Fundamentals of Semiconductor Devices
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Lecture - 45
Solar Cell (Contd.)

Welcome back. So, we are in the discussion for Solar Cells. If you recall in the last lecture I have introduced over a solar cell and also outline a few of the very important properties of solar cell and how the solar spectra looks like. Essentially, it is a p-n junction that has to absorb source sunlight and convert it into electricity.

Efficiency is a very important number for solar cell; I told you that in the solar spectrum if you look any you know you have to use a semiconductor for example. So, a semiconductor has a band gap; all the photons with energy more than or equal to band gap will be absorbed, but at the photons it energy less than the band gap will be transmitted they will not be absorbed; so those are wasted, right.

And the idea is that there are many kinds of solar cells, silicon solar cell, crystalline solar cell, amorphous solar cell, silicon you know which are cheaper, but also not as efficient, but they also good you know because they are cheap. Also wide kinds of solar cells in a perovskites and organic materials and so on, but here we will limit only to silicon solar cell with p-n junction which is widely used, ok.

So, I will list down the important points that we had covered yesterday and in the last class, and also, I will list down the points that we are going to study today and maybe in the next class so that you are basically aware of the working of solar cell and some of the you know important things that you should be you know; you should know about solar cell working, ok.

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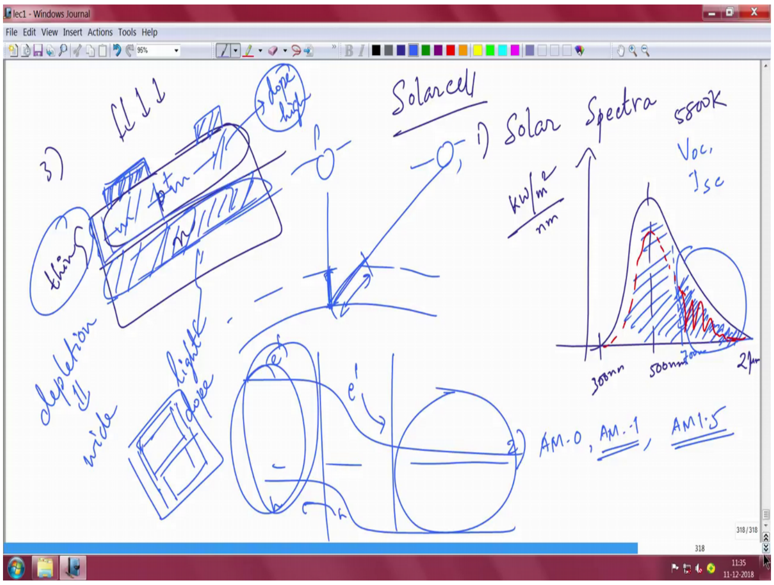

So, we will come to the white board here. So, what are the things that we had you know talked about yesterday? One thing is that I told you about the solar spectra. The solar spectra is like a black body, right, I told you it is like a blackbody here. The peak is around 500 nanometre and then it decays and becomes up to 2 micron. This is like a black body at 5800 Kelvin, this is the energy of the photo this spectra that is kilo watt per metre per unit area per nanometre wavelength, right because if you integrate up the whole thing then you will get kilowatt per metre square. This is around 300 nanometre, for example.

I told you if you use a semiconductor of any band gap, say you are using a semiconductor whose band gap corresponds to 700 nanometre; that means, E c by lambda is equal to 700. You will be abs able to absorb only this much of the solar spectra you will not be able to absorb the remaining.

I also told you that that does not mean that you have to use a semiconductor whose band gap is very small. So, that everything is absorbed because that will also not lead to efficiency, I will show you why. Because there are two things that are actually very important in solar cell; one is open circuit voltage one is short circuit current we shall definitely come to those. So, you cannot compromise on both you know that is why, so it is not the best of interest to actually have a small band gap material to absorb everything, that is not going to help.

Number 2 thing, I told you is that you know of course, AM air mass illumination 0 which is above the atmosphere, air mass illumination 1 which is at noon and at the evening you know you I told you this is the earth and this is the atmosphere. So, if the sun is here then the path length that it covers is this you know l, so it is 1. If it is in the evening here then the sun light has to cover this distance which is more than this distance if the depth ratio is called AM whatever. You know if the depth ratio is 1.5 then you call it AM 1.5.

Some, these are the some of the standards that are used and of course, you know if this was the blackbody curve and your air mass illumination will look lower than that, there will be some peaks also here because water vapour and other things will observe some of the wavelengths, so in the longer wavelength region. Then another thing I told you is that it is a p-n junction. So, you know you have a p-n junction and the sun light has to come from the top.

So, if p, the p has to be as thin as possible, p has to be as thin as possible. So, that you do not absorb so much on the p region you want to absorb everything on the depletion region, right. Why? This is the depletion, I told you because in a p-n junction if this is the fermi level. Only the photons absorbed in the depletion region will be swept away and contribute to electricity.

The photons absorbed here and here in the neutral region will give rise to electrons and holes which will diffuse and die away they will not contribute to electricity. So, those are useless photons that are getting absorbed here. You want to get everything absorbed in the depletion region not in the neutral religion, ok. And the depletion region should be large, that is why or take you know the depletion region should be wide. So, that you know it you can absorb more the photons here. You do not want the depletion to be narrow otherwise a very few photons will be absorbed. So, you want to dope the n-type light. So, you want to dope it light so that the depletion can extend very high very deep.

And you want to dope this very high the reason is you want to make it thin I told you, right, if you make it thin only then you will waste a less and less number of photons. So, you want to make it thin, so that you do not waste much, but if you make it too thin then your resistance, the lateral resistance because to you know you have to get electricity out which means you need to have metal contact, you will have a metal grid on top, ok.

If you look at the top view which is a solar cell, you will have some metal grid you know through which you are taking the electricity out, contact metal contact. So, those metal contacts you know you will take the electricity out. So, there is a resistance associated with this series lateral resistance. If you make it thin that resistance will be high, so you will drop unnecessary voltage you will waste. So, you do want the resistance to be low hence you dope it very high so that there are many carriers. So, even if it is thin your resistance is not sacrificed [FL].

Of course, you see this metal has to be there on the top know they will also block some on the sun light. So, that also reduces the efficiency. Your metals on the top will block, but you have no way out you have to give metals. So, people are trying to do thin metals so that you know the light absorbed or reflected off the metal is also low or people try to do transparent contacts also you know so that sunlight is not absorbed so much in the top metals. So, all these things are there solar cell is a vast area solar cell technology and physics of it is also very vast, is not sufficient in even one course I am only telling you a few lecture. So, we can only cover very basics, ok.

So, this is one important thing that the top layer has to be lightly doped, very very highly doped p plus and very thin, ok. So, that your depletion is extending towards the n and your; you know depletion and the more of the carriers absorbed.

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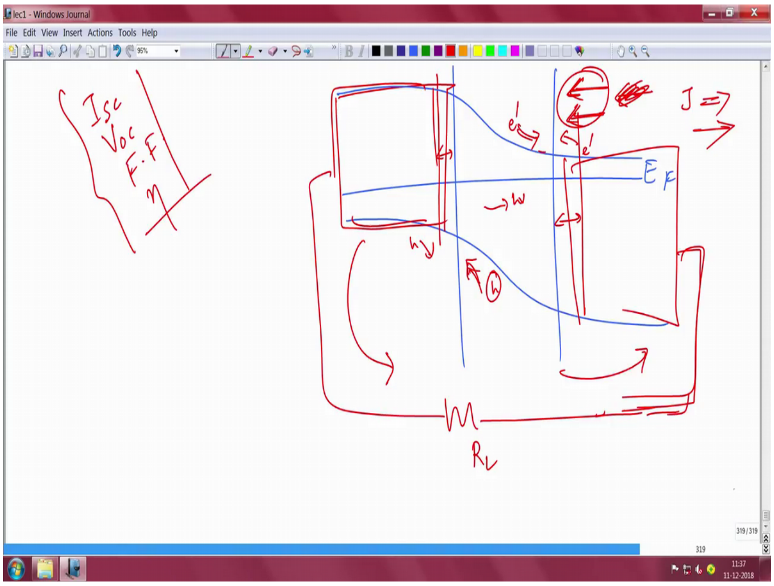

And of course, you recall I keep drawing this band diagram, but I will repeat it again here. Only the photons that are observed in the depletion will contribute to electricity because all the photons that are absorbed here will give rise to an electron, one photon will give rise to one electron and one hole that electron will be swept away by the field this side this is an inbuilt field you are not applying any voltage.

This hole will sweep away this side, so there will be electricity because of the electron going this way current will flow this way, because of the hole going this way current will again flow this way. This current is in the direction opposite to the forward bias current because for forward bias you inject the electron this side and you inject the hole this side.

So, the forward bias current is in this direction which is the ideal diode equation and your solar cell current is in the opposite direction. Remember, if you bias the device in reverse bias then your current will be in this direction ideal diode current. If you bias the devise in forward bias then your ideal diode current is in this direction, ok. So, any photon that is absorbed in the neutral religion is waste until at least one diffusion length here. Within one diffusion length it can actually diffuse and get this thing, but less then after that you know it does not matter. So, this is a photon that are wasted so, that those do not matter I mean those you want to minimise, right.

So, the main the important terms in solar cell are I told you short circuit current, I will come to that; open circuit voltage, there is something called field factor, and then there is something called efficiency. These are a four very important terms that you have in a solar cell you should know all this terms by the end of this lecture we will know what those terms are, ok.

What you will do here is that? If you do not have to apply any bias in the solar cell by the way there will be a load, ok. There will be a load on which the electricity will flow in this direction because electrons are flow in that way, also flow in that way you can actually think of solar cell like a battery, but is not like it does not store energy it is a source of energy. You connect it to a load and it will supply electricity, right.

Now, what we do is that we have to solve. So, I will go to a next page.

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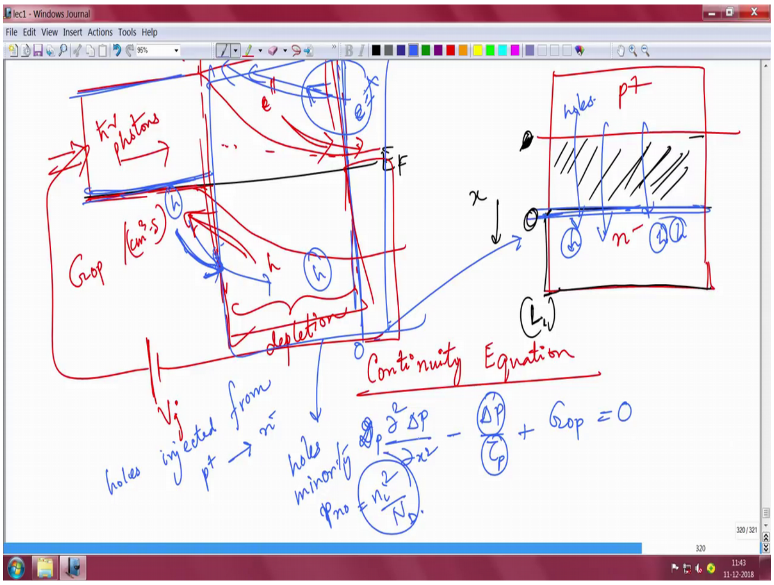

So, this is a solar cell and you know the recall the continuity equation, so I will take a probably simple case I will take a one sided junction which is a p plus and then n minus. Because it is p plus your depletion to the p side will be almost negligible, all the depletion will be on the n side only. So, this is a depletion region, ok.

I will take this as say the metallurgical junction. So, maybe this is the depletion region towards the n, photons absorb in this shaded region only will contribute. I will take the suppose this is 1, this is 0, this is x equal to 0 and this is say the width of the thickness of the if the length of the device eventually this is suppose L; L 1 this is the length of the device here.

You are going to; you know when you have a large field here, so the band diagram will look like this. So, you have a fermi level. On the p side your; on the p side you will have a very high doping. So, you know this is conduction band, the valence band will almost here because is very highly doped. All the depletion will extend on the n side like this, right all the depletion will extend on the n side so, this is the depletion region [FL], is the depletion region and that you know from your depletion your p-n junction classes. The p-type is very highly doped, so the depletion is almost negligible.

Now, whenever an electron falls here it gets swept away this side and whenever a hole gets here it will be swept away this side when photons are coming this way, ok, photons are coming that way. So, the photons that are reaching here will eventually lead to a we will assume that the whole junction is uniformly eliminated; that means, all the photons are coming this way, so there will be gradually absorb more here less will be absorbed on the other side.

But we will assume that all this depletion region is uniformly eliminated and the photon generation rate is suppose Gop, that is the number of photons falling per centimetre cube per second, ok. Number of photons per centimetre it can be 10 to the power 17, 10 to the power 18 whatever depends on the sunlight, right. So, it is a number of photons per centimetre cube per volume per second that is the optical generation rate in this particular depletion region here, ok.

So, we can because we are only talking about you know p plus n minus junction we do not have to worry about the minority injection to the p side of course, we are only talking about the electrons that are swept away to the n side and the holes that are swept out the p side. Now, if you recall you just assume that of this is a p-n junction of course, the p side is highly doped, but we can recall the p-n junction you know the continuity equation, we will continuity equation. So, let us do one thing.

Let us assume that for the time being we will not say that the solar cell is not biased, it gets self biased to the forward voltage that is different but we will assume that this is just a p-n junction that is biased to some voltage, ok. It may be forward bias, it may be reverse bias, it may be unbiased it can be anything, but I am just saying that there is a voltage here developing across the junction which is V j, this junction, ok.

So, we just have to solve the continuity equation for a p-n junction if this you remember very well. So, if you look into this then you know if the continuity equations for holes injected to the n side. If you actually if you forward bias this junction for example, if you forward bias this junction then holes will be injected this side and electrons will be injected this side.

Do not worry about the light falling here now, I mean they that will fall of course, but you assume that this is forward bias, you assume that this is forward bias. In reality a solar cell is not biased, it will self bias itself depending on the load and it will self bias itself for in the forward direction only. So, we are assuming that electrons are injected this side and holes are injected this side, ok.

In that case you this electron component going to the other side is negligible because this is highly doped the p side is very highly doped. If something is very highly doped only the carriers from the highly doped region to the lightly doped region matters, ok; that means, your electrons coming from this side to this side does not matter because it is highly doped. So, only holes going from here to there matter. You remember this equation. You remember the reason why I am telling you? That comes from the p-n junction ideal diode equation you will see that because of this high doping the electron current coming from this side to this side is negligibly small, ok.

So, anyway so, I can only talk about holes that are injected from the; I will only talk about holes because that is because it is highly doped injected from p plus region to n minus region. So, I can write only the excess holes that are injected, excess holes that are injected here, right, excess holes that are injected. In reality of course, the current will be opposite to this, because the solar cell you know will be shining light on that and so on and so forth. I will just say that this holes are injected; so I can write the holes are minority here. When the holes come here, they are minority they are injected, they are injected here, holes are injected here, the holes become minority here.

So, I can talk about the whole diffusion length in the n-type region into d square by excess hole by d x square then minus del p by tau. This is your excess holes that is decaying at a lifetime of tau plus the optical generation, right that is happening is equal to 0. This is your continuity equation and the ended boundary condition is there at the edge of this, depletion at the depletion edge here which is your 0. I am talking about this as 0, this as 0. At the edge of the depletion you remember.

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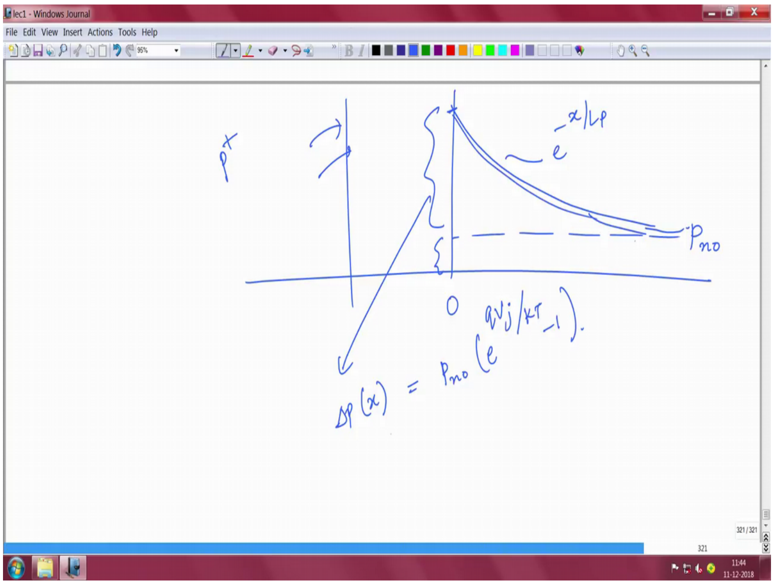

Let me draw the p-n junction in a profile again. If you remember if this is your depletion edge on the n side then your axis and this is your baseline minority holes p n 0. Remember, this is your n-type region. So, in this n-type region your holes will be minority, your holes are minority and the concentration is given by p n 0 its l a holes on the n side which is 0 which is equal to n i square by the doping that you are giving there which is N D, right which is N D; the doping that n-type doping that you are giving. So, that is your that is your baseline hole concentration minority hole concentration.

This is your p plus region from where you are injecting holes. So, the holes will essentially decay like this if you remember, they will decay like this. So, there is an excess carrier of hole here delta p at x equal to 0, that excess carrier actually the baseline concentration that you have e to the power q V j the k the junction potential by k T minus 1. This is your essentially the excess hole carrier concentration. With that if you add this base line then you will get a total concentration here. Anyways, this decay happens it for a long diode it happens minus x by L p sort of thing, right.

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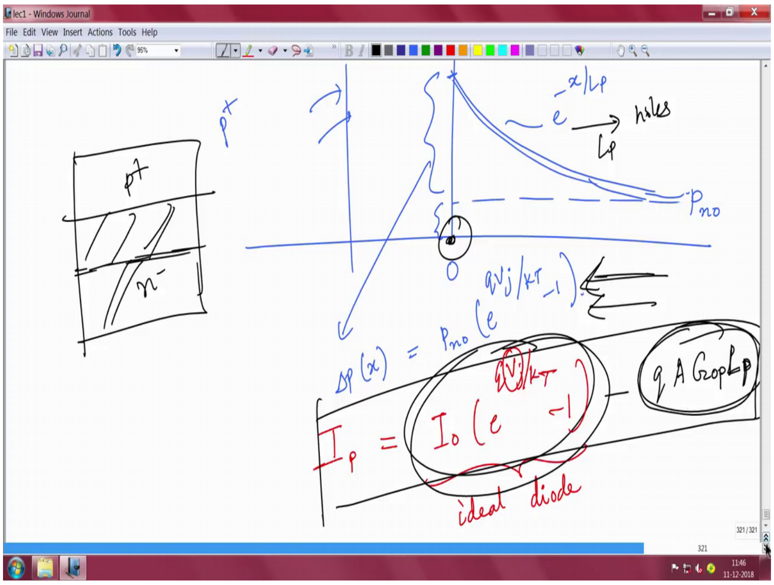

So, essentially based on this decay that is happening you can write down the diode equation, you have to solve this equation now. You have to in an idol diode equation you only this two terms, but now you also have an optical generation term. So, how you will solve with this equation and what do you will get as the solution; the solution will be say the current that is flowing.

The current that is flowing because of the holes getting injected from p plus will be like the I naught, e to the power q V j by k T minus 1, ok. This is the ideal diode equation whether it is a forward bias or a reverse bias does not matter. If you can put appropriate values for the junction value I either positive forward bias negative for reverse bias, this is the ideal diode equation. But the ideal diode equation you know the if it is a forward bias then it will go in one direction, right.

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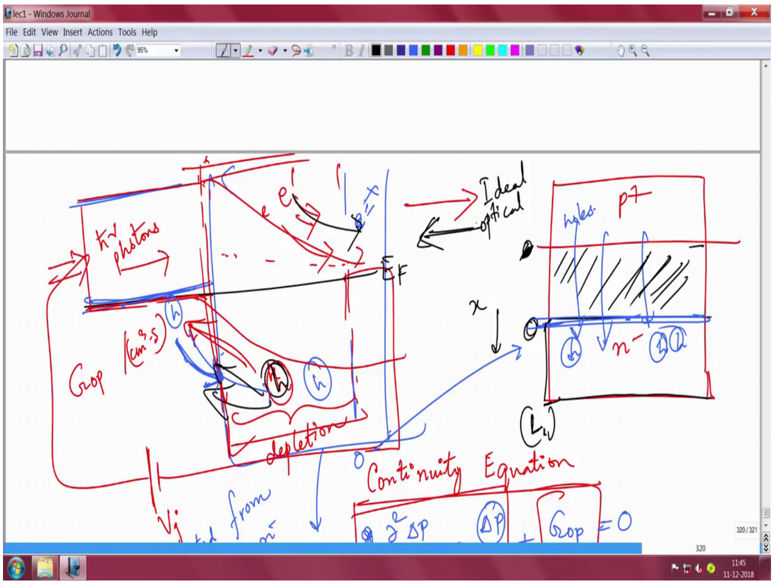

I told you it will it current will flow in the direction. But the optical generation of carrier is happening such that you know, I keep telling you that an electron that is generated here will be swept away this side and a hole that is generated here will be swept away this side. So, the direction of the current flow because this is the ideal diode equation current direction and optical generation you know because of the photons falling, electrons going this way and holes going that way the current is in this direction.

So, the current of the optical generation is opposite to the ideal diode equation. So, there will be another component here which is opposite to this and that is equal to your q area, the optical generation rate into L p; the diffusion length of holes in the n-type; remember, this L p represents the diffusion length of holes in the n-type. You remember that please do not forget the junction shape, this is p plus, this is n minus, this is depletion, this point at 0 corresponds to this boundary and, so they are decaying here. So, your; you know you have this kind of equation you will get. This is the total solar cell equation.

Now, if your solar cell is forward bias intentionally then this is your ideal diode equation that flows in this direction and this is your the optically generated current which flow flows in this direction. If your solar cell is biased in the negative direction, I am just telling a negative bias then this component and the ideal diode current also will flow in this direction, in which case the ideal diode current flowing in the opposite direction because its reverse saturation current will be in the same direction as the optically generated current. So, let us put things in perspective here, ok. Let us put things in perspective. Maybe you are getting little confused.

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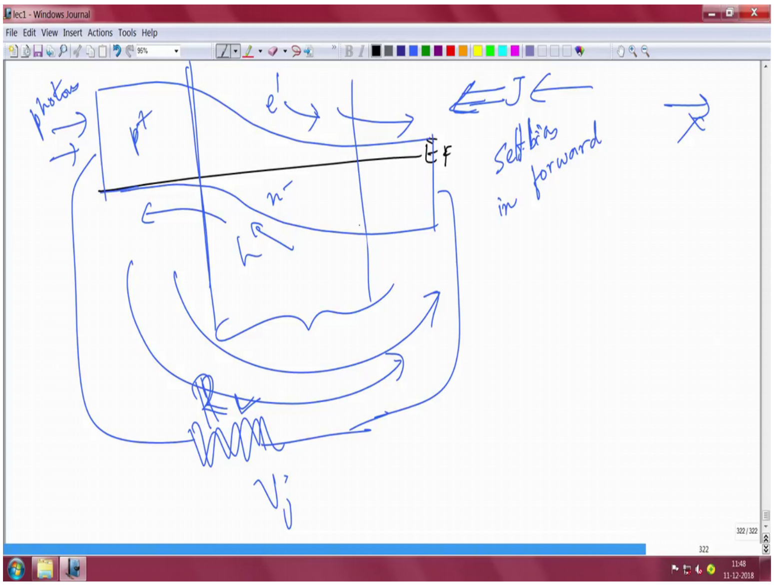

So, you have a solar cell here and this is a sorry this is a highly doped solar cell on the p side no. So, I will draw it fermi level here and you know what; this is like this is very highly doped. So, this you know all the depletion is on the n side only, this is a depletion on the n side, this p side is almost no depletion. This is p plus, this is n minus, all the depletion is on the n side.

So, we do not know what bias you are applying or what bias develops here some bias will be there V junction. But the photons that are falling, photos that are falling and generating electrons that are swept this way, holes that are swept that way results in a current which flows in this direction which is opposite to the ideal diode equation if the ideal diode is a forward bias thing, right.

Essentially, you do not; you never apply an intentional voltage in the solar cell, because solar cells are supposed to generate electricity. If you apply voltage externally then it there is no purpose of this. You distribute solar cells to this remote villages and poor people and other things, so that they can generate electricity from the sun light. If you tell them that you know what, you put the solar cell on your roof, but you also have to apply voltage to get electricity and there will be like you know boss we do not have electricity in our home how can we apply voltage there, right. So, the solar cell have to has solar cells have to generate electricity on their own. So, you cannot apply voltage. Please understand that.

You only have a load; you only have a load across which you can either solar cell. This load can be a television, your TV, your bulb, your radio, whatever you know your fan whatever air condition. This load will essentially; so, what will happen is that electrons will flow in this direction, holes will flow in this direction and the current will flow in this direction.

This flowing of the current in this direction will lead the solar cell to self bias itself, it will lead itself to self bias itself in the forward mode; self bias in forward direction. [FL] I mean a forward bias voltage will develop because a solar cell. Does not mean the current will be in the forward bias direction only. The net current will be actually in this direction only not in this direction, ok.

So, essentially what is happening is that you see my point, right. So, but in solution of this solar cell equation I am using it is just as standard p plus n junction, I am solving the equation I am getting this current expression, right.

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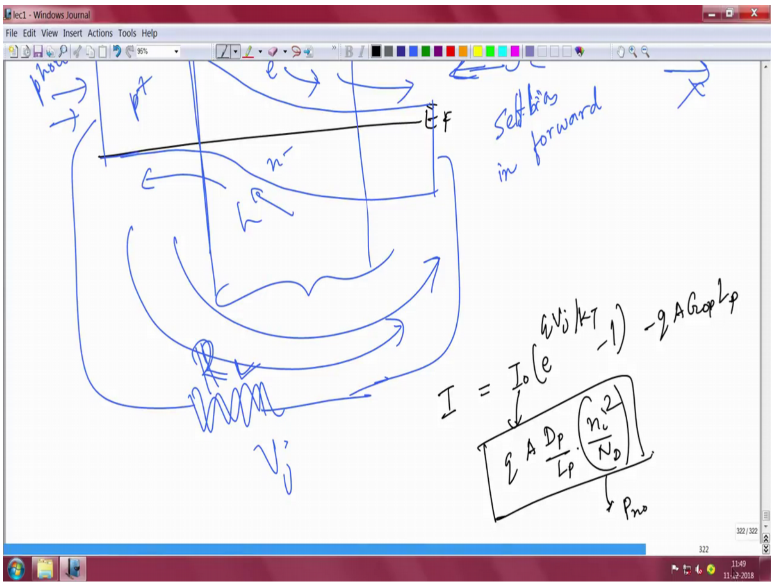

So, I am getting the total solar cell current expression as I equal to I naught e to the power q V this is junction potential that develops minus 1 minus q A the optical generation rate into L p [FL]. This I naught by the way was q A D p by L p into n i square by N D. This quantity is by the way the baseline hole concentration there, p naught the minority carrier concentration on the n side, right. So, this is your I naught, ok. Now, this is your I naught do not get confused here.

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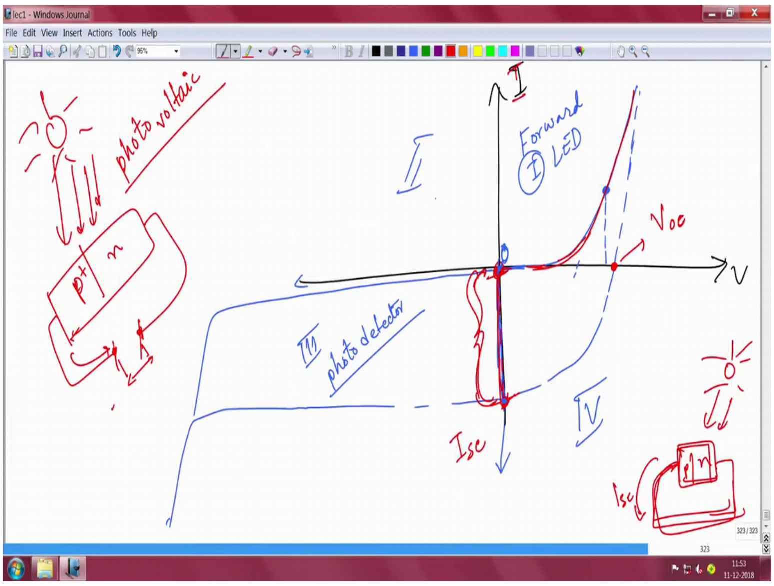

So, essentially you have your if you draw a I versus V for your ideal diode equation then it looks like something like this right. It turns sorry I am a bad drawing person. It turns on like that there is some turn on voltage here, on the reverse side there is very little current eventually it breaks down remember this, you remember this know.

Now, if I shine light what happens you know this curve actually shifts down. If I shine light this curve actually shifts down it will eventually break of course, at very high negative voltage, but this is your 0 voltage and 0 current, this point 0 comma 0 and your curve shifts down [FL]. You please observe this carefully, ok. So, this you know. So, the solar cell is operated in this quadrant. This is called the fourth quadrant. So, the solar cell is operated in this quadrant. I told you many classes before solar cell is operated in that quadrant, ok.

Your forward this is your pure forward bias without any light shining or whatever and this forward bias you know is quadrant 1, where LED is operated you have operate the LED somewhere here. So, that you get if you apply forward bias and you get light out, ok. In this quadrant there is nothing in the second quadrant. In the third quadrant you operate the p-n junction as a photo detector or photo sensor; we will come to that after this class of course, photo detector which almost like a solar cell only because you apply a reverse bias or you may not apply bias, but you typically apply reverse bias.

This is a solar cell. In solar cell you actually do not apply any bias. So, ideally at 0 voltage this is your 0 voltage, right. Please remember; please look at this carefully, this is a 0 voltage. But the load will make sure that you your solar cell becomes self bias in the forward direction, but the current will be negative; that means, you are supplying electricity to the load.

If it is in this regime; that means, you are applying a voltage you are getting current that is not your battery. Here you are in this fourth quadrant you will be actually is like a supplying electricity. So, you will at even 0 bias, at even 0 voltage on your device you get this much current. Do not you get this much current.

Even if you do not apply please listen this carefully, even if you do not apply any voltage on your solar cell just by shining light you get this much of electricity because the curve has shifted. This is called photovoltaic action; this is called photovoltaic action that you are getting electricity without applying any voltage that is a beautiful thing. This current that you are getting at 0 voltage without applying any electricity is called short circuit current, ok.

It is called short circuit current; that means, if you have a solar cell, if you have a solar cell I am talking about the p-n junction and you are connecting it is shorting it you are just shorting it without any load no load is there and you are shining light, sunlight then you will get some electricity know that electricity is called short circuit current. No load is there you; please remember there is no load.

You are short circuiting a p-n junction, please remember. You have a p or p plus n maybe, you are short circuiting it with a wire no load is there and the sun is shining. Then you will generate some electricity that electricity is called short circuit current that is this quantity.

And if you instead of short circuiting if you keep it open; that means, you do not you just keep it open there is no electricity flowing there, then if there is no electricity flowing there if you measure the potential here between these two points between the p-n junction. Now, you are shining light what is the potential that is developing you are not allowing them any electricity to flow by the way you are just measuring what is the potential. If you do not apply any; if you do not let the electricity flow by opening it connecting this making the circuit open then your current will be 0, 0 current is this point the light shining, right. 0 current is this point. Please remember this is your I on the y axis; so this is a 0 current.

So, at 0 current what is the voltage that you are measuring when you are shining light. This point is called the open circuit voltage; this point is called the open circuit voltage. We solve the continuity equation before this. This continuity equation will be used by the way this, ok. This continuity equation will be used to find out open circuit voltage and a short circuit current.

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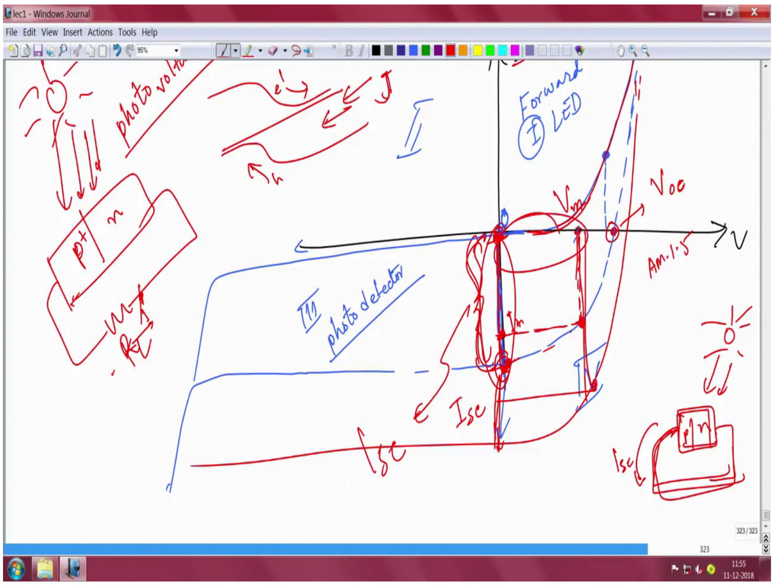

So, please remember that you are having an open circuit voltage when you are not keeping the circuit close; [FL] the circuit is open. So, this is the voltage that you are measuring across the p-n junction when you are shining light. If you short them no load is there then your current will be this at 0 voltage you are getting this much current, this is the quantity which is called the short circuit current.

But in a real solar cell because you will have a load in a real solar cell, you will have a load. So, your point will be neither here nor here, what you happen is that your point will be somewhere here. The load will define your point operating point and so you will operate at some volt your device your solar cell gets operated some voltage say V m I will call it and some current will give this point I will call say I m. So, you know your solar cell will operate at this point, ok.

So, you are going to actually get in the fourth quadrant where the solar cell has become forward bias itself because of the load. It gives you a negative electricity which means electricity is actually you know if you look at the p-n junction; although it becomes self biased your electrons will flow here holes will flow that side, that is the dominant current in this direction this J. This current in this negative direction because of this shining light make sure that your total current is negative here, ok. It is dominating director, but the device is self bias in the forward direction [FL].

So, this is your solar cell actually and of course, if you increase the intensity of the light suppose you go this is your suppose AM 0, this is you are a AM, AM 1.5 [FL] the evening. If you go to AM 0 outside the atmosphere you will probably get a higher current like this. Then you will be able to get even higher you know current higher voltage higher voltage higher current probably, ok. So, it depends on the intensity of the light of course, this is the thing.

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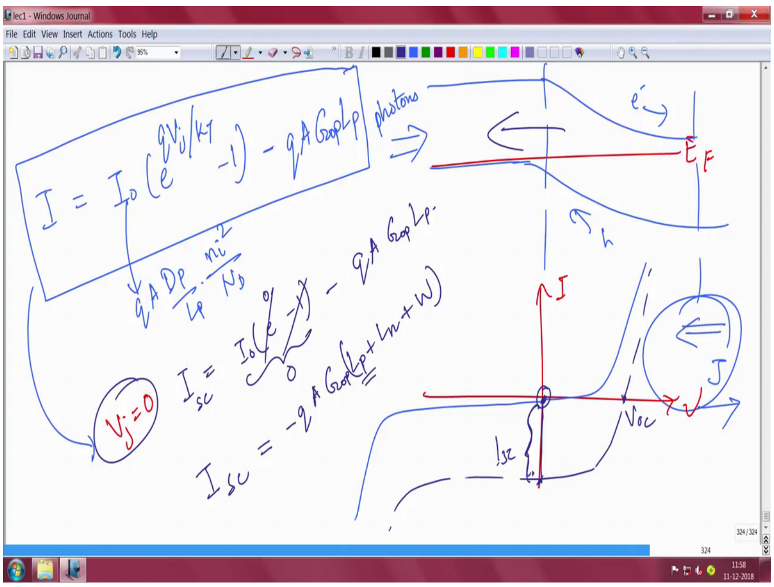

Now, this is a short circuit current, now this is the open circuit voltage that you know very well. Now, let us look at this expression for the total current in a solar cell. I will keep drawing the sum the band diagram; so as to make sure that this is your p very highly doped p-type p plus mildly doped n-type. So, all the depletion is on this side, ok.

Light is shining from the top this is the photons, ok. So, that is your photon that is absorbed electron is swept to this side, hole is swept to this side, total current the solar cell current is in this direction. Of course, the device will get solve forward bias. So, a small current will be in this direction, but the net current is in the other direction. So, the solution to this if you remember was I is equal to I naught e to the power q V j by k T minus 1, minus q A area, the optical generation rate into the diffusion length of holes, ok. And this I naught of course, is equal to q A D p by L p into n i square by N D, ok.

Now, in this expression if u set V j equal to 0 which means the what is the what does V j equal to 0 means. V j equal to 0 means that I will draw also the I V here, you know this is your I, this is your V, your I V looks like that. When you shine light then your I V looks like this, right your I V shifts. Those this is a short circuit current where the voltage is 0 and this is your open circuit voltage and the current is 0. So, if you set V g equal to V j equal to 0; that means, this you are putting this your putting this point where the voltage is 0, then you should be able to get the current as short circuit current. You agree?

So, if you put that then I will be equal to I naught e to the power 0 minus 1, which is 0 minus q A Gop L p. So, it means your short circuit current this is a short circuit current now because you know the applied voltage is 0. So, your short circuit current is actually minus. The negative means that a current is flowing in this direction, ok, q A Gop L p. Of course, if you have a p and n both are sort of equally doped or if you have a proper p-n junction, this is p plus n by the way. If this properly thing then it will be Gop sorry, then it will be Gop L p, L p plus L n plus the depletion width come actually also, ok.

Depletion width will always come by the way, depletion width will come, but typically the diffusion length is more than depletion width so you can you know assume to be disc if is the case. So, this is your short circuit current.

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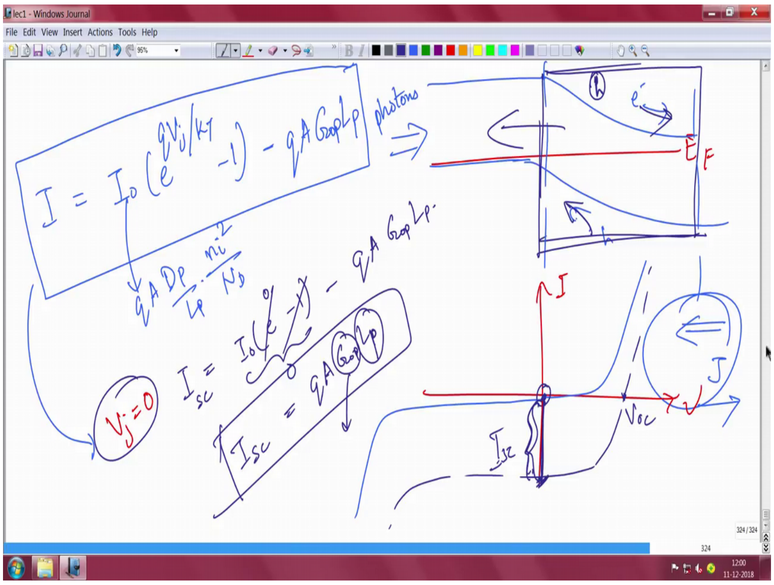

So, let us concentrate on this single junction only I mean the p plus n junction. So, in a way you are able to get the short circuit current of q the magnitude is q A Gop L p. So, what does it mean? You will see that the efficiency and the power output from a solar cell is higher if your short circuit current is higher of course, right that make sense the short circuit current.

So, the short circuit current is higher when you are optical generation rate is high, but sunlight is sunlight, you cannot you know increase the sunlight arbitrarily sunlight is sunlight. If you have a cloud in the sky or if you have dust particles accumulating on your solar cell, if we have rain and all this thing; then your optical generation rate will come down because the sunlight is not reach your solar cell so well.

Or maybe you are putting on the roof and a bird has dropped pottie that is also happens bird crap is also there all the time, ok. Then your optical generation rate will be low. So, your short circuit current will come down, your efficiency also will come down that is a real practical problem by the way, ok.

And you want the diffusion length to be large like. This the diffusion length is in the holes will diffuse know, ok so, the diffusion length which has to be large; the diffusion length of holes in the n-type. In other words, you know holes will go this way, electrons will go that way, but it is a p plus n junction only. So, anyways so, holes have to defuse longer and you will basically need a material with high crystalline quality or you know, if you have a poor quality than your diffusion length also will becomes short and your short circuit current also will come down, ok.

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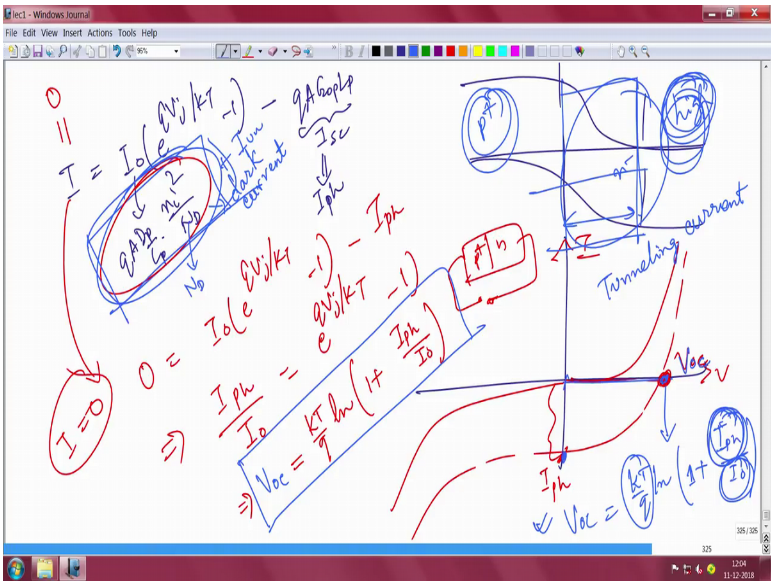

Next is you again come to this equation only, ok; you come to this equation only I equal to I naught e to the power q V j by k T minus 1 minus q A Gop L p. Now, you know the this is your short circuit current by the way or you can the short circuit current also you can call the photo current, I photo because when photons fall that current comes there, right and this I naught by the way is q A D p by L p. I keep writing this all the time and I square by N D, doping on the N D side, not the p side. And I keep drawing this diagram, so that you know it become becomes it becomes embedded in your mind, ok. This is a solar cell that have power you will get this kind of thing, right.

So, this is your short circuit current of photo current and this is your open circuit voltage. To get open circuit voltage this is your I this is your V. So, it get open circuit voltage in this session you have to set the total current to be 0, because that is the open circuit voltage. Like the solar cell that you have p plus n it keeps it is its kept open it is kept open. No current is flowing which is this point please remember that, so you will keep this I equal to 0. So, that they can this you know that is the voltage at which the junction will become the open circuit voltage will be obtained.

So, that is 0 equal to I naught e to the power q V j by k T minus 1 minus q A Gop by L p. I can say this is the photo current or short circuit current whatever you say, I photo or I short circuit. So, if you do that then I photo current or I short circuit current by the I 0 reverse saturation current equal to e to the power q V j by k T minus 1. So, I can write V j the junction potential that is developed is k T by q log natural log of 1 plus I photon or I short circuit by I 0, ok. This is your open circuit voltage actually. This is call open circuit voltage, ok. This is your open circuit voltage.

So, this voltage actually k T by q log of natural log of 1 plus I photo plus I naught, I photo plus I naught. This reverse saturation current also you can call the dark current or the leakage current because that is your reverse saturation current that is also in the absence of light you have that leakage. So, you see for a higher efficiency solar cell of getting higher power, you also want that your open circuit voltage is high; this open circuit voltage is high, short circuit current also should be high, both of them should be high only then you will get more power and more efficiency one cannot be high and other will be low that will make no sense.

So, for the open this is open circuit voltage; so for the open circuit voltage to be high what k T by q you cannot change that is 26 milli electron volt constant. What you have to do is that your photo current has to be high which means if your photo current is high your open circuit voltage also will become better. But you cannot control the open circuit voltage the short circuit current so much, it depends on sunlight and other things this dark current or this I naught has to be low which means this quantity has to be low.

For that quantity to be low if that quantity is low then your open circuit voltage will be high. For that quantity to be low your N D can be high which means the doping on this side also can be high, but doping this side is already very high this side I said light doping, but if you give higher doping on this side also not very high but high then you are going to get lower dark current and that will improve the open circuit voltage, ok.

That will increase the open circuit voltage, but that is not always true because if you dope it high there are two problem, [FL] problem is that if you dope it high this is also high then your depletion region will be narrow. So, the number of photons absorbed will be small and so you loose out the power. The number of photons absorbed will be low, you will loose out the power.

Secondly, if you dope this region also high this is already high then the depletion will become narrow and there will be tunnelling current for high doping. Tunnelling current is like a leakage current that happens because of electrons and holes tunnelling from one band to another band that will extremely increase the leakage current. That means, the dark current this quantity; this quantity will not be only this quantity; there will be another tunnelling current, that tunnelling current will be huge and that will make your solar cell efficiency go very very low because the leakage the leakage or a dark current will be not only this reverse saturation current, but also tunnelling current.

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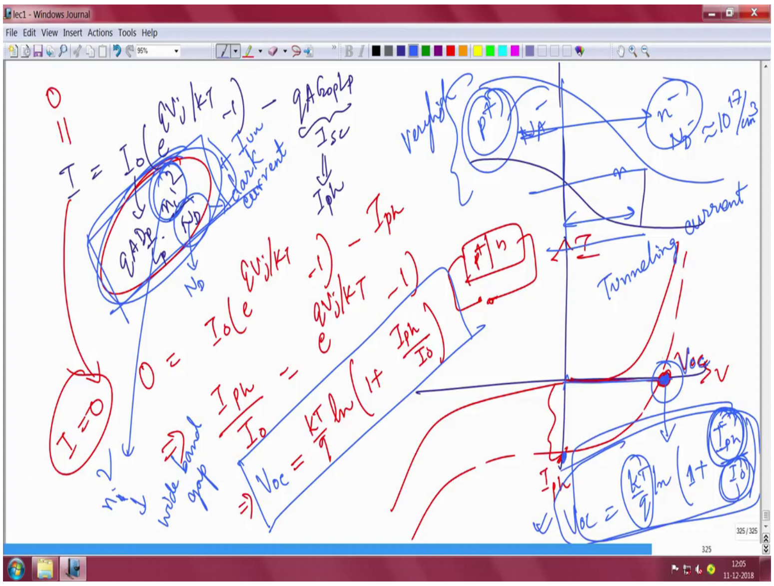

And that tunnelling current will happen if your this side is also doped high, if your this side is also doped very high, this side is also dope very high in that case your tunnelling current will dominate and your solar cell will not work or it will be very low. Because the short circuit current this open this leakage current will suit up. That is why you cannot dope this n minus region very high [FL] this two this. So, you cannot arbitrarily increases this quantity the open circuit voltage, ok.

Typically, for silicon solar cell the doping on this side will be around say 10 to the power 17 per centimetre cube, above that you will have problem, ok. This is very heavily doped, ok; this is very highly doped. One of the ways to actually you know reduce sorry increase the open circuit voltage is that this n i square can be reduced. This n i square can be reduced if you have a wide band gap material.

You see if you have a wide band gap material like gallium nitride or something if you have a wide band gap material then your n i will be very very low. If your n i is very very low then you do not worry about N D this can be lightly doped not a problem. If n i is very low then your shot this quantity open circuit voltage will be very high, but there is a problem. What is the problem do you know?

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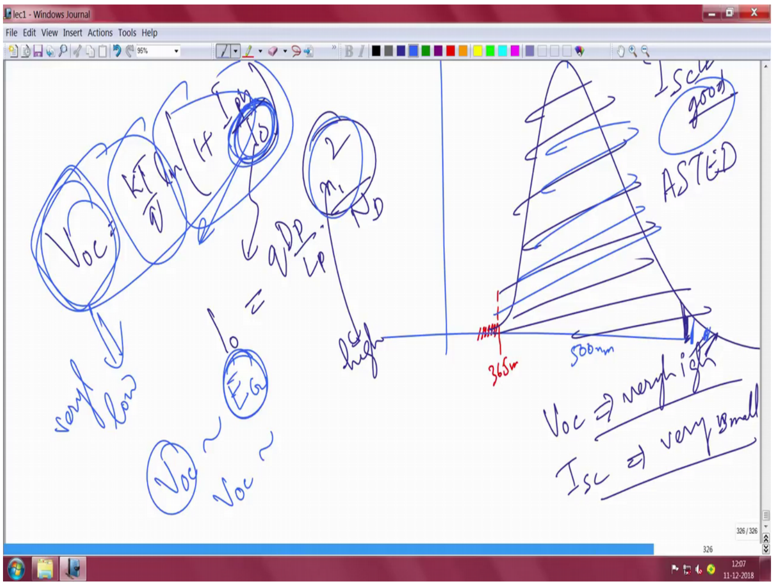

If your, this is a solar spectra if you remember. This is your 500 nanometre. If you have using a wideband gap material like gallium nitride whose band gap corresponds to around 365 nanometre then it will absorb only this much light, band gap is high no. So, what will happen is there all this area is wasted, wasted.

What is the point then? You are getting a very high open circuit voltage, very high, but you are wasting all the spectra. What will what does it mean? It means your short circuit current will be very small. So, you cannot do that; there is a problem, right. But if you do a very small band gap material if you do a very small band gap material for example, you do a very small band gap material here, so that I absorb everything.

So, then your short circuit current will be very high nice, very nice, very good short circuit current. But the problem is that your open circuit voltage if you look into expression of open circuit voltage it goes as k T by q L n of 1 plus I photon by I dot you know I naught. This I naught I told you q D p by L p n i square by N D. If you use a very small band gap material this n i is very high.

If this n i is very high, then your this quantity is very high this quantity is very high which means your open circuit voltage will be low quite low, very low. In other words, if you go for a small band gap material you will get, but better IC, but your open circuit voltage will come down because your dark current will become very high because of a smaller n i. If the dark current becomes very high this quantity will become very low this quantity this quantity will become very low.

In other words open circuit voltage is loosely proportional to the band gap. If you are using a small band gap material know your IC will be very good, but your open circuit voltage will be terrible if you are using a wide band gap material, then your open circuit voltage because the band gap is large you will get very high open circuit voltage, but you will waste the entire solar spectra solar, so your short circuit current will be low. So, that is the trade off you have to do, ok. You cannot arbitrarily have a very wide bad gap of very low band gap that is the trade off we have to do.

So, let us wrap the class here. We have discussed about solar cell and we will end the class here, so that you know you can go back and you can revise what you have learned. We have done the continuity equation and I told you how the I V looks like of a solar cell when you are shining light. The concept of open circuit voltage and short circuit current we have discussed. From the solution of the continuity equation I gave you the expression for short circuit current and the open circuit voltage I told you that both short circuit current and open circuit voltage needs to be high, then you will be able to get better electricity output, better efficiency better power out, ok.

There is always a load on the solar cell that will make sure the solar cell gets forward biased. Your photons that are shining will generate electricity that is in the direction opposite to the conventional forward bias diode, ok. So, those are the things that you have learnt. We will have one more lecture on solar cell that I will discuss about the limits of these efficiency introduce you know Shockley Queisser Limit, and field factor and efficiency, and discuss some practical problems and other things, ok. So, that will be discussed in the next class and we will wrap up solar cells.

So, thank you for your time.