Fundamentals of Semiconductor Devices

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Lecture - 46

Solar cell: Shockley Quiesser Limit

Welcome back so today we will conclude the concept or the discussion on solar cell, if you remember in the last class we had introduced the lot of new concepts on solar cell like short circuit current, open circuit voltage how the different band gap semiconductors will have different advantage and disadvantages. We have discussed the I V characteristics of a pn junction in the presence of light illumination, solved the continuity equation and use their solution of the equation to derive open circuit voltage and a short circuit current.

I told you that your open circuit voltage and short circuit current both have to be high in order for the solar cell to be efficient and deliver more power, but there is a limit of course on everything you can have arbitrarily have very high values there. Diffusion lengths and minority carrier lifetimes all these are very important concept in solar cell they should ideally be very high. And I told you the top layer has to be thin, so that you observe minimum photons which are you wasted in the useless; in the neutral region you do not contribute to electricity, you want the photons to be absorbed in the depletion region only, so the top layer is highly doped bottom layer is slightly doped.

We also found that the bottom layer should be ideally little higher doped so that the you know the short circuit current or the open circuit voltage improves. But the problem is you cannot drop the dope with very high because the tunneling will increase that is another thing. So, I told you there was a trade off you cannot have an arbitrarily highest band gap semiconductor or an arbitrarily lower band gap semiconductor, there is a trade off between the open circuit voltage and the short circuit current, so you have to get the optimum band gap [FL].

So, today we shall derive that limit and also discuss a few things on how to improve the efficiency of the solar cell what is fill factor and so on and so forth, so let us come to the white board.

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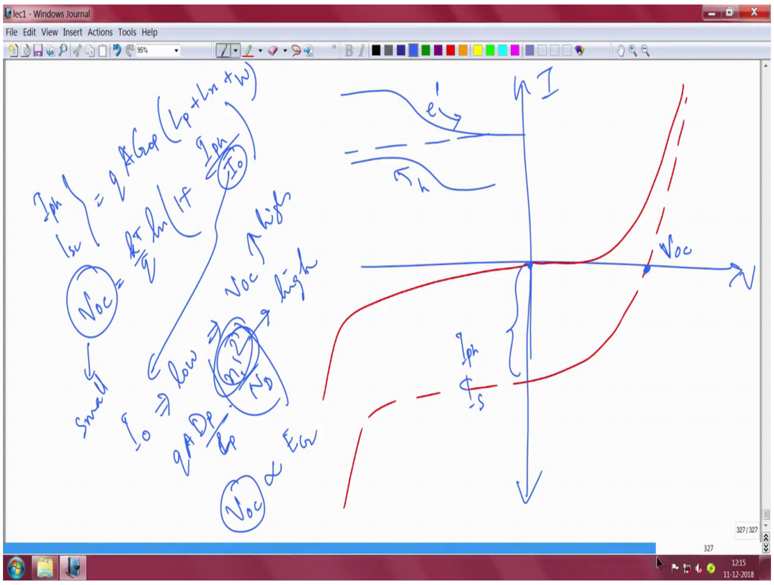

So, in the last class if you recall I told you there are two important things I will again keep drawing the IV characteristics so that is embedded in your mind. So, this is your ideal characteristics here in presence of light this becomes like this, of course this is your I this is your V, this quantity is your photo current or you can call it short circuit current that quantity photo current or short circuit current whatever you say you know it has given by q A; the optical generation rate typically it will be given by the diffusion length of electron, diffusion length of holes plus the depletion width.

Because you have a solar cell here all the electrons that are going has to be so this way holes that have to say that way, And then you have a open circuit voltage here, that open circuit voltage also is a very important parameter; open circuit voltage goes as k T by q log of 1 plus I photon by I dot short circuit by I dot, this I dot has to be low it has to be low in order for the open circuit voltage to be high and this I naught depends on q A Dp Lp into ni square by ND.

So, one thing is that if you use a white band gap material your ni square will be low that is why your dark current will be low, your open circuit voltage will be very high. But there is a problem I told you white band gap material will absorb only small fraction of the sun light maximum portion of the sunlight will be not observed and will be wasted so that is a bad thing. If you use a short band gap material we will absorb all the sunlight, but the problem is that your ni squared this quantity will be very high, first small band gap material this quantity is very high it means open circuit voltage will be very small. In typical open circuit voltage goes proportional to the band gap of the material, if your band gap is high; open circuit voltage will be high but you will waste most of the solar spectra.

Similarly if you use a lower band gap material you are going to get very high short circuit current, but lower band gap means your open circuit voltage will be low. So, there is a trade off, there is a severe trade off that you have to actually live with; you cannot do much about it. So, let us come to that thing again I know in context of this I will tell you in this context I will tell you what you have to do.

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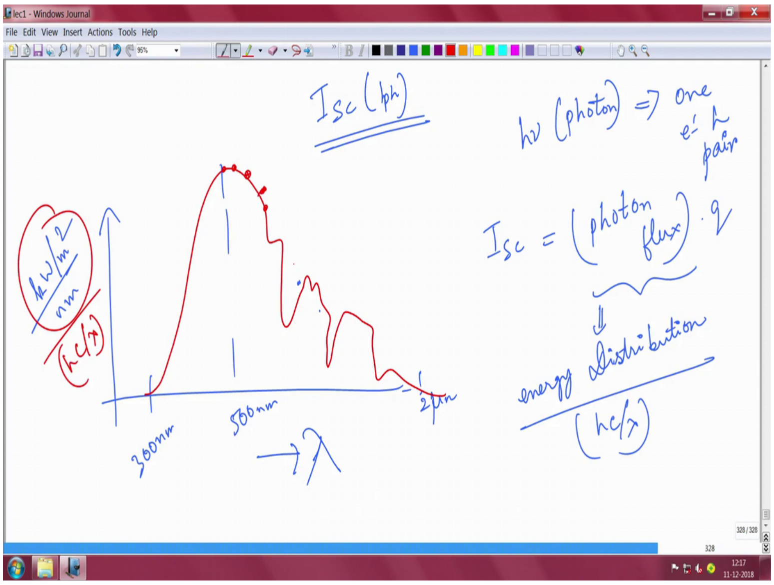

So, you know if you look realistically the short circuit current or the photocurrent whatever you say; essentially from to get an idea of how the short circuit current behaves with respect to photon flux and all. You know one photon h nu one photon ideal case is that it should give you one electron hole pair you agree? One photon should be able to give you one electron hole pair in the best case scenario which means your short circuit current or your photo current will depend on the photon flux, photon flux times the charge of electron which is q 1.6 minus 19 coulomb. Photon flux actually is how many photons are there per unit wavelength of the solar spectra [FL].

So, essentially photon flux is your energy distribution of the sunlight which is your energy spectra that we keep talking about energy distribution of sunlight divided by the energy of each photon which is h c by lamda; lamda keep changing right.

So, if you recall you had your energy; the energy of the sunlight in kilowatt per meter square per nanometer. So, it looks something like this right this is around 2 micron the peak is around 500 nanometer, this is around 300 nanometer right this is around 300 nanometer now at this is wavelength; this is wavelength.

So, at different wavelengths you have different power here this is of course not AM-1 this is AM-0 outside the atmosphere. Inside the atmosphere of course you will have a different spectra; you will have a spectra like some absorption will happen right like that because some water vapour and other things will absorb any ways that is you can take the real.

So, if you divide this quantity by h c by lambda which means the energy at each point energy at this point, energy at this point; this point this point energy at each point if you divide that is hc by lambda is different at this each point; then and h c by lambda is joule by the way.

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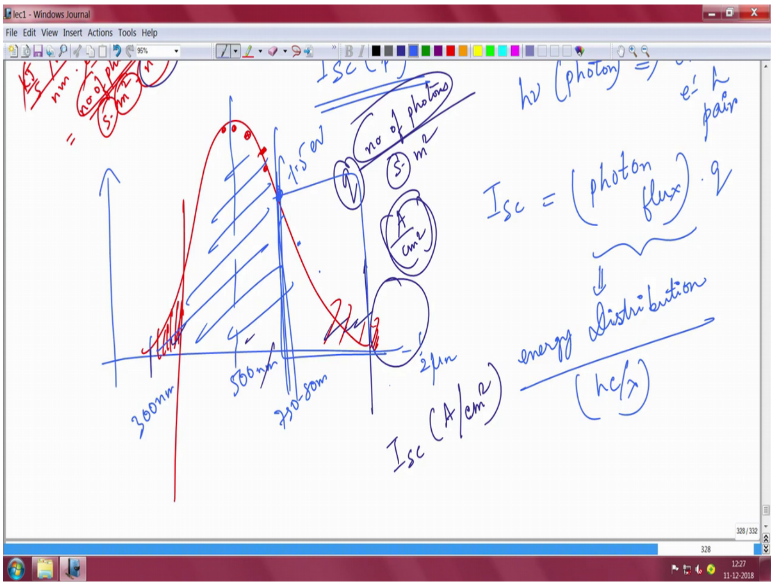

So if you derive kilowatt per meter square per nanometer, if you divided it by Joule what will happen kilowatt is nothing but kilowatt is nothing but kilo Joule per second. So, what will happen is that you will get number of photons unit will be number of photons per second per second per meter square per nanometer for each nanometer right, because your Joule, Joule will cancel.

So, this is your photon flux number of photons number of photons per second per centimeter square per nanometer. So, if you integrate this over if you integrate this over a band gap suppose I take a band gap which is suppose this I take this band gap which means I observe everything here I do not observe everything above that. So, then I can integrate this area so that this nanometer can goes away because, you are integrating with respect to nanometer here; you will get number of photons per second per unit area you.

If you integrate this part and then you multiply the charge of electron you will get coulomb this is coulomb per second that is ampere, you will get ampere per centimeter square number of photons will give you that thing the number of electrons holes one; one electron pair hole from one photon best case. So, you will get current; you will get the short circuit current in amp per centimeter square amp per meter square that is what you do.

So, if you do that then if you take a white band gap material than your you know here for example, then only absorb this. If you take a narrow band gap material like the band gap is here then we absorb everything here you do not absorb this you can do that ok.

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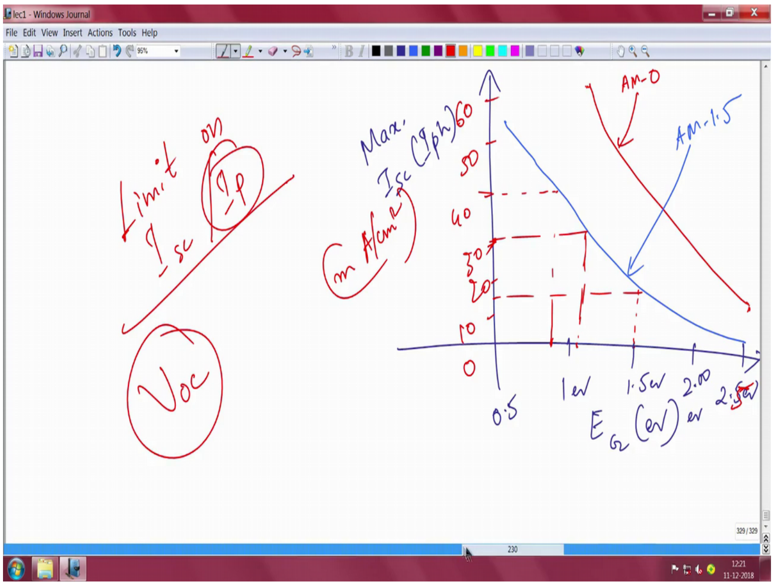

So, you can do the integration and find out the current, what you can do is that you can then plot the maximum short circuit current out of photo current that you can get from the photon flux of the sun as a function of energy of the band gap of the material, because this is 0 for example, of course 0 means nothing else 0.5 ev and this is suppose 2.5 ev.

So, this is 1 ev this is 1.5 ev, this is 2.0 ev right so this is the thing, so if I look at A M-0 elimination which means outside the atmosphere; it will become something like this. Over to higher band gap your short circuit current will decrease that I told you qualitatively, that smaller band gap you see that smaller band gap; you are going to absorb everything no so you are going to get more short circuit current.

At wider band gap material if the band gap you know this is your spectra, if your band gap is here you will only observe this much. So, the short circuit current will be low, so that is what it means if your band gap is high like 2.5 ev; your short circuit current will also be low at lower band gap you will have large short circuit current. What is the axis here axis growth from 0 and this is your amp per centimeter square milli amp per centimeter square and you know up to 60 may be milli amp 50, 40, 30, 20, 10.

If you talk about AM-1.5 which means inside the atmosphere in the evening sort of thing then you will start from may be 50 and you will go back to may be less than 10 like this, this is AM this and this is AM-0.

So for example, if you use a band gap of silicon which is 1.1 ev; 1.1 ev we will probably get around maybe 30 milli amp per centimeter square, if you use germanium which is 0.7 may be you will get 40 milli amp per centimeter square. If you use you know gallium arsenide which is 1.4 you are going to get maybe 15 20 million amp per centimeter square.

So, your short circuit current will become better or higher if your band gap is lower [FL], so that much we know now what about this is the short circuit limit on the limit on the short circuit current right; this is the limit on the short circuit current or photocurrent. Now there is also limit on open circuit voltage and that will have a reverse impact on this with higher band gap material we will have a higher open circuit voltage.

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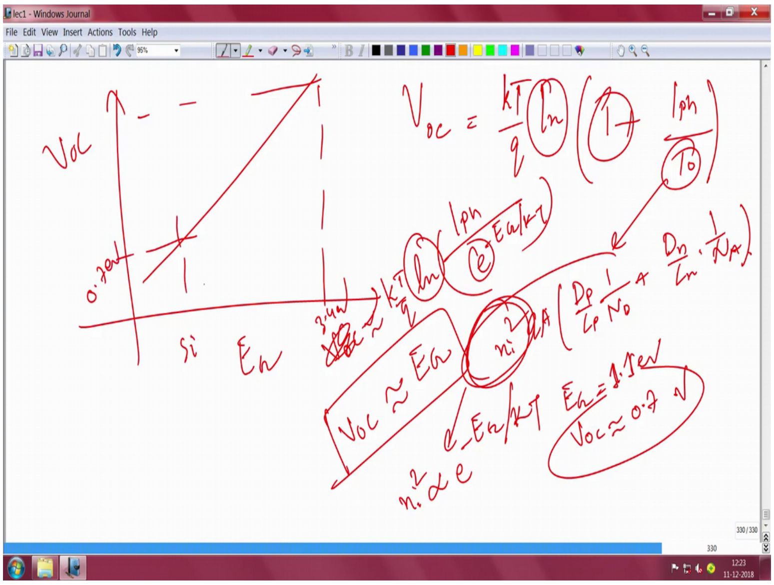

So, open circuit voltage is k T by q ln 1 plus I photocurrent by I dot current [FL] and if you take this I dot current you know q A if I take both n and p side then of course, Dp by Lp you know this will be ni square; 1 by ND plus Dn by Ln 1 by NA sort of thing right. Now for the best case silicon your band gap is around 1.1 ev, but not all the band gap will be converted to open circuit voltage; open circuit voltage will be typically around 0.7 0.8 volt only.

So, that is not a good thing but this is the limit when you cannot get more than that anyways this depends on the depends on the this factors as well as ni square; ni square is very important. So, that is why you need that is ni square this ni square is proportional to the e to the power minus E G by k T which means and this is ln by the way. So, it is like open circuit voltage is equal to k T by q ln if I ignore this 1, it will be like I photon by I dot, I dot depends on ni square and ni square depends on e to the power minus E G by k T.

So, this ln and e it will make sure that your open circuit voltage is loosely proportional to band gap that is why I keep telling you. So, you know you can say that open circuit voltage depends on the other parameters also here also it depends on you know the diffusion lines and other things, but with higher band gap this is your E G with higher band gap your open circuit voltage will slowly increase. So, if you have gallium nitride at 3.4 ev your open circuit voltage will be very high; if you use silicon then your open circuit voltage will be 0.7 Volt.

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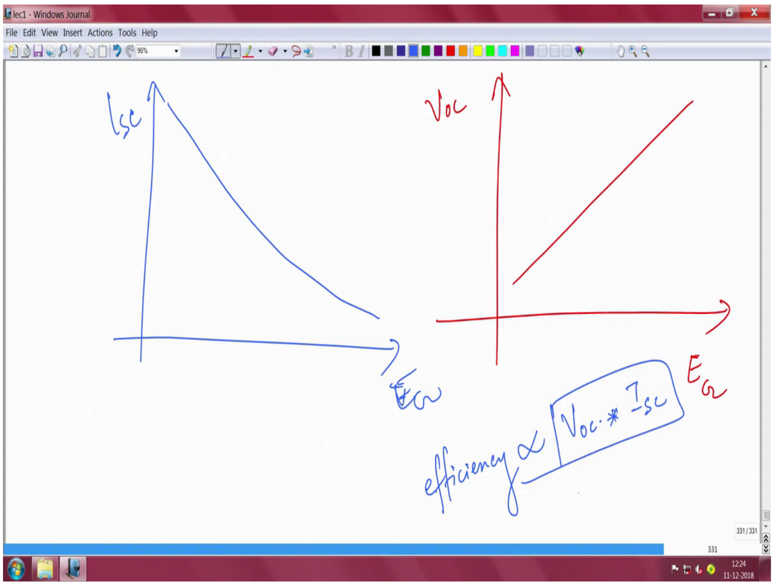

So, that is why now the problem is that, that is the problem; the problem is that your open circuit voltage and this is your band gap of the semiconductor what band gap will you use? Semiconductor conductor what band gap will be better? Open circuit voltage will go linearly as band gap and then you have short circuit current or the photo current; this is your band gap, your short circuit current comes down as with the band gap.

And you will see very soon that your efficiency of the solar cell in some way I will come to that efficiency of the solar cell is proportional to the open circuit voltage multiplied by short circuit current, there is the efficiency of the solar cell do you know why? That is how it is there actually [FL] I will come to that soon.

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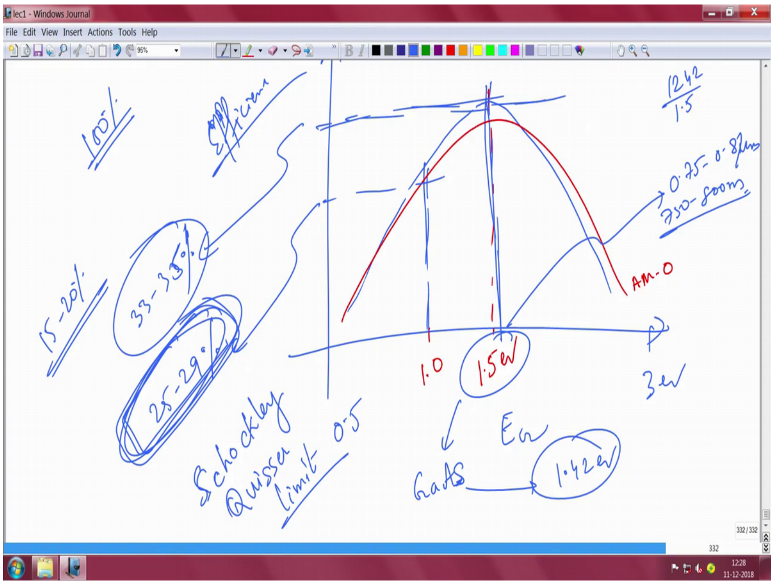

So, essentially when you do that optimal, your; you know optimal efficiency; your efficiency about the solar cell I have not defined efficiency, but I will define it very soon. Because your you know it with respect to band gap this is say 0.5, this is say 3 ev or something you know what one of them the current comes like this the voltage rise like this.

So, you mean the open circuit voltage. So, you now know how it will look like; it will look like something like this the efficiency and the peak efficiency will occur at a band gap of around 1.4, 1.5 electron volt. This is silicon by the way 1.0 and of course, this efficiency curve also will depend if this is AM-0, then your AM-1.5 will be different little bit it will be little different actually AM-1.5; although it will be low at the peak actually AM-1.5 it will be little higher for some reason let us not come to that.

Anyways the peak will be almost here and this efficiency that you get here this efficiency the maximum efficiency that you can get here is around 33 to 35 percent if I recall and silicon gives you around you know 25 to 29 percent.

So, silicon is not the best band gap, but it is not low either. Silicon gives you fairly high efficiency the best efficiency will come from around 1.5 ev and you know gallium arsenide 1.5 1.4 gallium arsenide has a band gap of 1.42 ev. So, that is almost optimal band gap to get the highest efficiency. So, highest efficiency solar cells can be made it by gallium arsenide based devices that is 35 percent, but the expensive also by the way 35 percent you can get single junction 33 35 percent and silicon will give you around 25, 29 percent best case which is not very bad so, it is still there.

About of course, solar cells will not have like100 percent 90 percent efficiency the best single junction solar cell or single material solar cell is only that much 33, 34 percent no more because your band gap condition come know because your band gap restriction comes that is why this happens there. And you know if you remember this of course, the peak of these at 1.5 ev will correspond to around I think lambda of how much? It will be around 1242 by you know 1.5. So, may be around 0.75 or 0.8 micron like 750 or 800 nanometer.

So, if you look at the solar spectra; where is a solar spectra? Solar spectra is here right; so this is solar spectra. So, maybe actually you know this is the peak at 500 but actually around 750 or 800 nanometer, you have this is the band this corresponds to by the way 1.5 electron volt your efficiency speak here.

So, this much you have to observe this will anyways reject because you know you cannot you have to trade off between the short circuit current and the open circuit voltage that is why that happens. So, this limit this limit that we have here is called the Schockley Quisser limit; Schockley Quisser limit so that limit put say in your this kind of condition. Commercial silicon solar cells will be probably 15 to 20 percent efficient; you actually get silicon solar cells that are very high efficient.

But many of the cheap solar cells that are very low cost 12-15 percent efficient amorphous solar cell, crystalline solar cell close the 20-22 percent probably not more so, much. Because this is the best solar cell efficiency people are already achieving I mean silicon just been demonstrated, but the commercial once you cannot the better efficiency you want to get the more costly it will become know, because it to refine the silicon and so, many things.

So, you know amorphous silicon solar cell 12 15 percent you know that is pretty good you get very cheap cost; so that is the thing. You cannot help of course, 100 percent efficiency you know there is an always entropy loss, there is a black body radiation loss and so, on and this is the band gap concept that is why this is the band gap concept puts this kind of restriction.

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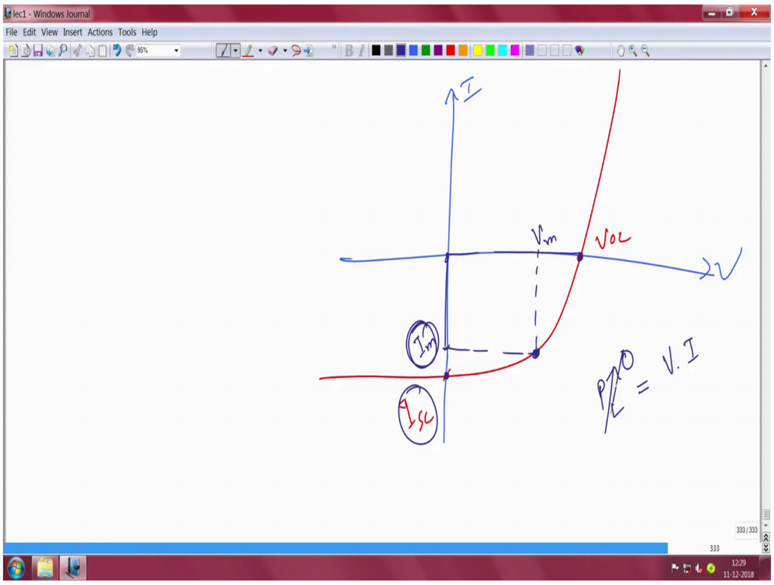

Now I have talked about efficiency, but let me talk about what is efficiency actually; although I have already talked about efficiency and also if you recall the I V characteristics again I will draw the I V characteristics I will draw the I V characteristics of only solar cell now I will not draw the pn junction normal I have it is a pn junction on the elimination.

So, it will look like this right. This is a open circuit voltage, this is your photo current or short circuit current. I told you whenever I connect the load then what happens is that, your load will self biased and it will make sure that it gets biased at some voltage here Vm and some current will come here I m. This is where you operate the solar cell, you are going to get not the entire short circuit current, you are going to get only I m current. You are not going to get entire voltage because if you operate at this point there will be no current in the device your power will be 0.

Power that you are delivering to the load power that you are delivering to the load is what voltage you are actually having in the solar cell junction times what is the current that is coming out. If you actually make sure that there is an open circuit voltage to get maximum voltage, your current will be 0, your current will be 0 your low your power is also will be 0. If you also operate the device such that you have all the short circuit current coming out, but the voltage is 0 at this point then also the power will be 0.

So, the power has to be optimum at some point the load has to be adjusted according to that. So, you are getting this.

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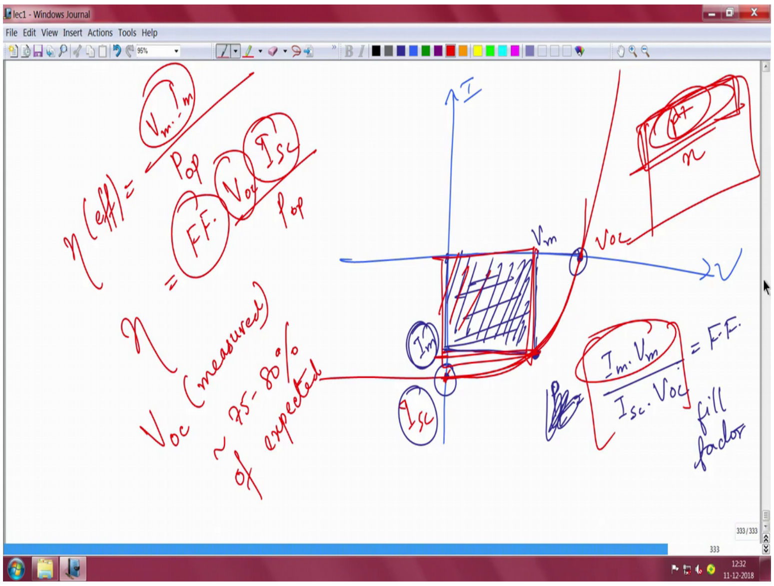

So, this square you see is actually the power that your delivering to the load; I m time V m that is your power that you are delivering to the load. And this power that how an you know this power this one divided by the product of I sc into V oc V oc this quantity multiplied by this quantity, this is called the fill factor FF.

This fill factor is a measure of how squared this profile is you know say this I V that is going how squared this is, this should be as squared as possible then only your fill factor will be better. And fill factor being high is very important for a better efficiency device also by the way; the fill factor is very important.

So, this is your fill factor you know that is the ratio of the power the delivering divided by V oc into I sc that is a fill factor. And efficiency is defined as what is the power your delivering to the load which is your power to the load which is your V m into I m divided by what is the input power from the sun; sun light is shining there know.

So, it is Vm I m can be written as fill factor times V oc into I sc by the optical power input from the sun. That is why efficiency is proportional to fill factor which means how squared this is sort of thing where your putting biasing here and also is proportional to the product of short circuit current then open circuit voltage just telling you that for higher efficiency solar cell for getting more power you need to have this kind of higher open circuit voltage, higher short circuit current also.

The technically speaking the open circuit voltage that you measure, the open circuit voltage that you actually measure actually get is around 75 to 80 percent of what you expect of what you expect. And that is because your solar cell has this sort of structure p plus n sort of thing because the top layer is very highly doped because is very highly doped your band gap at the top layer becomes slightly lower. The band gap becomes little lower, minority carrier concentration you know the minority carrier life time suffers (Refer Time: 21:07) recombination happen.

So, all these things makes your efficiency, your open circuit voltage goes slightly down like 80 percent of what is expected; because your top band gap becomes lower reduces because of extremely high doping.

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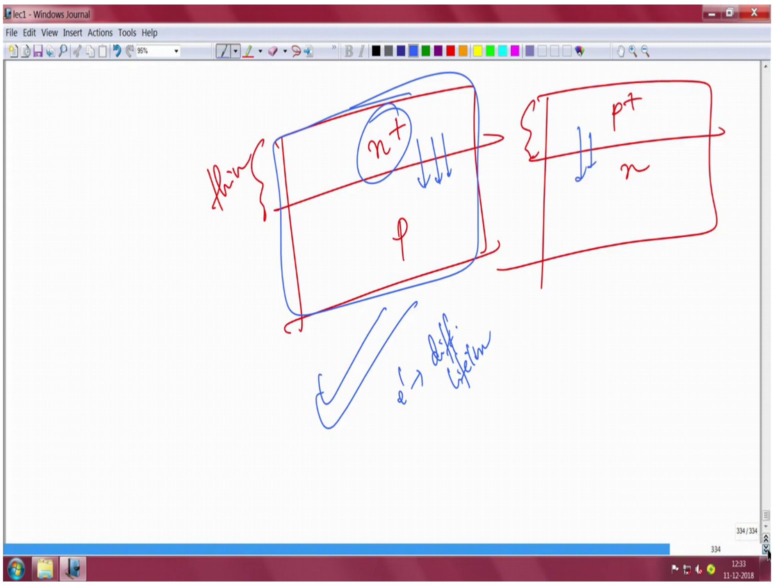

So that you should keep in mind. [FL] And between you know you can have either structure like this you can either have a structure like p plus and very thin p or you can have a structure like n plus p very thin n of course.

You can have either these two structures, but preferably this structure is better because you know electrons injected to the this side, electrons have a higher better diffusion length they have better diffusion length and carrier lifetime, then holes than holes. So, you can say that n plus will get better you know, electrons will have better properties because electrons are basically the carrier here so, much. So, electron n plus p is generally preferred than p plus n that is one thing.

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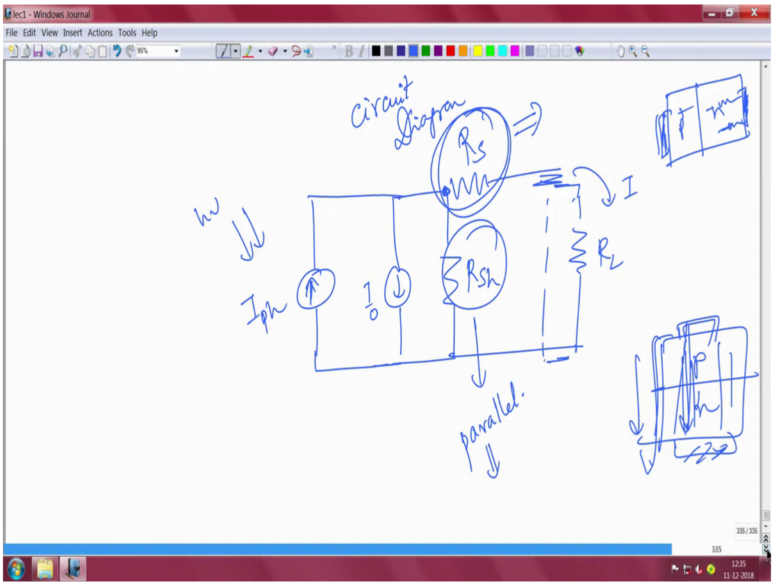

And how to increase efficiency of solar cells, but before that I will quickly draw you the; how; you cannot increase the solar cell efficiency of a single junctions anyways I will draw you the circuit diagram for solar cell just in case it is important. Essentially what happens is that a solar cell is like a battery. So, you have this current source which are called the I photo or whatever, this is your current source this you know when sunlight falls here, you get this current out right and this current is in the direction opposite to the ideal direct current.

So, I will keep that is I naught this is the ideal direct current and you eventually have a load here on which you basically deliver current and you are developing the voltage across this load. But the problem is that there are two parasitic resistances; one is a series resistance, call R S series resistance and one is called shunt resistance shunt resistance. These are parasitc resistances or unwanted resistances that are there in the solar cell which affect your performance. This series resistance comes because of series resistance that in the circuit.

So, essentially in a pn junction this represents the voltage that is dropping across the neutralism. So, you have like p plus n. So, this neutral region has a voltage know, this contact has a voltage this contact has a volt I mean resistance, resistance this contact has a resistance also in a pn junction the neutral legion; we have some resistance all these are these are [FL] these are affecting the device.

So, those are series resistance; you should not want a device or highest resistance because you will be dropping unnecessary voltage on them the contact, the neutral region and so, on. This is shunt resistance, these are like parallel path; you have a silicon in a device wafer and then you have like a pn junction for example, this will refer to the defects and dislocations if you have so, which top down there can be leakage.

This is a bottom contact, this is a top contact is there defects and dislocations here what will happen then? You will have you know a surface leakage maybe you will have this leakage path which run parallel to the actual device. There is a shunt resistances you want to also lower the shunt resistance, but this is your equivalent circuit of your solar cell [FL] equivalent circuit of a solar cell.

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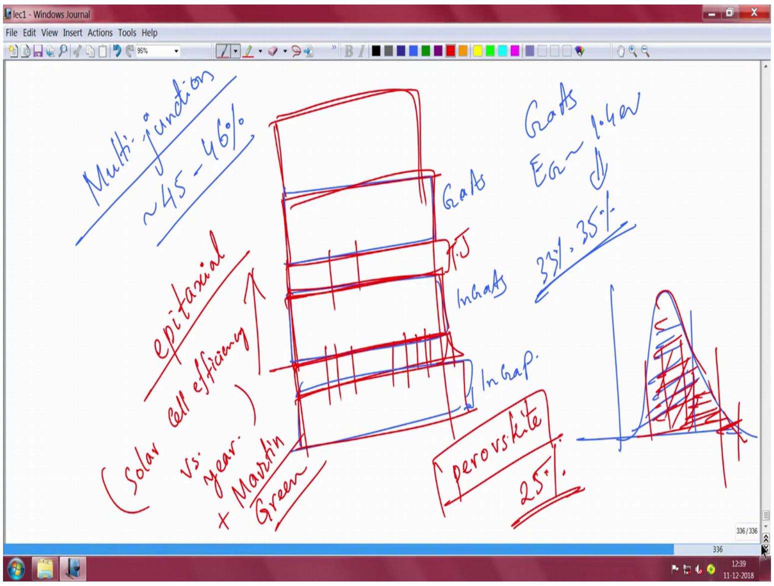

And the way one way is to actually and the increase the efficiency of single junction solar cell gallium arsenide with a band gap of 1.4 ev will give you the maximum efficiency around 35 percent or 33 percent single. But you can do is that, there is something called multi-junction solar cell; these are not used for like day to day lighting, these are used these are very expensive, but this can give you very high efficiency these are used for space and other applications where cost is not important where performance is more important.

This can give you performance if I recall upto I think 45 or 46 percent may be more I forgot; efficiencies have been demonstrated in multi-junction solar cell; some of them are used in space. Multi junction solar cell [FL] you use materials of different band gap to observe different part of the spectra. So, you might have a gallium arsenide that will absorb 1.4 ev, then you might have indium gallium arsenide, you might have indium gallium phosphide, gallium phosphide; these different materials will absorb different part of the spectra. So, this is a sunlight know; so gallium arsenide will absorb that; what about the rest? So, you use InGaAs, InGaAs band gap might be here.

So, (Refer Time: 25:38) to absorb this then In GaP might be here. So, you absorb you absorb everything. So, you absorb everything without compromising on the open circuit voltage so, much. And you these are all on top of each other; these are not separate devices that are you are bonding or sticking it a glue, these are grown epitaxially.

Remember growth of epitaxial material m v m o c d these are grown epitaxially which means material on top of each layer has to mimic the crystal structure below. So, the material science, material challenge is huge, because this are dissimilar materials you will have defects and dislocations that we will found at the interface because they are different materials; those will also kill the device.

So, you may not get the best advantage. So, the material science is very heavy here, you want to grow them epitaxially which is superior material and crystal quality, overcoming the defects and dislocation that will come up so that you can stack up different material and you join them by layers call tunnel junction. Narrow band material called the Tunnel Junction TJ; tunnel junctions which essentially allow the carriers to tunnel between two different layers. This is a complicated thing; you do not have to study, but you just know that there are this multi-junction solar cells.

So, that different junction will absorb different solar spectra will absorb, it will give you a very high efficiency of 45, 46 percent depending on the design. Infinite number junction can stacked up, but technically you can get 67 60 percent to 70 percent efficiency theoretically. If you stack up infinite number of junctions of different band gap; the materials science will not allow it.

Please remember materials science will not allow it because different grow infinity number of layers of different material will care a lot of stress problem, there will be lot of strain mismatch epitaxial issues, material quality. So, that will not allow you to do that, but theoretically you can; not practically, please remember that.

So, these are epitaxial growth techniques that are done, this is also very area of research that has been you know going on. But now perovskites are complex oxides that have come very recently, but these are growing up crazy because they are having very high efficiency of almost up to 25 percent now within a few years of research.

So, these people are going very crazy on perovskite solar cell, you can also google up perovskite solar cell you know that is a very hot topic of research. And although I am not shown here you can google up something like solar cell efficiency solar cell efficiency versus year; which year had how much solar cell efficiency this was I think it is a classic a very classic plot is there and it was by Martin Green; the person's name is Martin Green.

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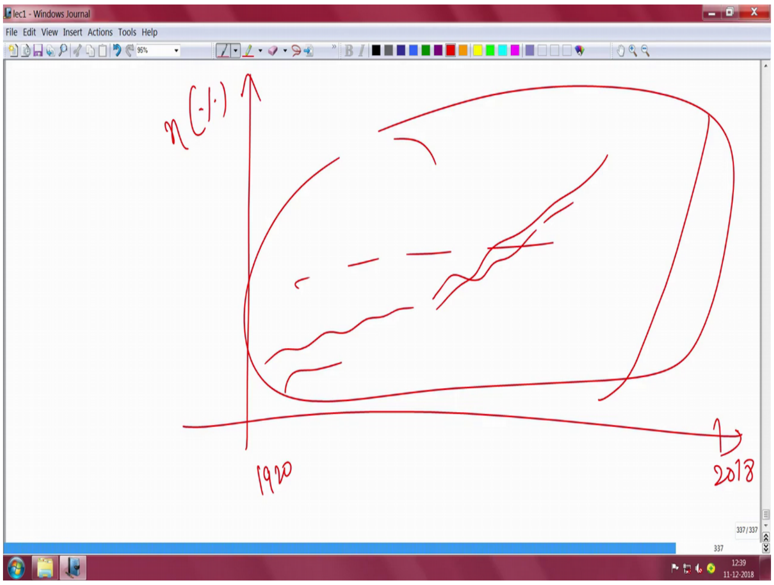

If you search for it you will get a plot; and that plot is like a very sacred plot for solar, here efficiency in terms of percentage in this and then under y minus we have here. I think write from like 1920s to 2018 and it will show you different technology like silicon technology will how it is growing, the gallium arsenide technology how it is growing, perovskites coming here and going here like this. All these different technologies will be shown here. That is a very important graph to I know just to be aware of the quadrant solar cell technology are heading by.

So, solar cell of course, dominantly silicon solar cells is still widely used and they will be used just cheap also very good efficiency you can get, they also organic solar cells and other kinds of solar cell which might be cheaper, people have been doing a lot of research in this area.

So, in this I think we are now ready to wind up the lecture here, we have finished the discussion on solar cell. Most of the important things that we have to know like fill factor efficiency, short circuit current, the band gap Schockley Queisser limit, minority diffusion length like carrier lifetime all these are covered; so we are done with solar cell now.

So, you know how solar cells work, you can co-relate yourself that is efficiency if someone says commercially I have a solar cell that is 18 percent efficient or 22 percent efficient you know where you stand right. If someone gives you a trap like I have a 50 percent efficient solar cell that I am a rooftop you know that person is basically not speaking the truth right; all these things you know now.

So, you can also calculate the amount of current that you can get from the area of the solar cell you know, the best short circuit current you can do; those calculation then the realistic estimates on the cloud cover and dust particles all this things realistic, but practically I am theoretically I am speaking.

Next class we shall begin photo detectors which is very similar to solar cell; very very similar to solar cell, except that sunlight is not the only source; you might want to detect ultraviolet, you might want to detect infrared, visible whatever right. So, in photo detectors very similar to solar cell, but they are operated in third quadrant. So, that will be a agenda for the next couple of lectures.

Thank you for your time.