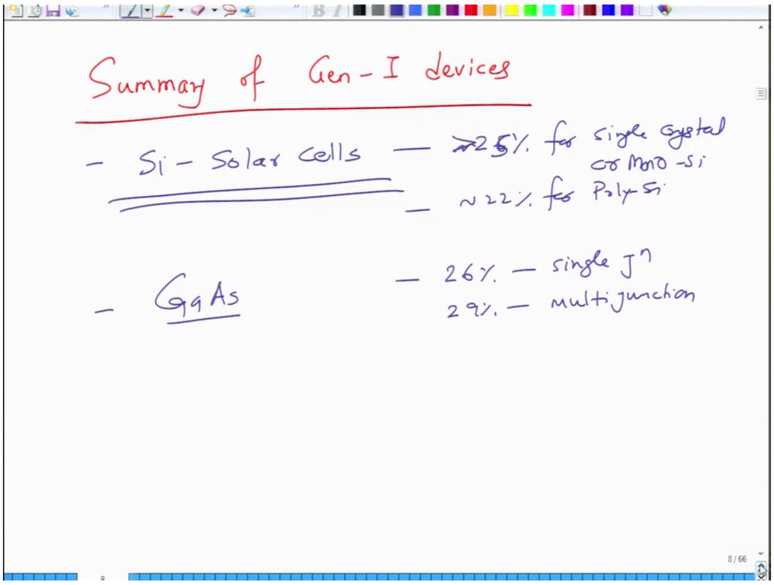

Summary of Gen-I devices

- Si - Solar Cells — >25% for single crystal or Mono-Si
  — ~22% for Poly-Si
- GaAs — 26% — single J^n
  29% — multijunction

So, so this is not the end of the lecture, but in summary about the first generation solar cells summary of Gen-1 devices. So, we have silicon solar cells the commercial once whose efficiency is 26 percent for or you can say more than 25 percent for single crystal silicon single crystal or mono-silicon and about 22 percent for poly-silicon right solar cells.

Then we have gallium arsenide, which have certain advantages in terms of silicon, because it has higher carrier mobility and so on and so forth, but gallium arsenide again is about 26 percent for single junction and about 29 percent for multi junction. But silicon is the one which has dominated the commercial market because of lower cost, so that is why we use silicon and gallium arsenide is also very suitable for making multi junctions in comparison to silicon.

First gallium arsenide band gap tenability is better, it can you can use higher and lower band gaps to harness the device thickness of this is about, let me just tell you the device thicknesses. So, the base is nearly so this is about 4 micron and this is about half a micron.

So, although you can have a substrate which is which could be thicker, the device thickness is not very large. So, you do not require very large volume of material to deposit on the substrate. However, if you are using gallium arsenide as substrate, that increases the cost, but if you can use germanium as a substance that will lower the cost.

So, absorption volume is actually only four and half micron as against very large thickness in case of silicon all right. So, now we look at the Gen-2 technologies, which are basically thin film based technologies.

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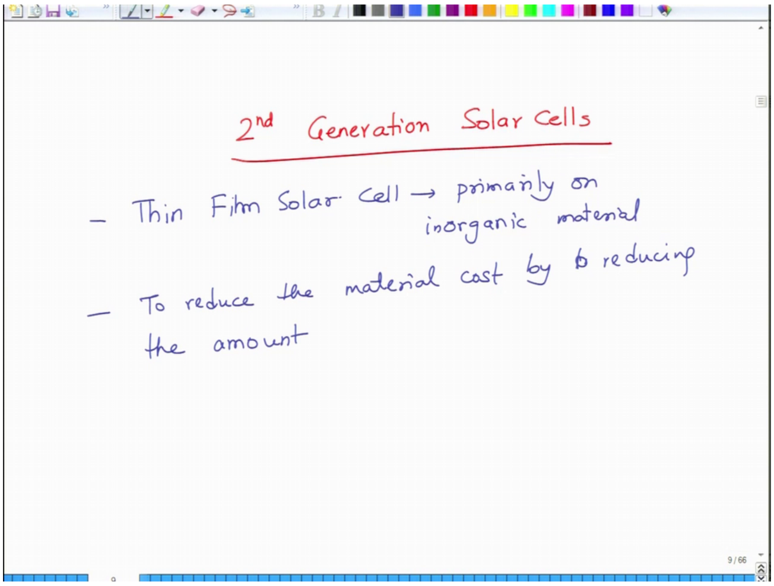

2nd Generation Solar Cells

- Thin Film Solar Cell → primainly on inorganic material
- To reduce the material cost by b reducing the amount

So, so we move on to a new topic which is second generation solar cells, solar PV technology. Second generation PV technologies have it is mainly it mainly revolves around thin film solar cells primarily based on inorganic materials.

And the idea to use thin film is because you do not require such a large volume of material for absorbing the amount of light that you can actually absorb. So, to reduce the material cost by limiting its by reducing its amount ok, so that is why thin films are going to be used.

And however, thin films requires to be deposited by a process which can make good quality thin films, so that is why its development did not take place earlier, because the vacuum pumps and vacuum technology was not very mature at that time. Since in 80s onwards vacuum technology matured that is why, thin film technology also got superior and that is why most of the thin film devices also got a kick because of improvements in the vacuum technology and equipments, you could make cleaner materials and thin film for.

In thin film for the cleanliness is very important, because a small dust particle gets in which is of same dimension as thin film your thin film will be dead, so that is why you require a very clean atmosphere for thin and that is why vacuum is preferred over air.

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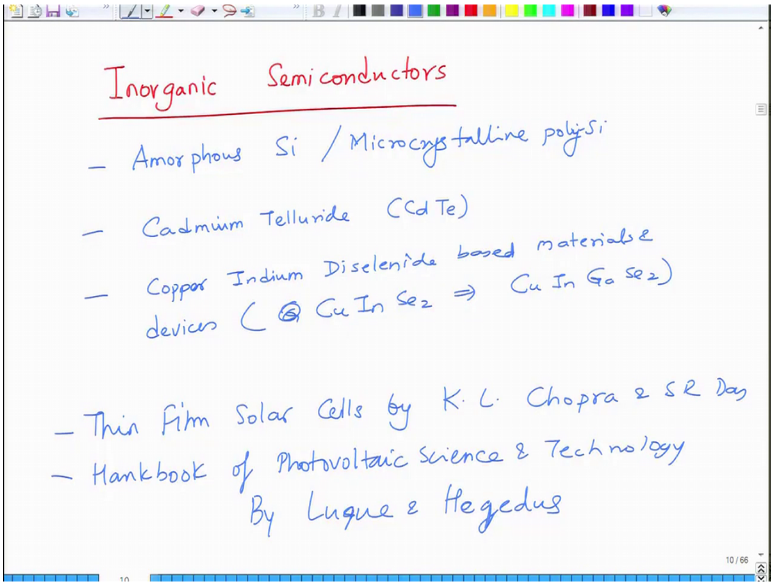

Inorganic Semiconductors

- Amorphous Si / Microcrystalline poly-Si
- Cadmium Telluride (Cd Te)
- Copper Indium Diselenide based materials & devices (Cu In Se_2 ⇒ Cu In Ga Se_2)

- Thin Film Solar Cells by K. L. Chopra & S R Das
- Hankbook of Photovoltaic Science & Technology By Luque & Hegedus

So, the type of materials in thin film technology is that we have so inorganic semiconductors mainly, especially in second Gen I mean third Gen are also thin films, but second generation are mostly based on inorganic semiconductor. So, we will talk about so we have first we have amorphous silicon, sometimes people also talk of microcrystalline poly-silicon, where crystallite size is smaller.

Then we also have cadmium telluride, which is called as Cd Te. And then we have copper indium diselenide based materials and devices and devices. So, which is basically Cu indium Se 2 and if you dope, it with jelly gallium, then copper indium gallium selenide, and this is mainly done to basically change the band gap.

So, we will see that on the on the as I suggested earlier, the books you can read is by you can read thin film solar cells by K. L. Chopra and S R Das. Second one you can see is handbook of photovoltaic Luque and Hegedus l u q u e ok. So, now thin film technologies are used this is that the genesis lies in changes in the difference in the absorption coefficient.

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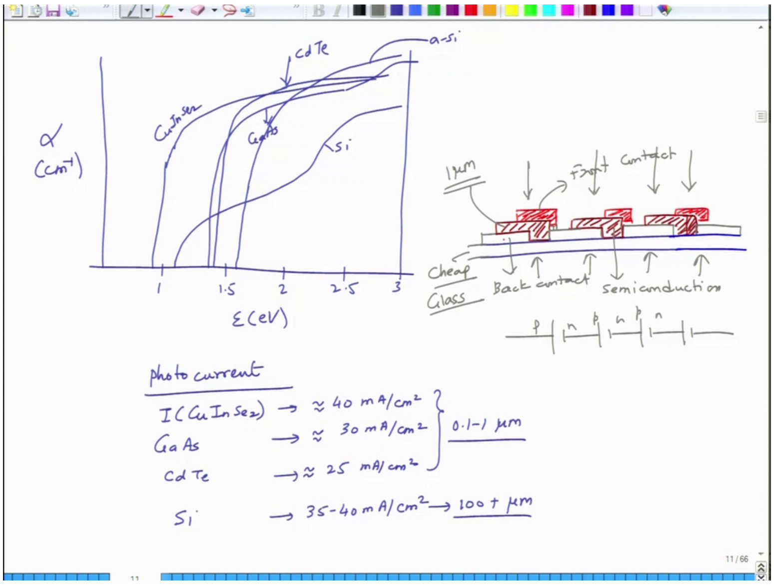

photo current

$I(CuInSe_2) \rightarrow \approx 40\ mA/cm^2$

$GaAs \rightarrow \approx 30\ mA/cm^2$

$CdTe \rightarrow \approx 25\ mA/cm^2$

} 0.1-1 μm

$Si \rightarrow 35\text{-}40\ mA/cm^2 \rightarrow$ 100 + μm

So, if you draw for example absorption coefficients of different materials, you are silicone is has a band gap of you know 1.1 electron volt. So, let us say we plot it from 1 1.5 to 2.53. So, 1, 5, 2, 2.5, 3 this is E in ev ok. So, silicon has a band gap which is lower and hence it will start at somewhere here ok, and this goes little bit lower band gap which increases somewhere around here ok.

And then we have you know we have copper indium gallium selenide, which is even lower band gap, but its but its absorption coefficient is actually pretty good, this is C u S e 2, this is silicon. On the other hand, your gallium arsenide and CdTe both have band gaps, which are about so this will go somewhere here and increase in the end.

And then CdTe has band gap which is slightly better like this. So, this is CdTe, this is gallium arsenide and then amorphous silicon comes somewhere here amorphous, because it is a amorphous it has higher band gap, but it has higher absorption coefficient, it tends to act as a direct band gap semiconductor so this is a amorphous silicon.

So, if your absorption coefficient of material is higher, then you can reduce the volume of material that is required to absorb the same amount of radiation; so that is why the photocurrent observed from these materials is quite high. So, photocurrent observed from so photocurrent of for example, I in case of copper indium selenide can be quiet high; it could be nearly 40 milliamps per centimetre square. It is band gap is also lower and substrate absorption coefficient is also higher, it can give you pretty high photo currents.

If you look at in case of gallium arsenide, gallium arsenide gives you values of the order of 30 milliamps per centimetre square. Cadmium telluride gives you of the order of about 25 milliamps per centimetre square, very high current that you can obtain in case of cattle and these currents are obtained at thickness of nearly 0.1 to 1 micron, whereas in case of silicon the high current of approximately you know, you can reach the saturation of about 35 to 40 milliamps per centimetre square that is obtained at a thickness of nearly 100 plus micron. So, you can see that amount of material used is 100 times higher ok.

And this is a major deterrent, and this is a major motivation also to make a thin film silicon solar cell. So, the idea is that you have a glass panel all right. On the glass panel, you first deposit let us say contact. So, we first make contacts like this right and between the contact we put in the semiconductor, so we put in the semiconductor let us say all right.

And then of course, you have contact on this side also ok. And then on top you put a back contact, a front contact. So, a front constant could be something like this, you have to isolate them though. So, you make a front contact you make a back contacts, so make them touch each other so one. So, you have then you put a top contacts so and so on and so forth.

And then of course, you make a you make a top glass cover ok. So, you have n you have back contact, you have front contact and you have in between semiconductor. So, for every device you know if you connect them in series, then top of front and the bottom of next can be connected. So, if you series connect them that is possible so you will have a combination like this p n p n p n things like that so that is how they will go in series. So, p n p n p n ok.

So, now these devices the idea is here you use a glass panel, this glass panels cheap that is not a as expenses as the material is you are putting only a micron of material, which is 100 times lower than the amount that you need to use in silicon. And then use a front metal contact, which can be put by process like evaporation or something like that. So, the advantage here is that you are able to make junction and this is this is from the front the light will come.

Light will also come from here, so you can also eliminate from this side, because on one side you have glass on other side its open or you can put something else on top as well, you can put glass also again on top. So, light can come from both the sides this also gives you a freedom in terms of choosing the electrodes.

So, you use ethane amount of material you can you can throw the light from any side that is why, there are two configurations which are possible in thin film solar cells; substrate and superstreet light can come from either side. And it allows you to do use, it allows you to reduce the amount of material. So, this is the motivation behind using thin film solar cells as this was the motivation in second generation. So, we will stop here today. We will now discuss the thin film technologies in terms of materials and issues in the next few lectures.

Thank you.