Solar Photovoltaics: Principles, Technologies and Materials

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Lecture – 29
Generation I Technologies (Mono Silicon Solar Cells)

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

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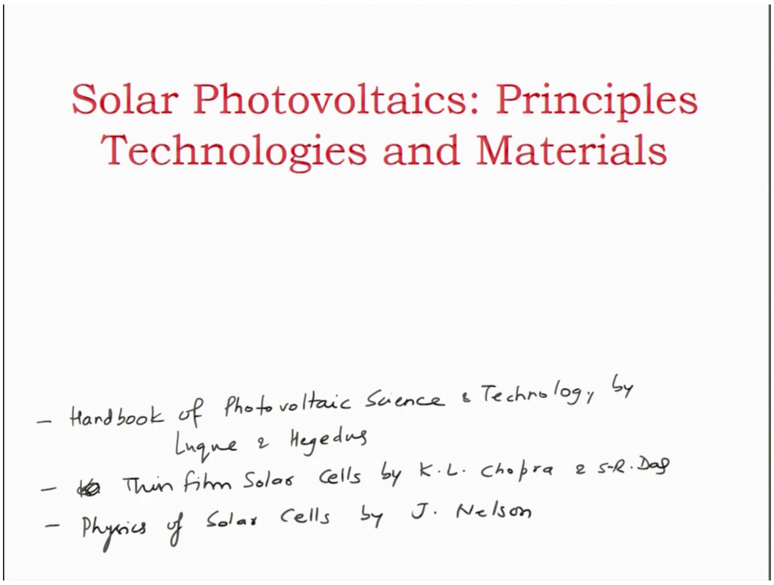

Solar Photovoltaics: Principles Technologies and Materials

- Handbook of Photovoltaic Science & Technology by Luque & Hegedus
- Thin film Solar Cells by K.L. Chopra & S.R. Das
- Physics of Solar Cells by J. Nelson

So, a lot of it now is based on solar cell technologies. So, I would recommend a few books to you. So, you can have for example, you can have a look at handbook of although I might have told you this earlier, but science and technology by Luque and Hegedus. This is a nice book and then you can also look at from the perspective of thin film solar cells, you can look at thin film solar cells by K L Chopra and SR Das. And you can also look at physics of solar cells by Jenny Nelson in addition there are lot of papers reviews and articles which can be dealt with especially for third generation they are not present in the books and there are lot of other books present in the literatures we can look at many other books.

So, now, let us just do a bit of recap in the last, what did we do in the last lecture. So, in the last lecture we looked at basically started about discussion with silicon and monocrystalline silicon as we know.

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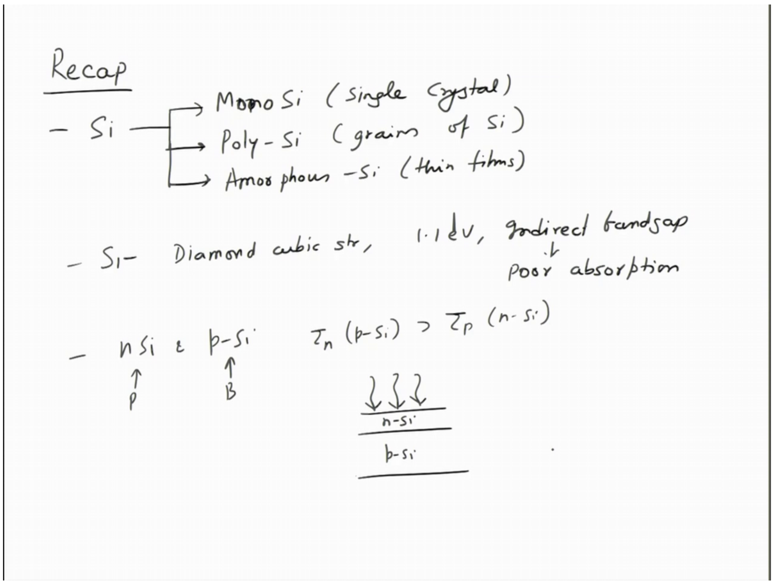

Recap

- Si → Mono Si (Single Crystal)
→ Poly - Si (grains of Si)
→ Amorphous -Si (thin films)

- Si - Diamond cubic str, 1.1 eV, Indirect bandgap
↓
poor absorption

- n Si & p-Si τ_n (p-Si) > τ_p (n-Si)
↑ P   ↑ B

n-Si
p-Si

So, silicon is present in basically three primarily forms one is mono silicon, which is basically single crystal silicon. So, vapor is single crystal there are no grain boundaries and grains and then we have polysilicon which we call as polycrystalline silicon. So, you have grains of silicon which are bigger, quite bigger than the thickness of the device and then we have amorphous silicon. These are three major technologies that are present in the market and these are thin films.

And silicon as we know is a diamond cubic structure material, it has a band gap of 1.1 e v it is a indirect band gap semiconductor and as a result it has poor absorption of light ok. And one uses in the solar cell context, one use n silicon and p silicon both of these are made by doping. So, n silicon is for example, made by phosphorus doping, this could be made by boron doping and this doping leads to reduction in the carrier mobility as well as lifetime.

However, p doped silicon has higher life time. So, tau n in p silicon is larger than tau p in n silicon. So, it carrier life seem. So, little larger in p and n silicon a p silicon over n silicon as a result p silicon is the base n silicon is the typically the emitter. So, device form is like this. So, you have n silicon on top, p silicon at the bottom and the radiation comes from top.

So, important thing in this configuration is since silicon is a opaque material well most of the. So, and it is the light absorber, the kind of contacts that you put on top of it that is very important. So, generally the way silicon is made is silicon is made with. So, there are certain design considerations that we need to follow to make it good device.

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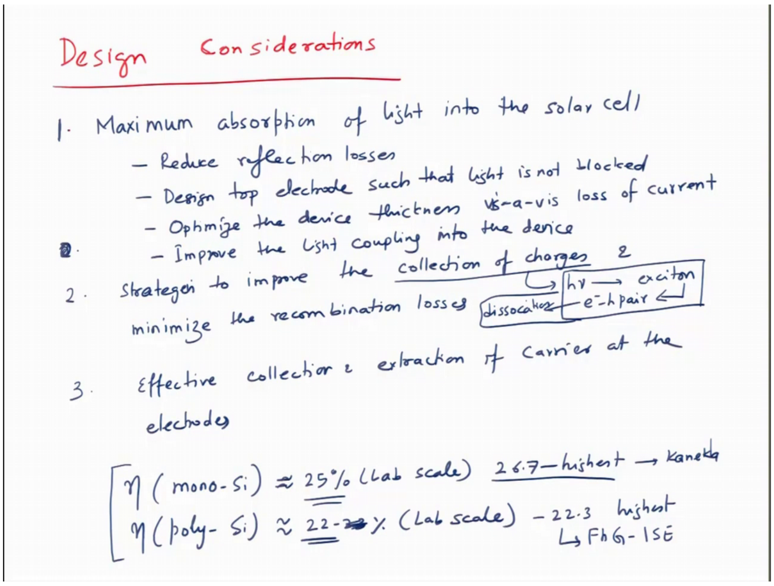

Design Considerations

1. Maximum absorption of light into the solar cell
   - Reduce reflection losses
   - Design top electrode such that light is not blocked
   - Optimize the device thickness vis-a-vis loss of current
   - Improve the light coupling into the device
2. Strategies to improve the collection of charges & minimize the recombination losses

   ↳ $h\nu \rightarrow$ exciton ↲ e⁻-h pair — dissociation

3. Effective collection & extraction of carrier at the electrodes

η (mono-Si) $\approx$ 25% (Lab scale) 26.7 — highest → Kaneka

η (poly-Si) $\approx$ 22-~~23~~% (Lab scale) - 22.3 highest ↳ FhG-ISE

So, what are the design considerations in the first design consideration is the light which is incident on the solar cell. So, maximum absorption of light into the solar cell ok. So, what does it mean? It means one you reduce the reflection losses and that we also see in quantum efficiency right. So, reduce reflection losses which means you need to do some sort of things to do some sort of modifications to the surface. And then also you need to design your top electrode such that light is not blocked and then you need to and of course, silicon is fixed right. So, you cannot change the material, but you can adopt strategies so that you can have maximum absorption intra.

So, what we do is that in that case optimize the device thickness ok, but and this is with vis a vis loss of current alright because if you make a very thicker then the combination becomes a problem. So, as a result you need to; you need to basically optimize the device thickness so that you have maximum absorption and maximum current. So, there is optimization between the two.

And then second thing is how do you improve the strategies to improve the collection of charges and minimize the. In this thing we can also add one more thing in the top thing is to improve the light coupling, improve the into the device. And then how do you improve the collection of charges and minimize the recombination losses and we have and third finally, we will have how to have effective collection and extraction of carriers at the electrodes.

The collection of charges here means basically in the top and the second point is your photon gives h to exciton and exciton then converts into electron hole pair. So, we would like to maximize this process and then which is going into free so and then we have dissociation right. So, we must have a strategies to maximize this process, that is photon is absorbed exciton is created electron hole pair are formed and electron from whole pairs then get dissociated, this is what we have to maximize.

So, these are certain design consideration that we need to that we consider in device fabrication and as a result of various strategies silicon efficiency as far as they are concerned. So, a silicon of as far as mono silicon is concerned mono silicon efficiency is of are of the order of 25 percent at the lab scale. They have achieved nearly 25 percent or may be higher, little bit higher whereas, in case of poly silicon efficiency is are of the order of 22 to 23 percent at the lab scale.

Perhaps 22 percent is the more accurate number over 23. So, nearly 22 percent that they are not very fix numbers, but nearly 22 percent, if I look at the correct numbers. So, in this case its actually the lab scale is 26.7 percent is the highest ok, this is as of 2017 and the multi crystalline has a efficiency of 22.3 is the highest and this is a from Kaneka. Whereas, this is from German manufacturer FhG ISE, I think is Forschung Zentrum in Germany ok.

So, these are numbers that have been achieved after modifying various design considerations, this is a material silicon material is same. I mean you know you know it started with low efficiency and today we are standing at 26.7 in case of mono silicon in 22.3 in poly silicon. It has come mainly through making modifications in the device and going through various design modifications ok. Going through several minute tiny changes in the devices which have led to significant improvement in the performance.

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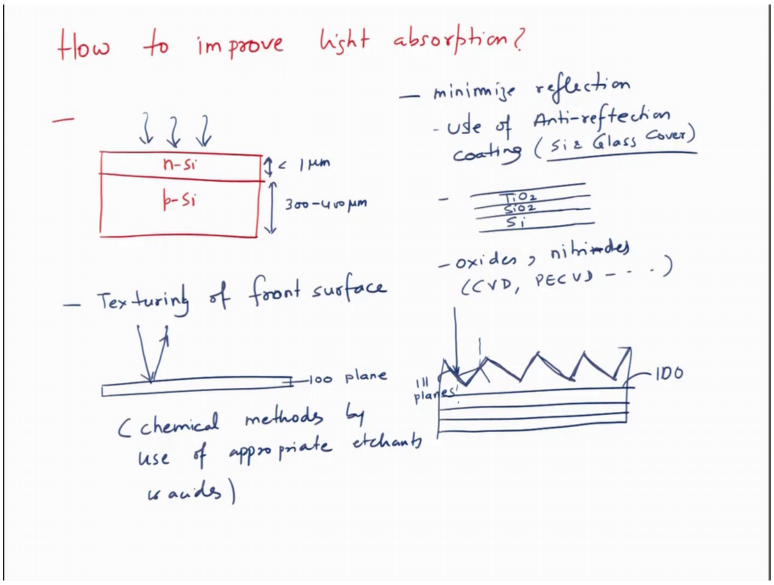

How to improve light absorption?

- minimize reflection
- use of Anti-reflection coating (Si & Glass Cover)
- oxides, nitrides (CVD, PECVD - - -)
- Texturing of front surface

(chemical methods by use of appropriate etchants or acids)

So, now if we go to strategies 2 for example, how do you first thing that we follow is. So, we have this as a solar cell device and on top we have n silicon and the bottom we have p silicon ok. So, this n silicon is of course, because n silicon is little thinner. So, it is about its less than a micron whereas, this is about 300 to 400 micron ok. Now this light comes from top here, one thing first thing is to minimize reflection and this reflection is minimized by use of anti reflection coatings.

And generally we have a by layer of you can say. So, on silicon you can have SiO 2 and on top of that we have a layer of TiO 2 ok. So, this leads to improved antireflection properties of silicon surface ok, you can also provide arc on glass. So, use of arc is done both for silicon as well as glass cover on top and there are various oxide coating. So, these are basically antireflection coatings are oxides, nitrides and generally they are deposited by processes such as CVD PECVD and so on and so forth. Chemical vapor deposition processes which are large area processes and these layers basically reduce the they are very thin layers, but they reduce the reflection losses.

Second thing that is achieved is to do the texturing of the front surface. Now texturing means, see silicon generally silicon wafer is this plane is 1 0 0 ok, this is 1 0 0 plane; 1 0 0 plane is generally cut flat so, it is (Refer Time: 12:59) planar surface. However, in silicon within 1 0 0 so, if this is 1 0 0 plane you will always have these 1 1 1 kind of planes, because it is a cc structured cubic material, theses are 1 1 1 planes ok. If you do the etching of silicon in such a manner so that you are able to expose these 1 1 1 planes in such a fashion so that this is removed and what you are left with the surface like this.

So, we have a surface in which we do not, although that although the; although the these planes are all 1 0 0 planes, on the top because of chemical etching we are preferentially remove the atoms from certain plane so that 1 1 1 plane is exposed. So, these are all 1 1 1 planes, which are at certain angles to 1 0 0 you can calculate it is about 54.7 degrees. So, these 1 1 1 planes improve the optical absorption. So, when the light now comes in this case of the light came it would directly get reflected ok, here if a light comes in this fashion part of it will get absorbed, part of it might get reflected it might go there then it might go there.

So, basically you have minimized the, you have maximize the absorption of light this by this doing by this surface texturing. So, this surface texturing can be done by chemical methods by use of appropriate etchants or acids ok. This is one strategies that is adopted, second strategies that you can absorb adopt is to improve the contacts; contacts design.

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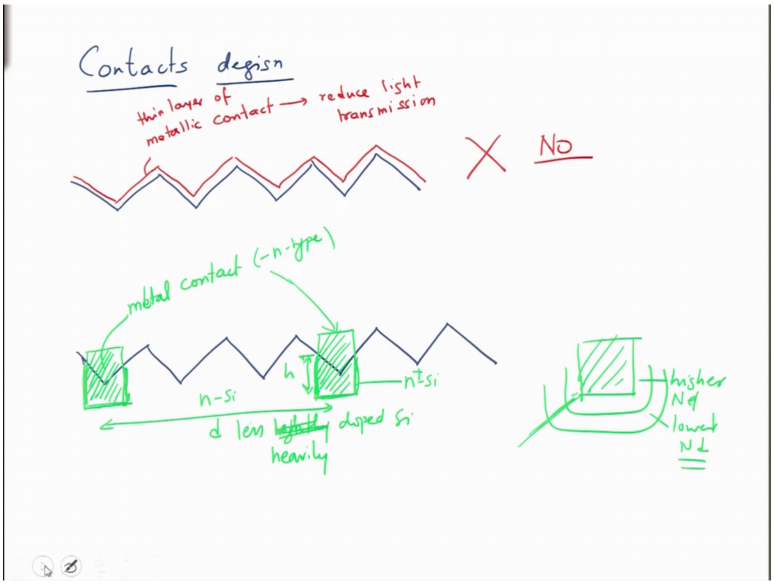

So, of course, one is strategy is you have this surface, textured surface and if you want to put contact on it of course, you will have to put contact because you want to extract the charges; when you put the contact if you put the contact like this which is a metallic contact ok, if you put a metallic contact like this. So, this is metallic contact since, metals are opaque this is going to reduce light transmission even if you put a thin layer of metal with certain transmission it is going to reduce the light transmission ok. So, this is no, which means you cannot completely cover the surface of silicon with the metal because it will block the light; even if it is a thin layer of metal.

So, another strategy that is useful to adopt is to use this kind of surface. So, again have textured silicon surface and you use you use the contacts which are buried inside. So, you have deep contacts. So, you have contacts in this fashion, buried inside the solar cell. So, you have contacts buried at certain interval. So, these contacts so you have, you maximize the interfacial area ok. So, this is metal contact you have to of course, optimize the spacing between the these two as well as the height h, so that you have minimum parasitic resistance losses.

Because if you make them too far then your resistance will, device resistance will increase your connection will be poor. So, there is a need to optimize the spacing and the length of this contacts and the depth of this contact, but; however, if you do this then you do not compromise on the light absorption. The light the most of the silicon surfaces still available for light absorption by directly come in contact with the light, without having any intermediate blocking layer to prevent the light from coming. So, these are basically metal contact basically, n type contact because underneath you will have n silicon ok.

So, in the vicinity of these contacts the silicon is little heavily doped. So, in the vicinity silicon is n silicon n plus silicon and the underneath it will be little lightly doped, less heavily doped silicon. So, basically what we have? We have a differential in dopant concentration in the silicon in the vicinity of contact. So, if this is contact, if you zoom it up in the vicinity you have higher dopant concentration higher Nd and the region surrounding it you have lower Nd.

This helps to prevent the recombination near the contacts and also it helps to make a good graded contact because carriers will go excite carriers will go fast towards the contact. So, when you have this little grading, little gradient like a in the dopant concentration there is a gradient in the bands also.

So, carriers get slowed down as they reach the contact. So, the surface recombination is little lower as compare to; as compare to having a uniform doping around it. So, these are certain ways to.

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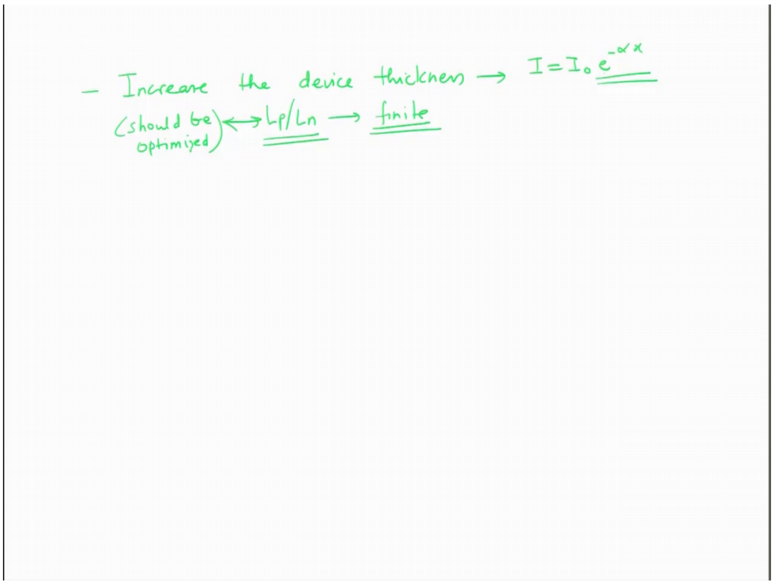

- Increase the device thickness $\rightarrow$ $I = I_0 \underline{\underline{e^{-\alpha x}}}$

(should be optimized) $\longleftrightarrow \underline{\underline{L_p/L_n}} \rightarrow \underline{\underline{\text{finite}}}$

And then of course, you can also increase the device thickness, because if you increase the device thickness we know that I is equal to I naught exponential minus alpha x. So, if your x increases your absorption will increase right, amount of light absorbed will increase. So, transmitted light will reduce as your thickness increases as a result you can increase the device thickness; however, device thickness cannot be increased indiscriminately because of constant with L p and L n right. Because these are finite numbers, so if you increased too much then you will have a lot of recombination in the device.

As a result, the device thickness should be optimized vis a vis L p and L n. And as I said top contact coverage the coverage area of the top contact metal contact has to be optimized. So, these are certain methods to improve the optical losses to reduce the optical losses.

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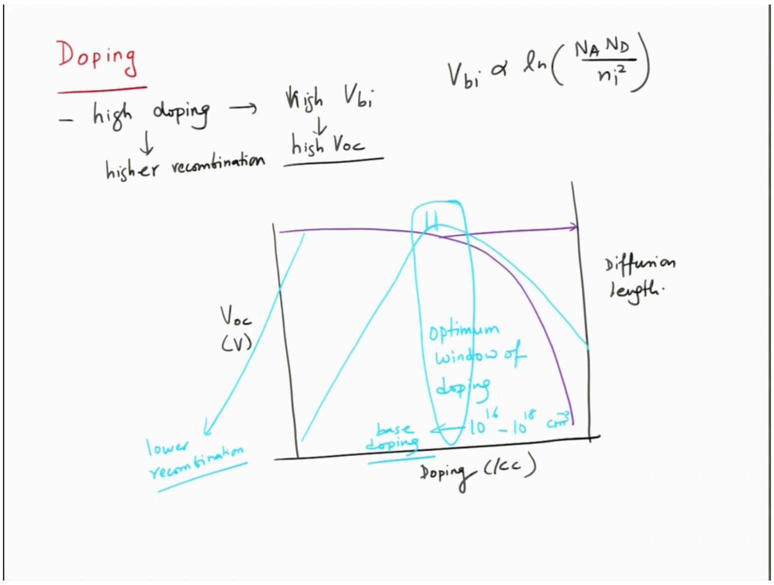

And then of course, doping place a very important role; doping helps in so high doping leads to high building field right high V b i because V b i is proportional to l n of N A N D divided by n i square. So, if we have high V b i you are likely to get high V o c also, so, this may lead to high V o c.

But, when you increase the doping also leads to higher recombination at especially at heavy doping. So, if you plot the V o c. So, this is for example, doping concentration in per cc and this is for instance your V o c in volts and then we have here let us say the diffusion length because diffusion length ok. So, generally the diffusion length so if I plot diffusion length has blue or purple so this diffusion length goes down at higher doping level ok. Because a scattering increases as a result your mobility decreases your diffusion lengths go down. Because your life times go down, but on the other hand your doping tends to increase the V o c, so, your V o c tends to increase.

But because of this change in the because of this change in the diffusion length the V o c again reduces because your current started using then V o c as we know is a function of current also. So, as a result there is a optimum V o c that you get for there is a optimum window of doping at which you get maximum doping. So, you can say you have a optimum window of doping and this is around you can say about 10 to the power 16 to 10 to the power 18 per centimeter cube, if you think of this base doping ok. So, doping is so on the left hand side you have decreased recombination. So, at this on this side you have lower recombination, because you have lower carrier concentration may not a carrier concentration is lower as a result your recombination is lower.

But on the other side you have higher recombination because of reduced diffusion length. So, there is a; there is a optimum that you need to work out and this optimum is somewhere around this number in terms of V o c. Then of course, you need to again worry about the surface recombination to collect the charges efficiently.

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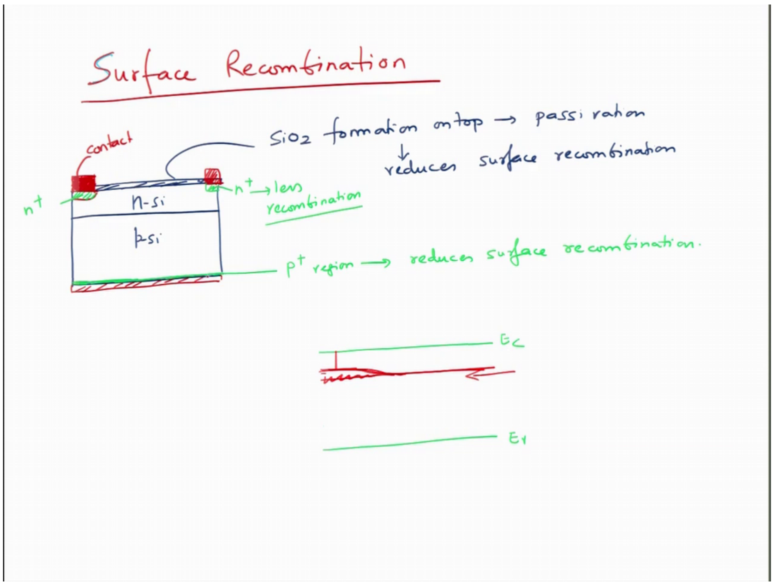

So, surface recombination one thing there are lot of things people do. So, for instance if you have a solar cell like this, it you have so, you have n silicon you have p silicon. So, what generally people do is that one they make a layer of silicon oxide on the top surface. So, this is S io 2 formation on top a thin layer of silicon layer which leads to surface passivation by suppressing the dangling bond density. So, that reduces a surface recombination. So, reduces surface combination then we have if you have contexts let us say if I put contexts now let us say these are my contexts this is again another context somewhere here context has to be in touch with the silicon.

So, oxide is at the places where there is no contact an oxide is transparent to light. So, it does not affect absorption. So, near the contact generally if this is contact underneath you have this region as, as we said is heavily doped. So, this would be n plus, this would be n plus and this again keeps the minority carrier away from high recombination.

So, there is less recombination alright, as you applied a bias the minority current increases and minority carrier concentration is. So, you would like to prevent the recombination to have to reduce the recombination current and then we have we also do heavy doping at the rear of the cell. So, this region is also little heavily doped.

So, you can say this is P plus region again reduces the surface recombination ok, and the reason basically is suppose you have you have this silicon if this is P type layer lets say E c E v and in the bulk you have this as let us say Fermi level, when you heavily doped the Fermi level goes down little bit here. So, as a result carriers have carriers find a more higher barrier for so basically in terms of; in terms of holes the going down is a barrier, in terms of electron going up is a barrier. So, if you look at the electron if you look at n side. So, I think it is more clear from the n side

So, let us say this is the Fermi level uniform Fermi level, but if you raise the Fermi level. So, let us say the carrier is coming from this side if you raise the Fermi level little bit here if this Fermi level is higher as compared to the Fermi level somewhere else the carrier will face a little bit of barrier, this slows down the carriers and as a result there surface recombination is lower.

So, that is why there is a there is a gradient in composition that is put near the surface near the contact on the top side and again near the contact on the bottom side both of these keep the carrier away from recombination.

So, recombination losses are reduced in both the cases, and this again is the contact on the backside alright. So, this is what is done to improve the contacts and a typical solar cell of a. So, silicon we have seen what kind of solar cell we can have.

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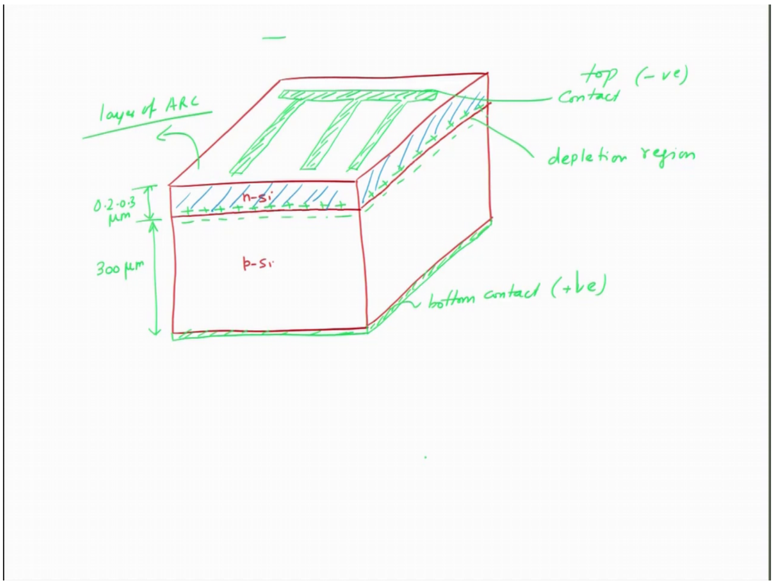

So, this is what is the design overall design ok. So, on top we have n silicon and the bottom we have p silicon. So, on the; so on this side so this is let us say n silicon part, on the top we have contact fingers. So, the contact fingers will be somewhere like this and you need to optimize their length and their breadth so that you have optimized series resistance because and you cannot cover the surface too much because of optical losses.

So, these are contacts on top, similarly you will have a contact at the bottom. So, this is bottom contact, which is positive this is negative and this is about 300 micron and this is about 0.2 to 0.3 micron. So, whole device is of roughly 0.3 mm thick and in top we have a layer of ARC that is Anti Reflection Coating and your light comes in this fashion it will come from top and then it will get absorbed in the rest of the solar cell and in the here you will form the depletion zone.

So, you will have positive charge is here and your negative charges will be here. So, this will be your depletion region and since top is more heavily doped as compared to bottom the depletion region is more in the p side than in the n side n side is much more thinner. So, this is typically the, this is a typical design that you have for silicon solar cells. And we will now move on to the next lecture in which we will talk a little bit about the multi silicon solar cell and poly silicon solar cell and little bit about the silicon manufacturing.

So thank you.