Solar Photovoltaics:
Fundamental Technology and Applications

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Lecture-10
Principle of Solar Energy Conversion

Welcome everyone, in last few classes we have given an introduction to the semiconductor, if you remember we have learned that the solid materials can be divided into 3 different categories namely conductor, insulator and semiconductor based on their band gap. In today's lecture we will learn about how we can use these semiconductor materials to make a photovoltaic devices or in more precisely how a solar cell device work.

Now before going to this working principle of a solar cell device we need to know which is the source of light here, as you all know that sun is the source of here we are mentioning, so solar radiation comes from the sunlight.

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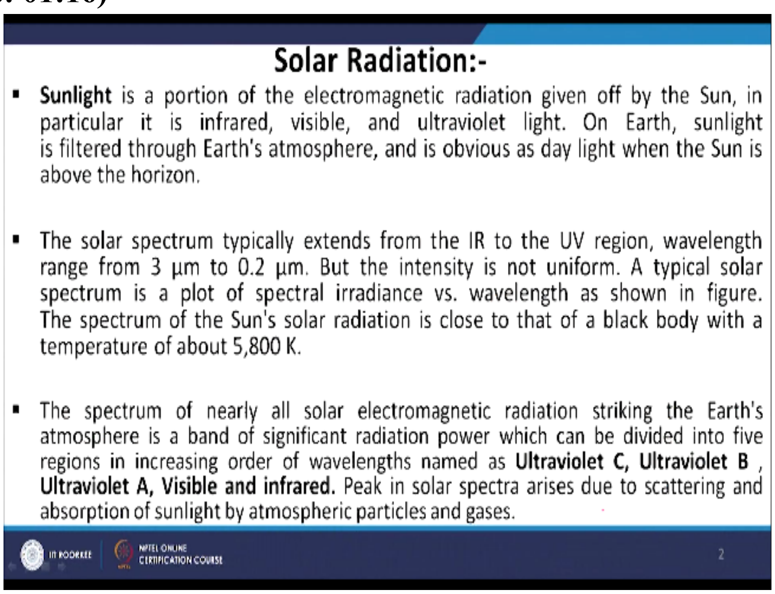

Sunlight is a portion of the electromagnetic radiation given up by the sun, in particular it is infrared visible and ultraviolet right. So it means that the sun lights electromagnetic spectrum that spans behind all the electromagnetic wavelength including visible near infrared and ultraviolet light. On earth sunlight is filtered through earth's atmosphere. So whenever the sunlight falls on the earth's surface it comes to the earth atmosphere.

And the earth atmosphere there are lot of gas molecules exist there, so some of the radiation gets scattered and some of the radiation get transmitted and it is obvious as the daylight when the sun is above the horizon. The solar spectrum typically extends from the IR to UV region, wavelength range from 3 micron to 0.2 micron, but the intensity is not uniform, a typical solar spectrum is a plot of spectral irradiance versus wavelength, will show this in the next slide.

The spectrum of the sun solar radiation is close to that of a black body with a temperature of about 5800 Kelvin, you all know about what is a blackbody. So the Max Planck he has first talked about the black body and what he said that a black body emits electromagnetic radiations, later on Einstein extended this idea and he said that it not only exhaust it, it also whenever the electromagnetic spectrum lies in the space it also lies in a quantized photon.

Now the sun's spectrum or the solar radiation resembles that of a black body radiation at 5800 Kelvin. The spectrum of nearly all solar electromagnetic radiation striking on the earth's surface is a band of significant radiation power which can be divided into five regions in the increasing order of wavelength named as ultraviolet C, ultraviolet B, ultraviolet A visible and infrared and this very essence or these classifications is due to the order of wavelength.

Peak in solar spectra arises due to the scattering and absorption sunlight by atmospheric particles and gases, if we now plot the solar radiation spectrum.

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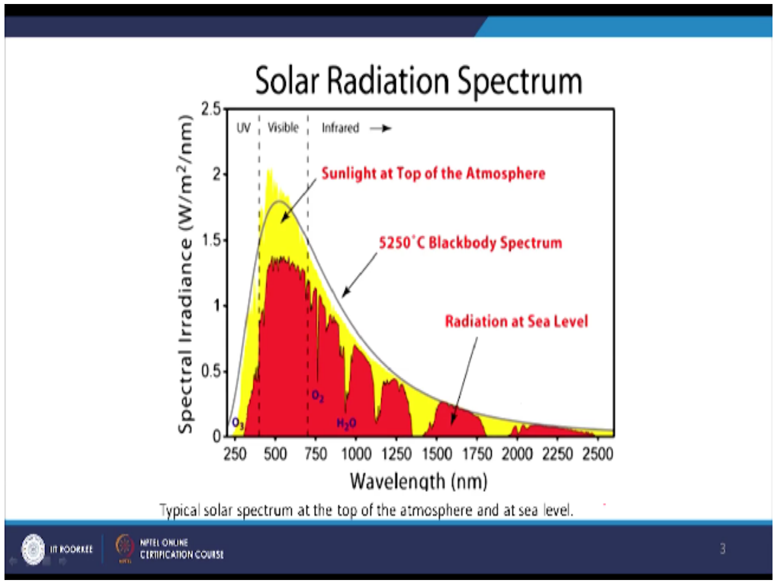

So in my y-axis we have solar irradiance which has a unit of watt/meter square/nanometer and the x-axis is the wavelength in nanometer. So if you look that the sunlight at top of that atmosphere, so before it penetrates the atmosphere it has a spectrum which looks like the yellow shaded regions and it resembles pretty much like this red shaded regions which is the blackbody spectrum at 5250 degree Celsius.

But when the sunlight hits on the earth's surface it feels the scattering from the atmosphere. So wherever it goes on the earth's surface, so radiation at the earth's surface is little bit different as it is from the top of the atmosphere. Now in this perspective we need to know some terminology one of the very important terminology in solar photovoltaics is air mass coefficient, very often it is called as AM which stands for air mass.

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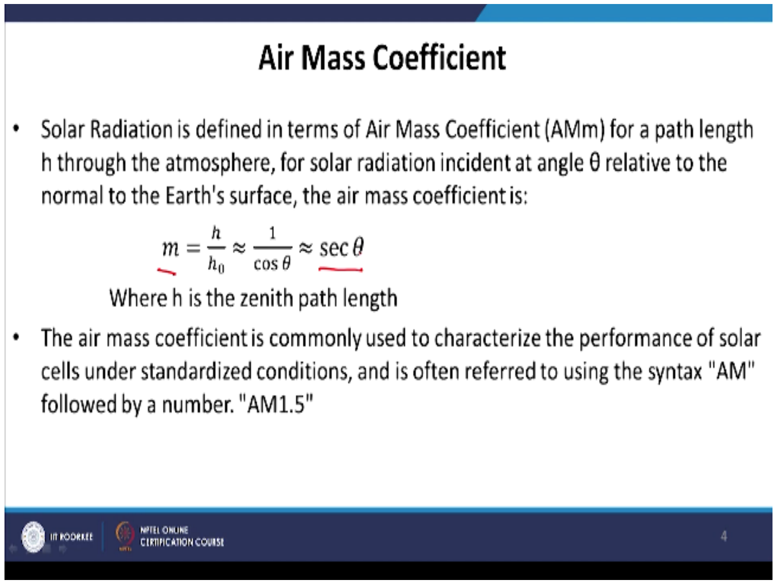

Solar radiation is defined in terms of air mass coefficient and it is defined in terms of a path length through the atmosphere, for solar radiation incident at an angle theta relative to the normal of the earth's surface the air mass coefficient is defined as M = h/h0 = 1/cosine theta. Now 1/cosine theta is second theta. So that is what we have written M = 1/cosine theta or sec theta, where h is the zenith path length here.

The air mass coefficient is commonly used to characterize the performance of solar cell under standardized conditions and is often referred to by using the syntax AM followed by some number like M1 or M1.5 or M2.5. We will see that what does this number represent in the next slide.

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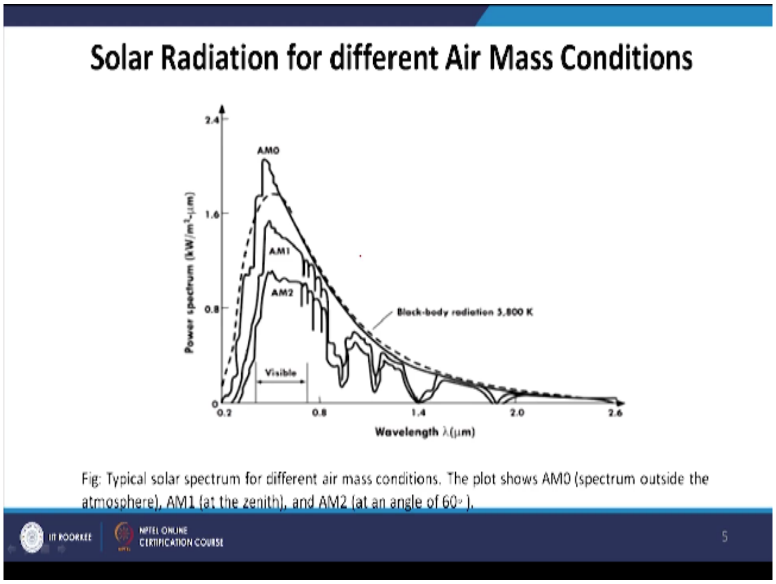

Solar radiation for different air mass coefficient is given here as you can see from this diagram the M 0 is shown by the topmost corner, while the M 1, M 2 and the other values of the M is plotted in this curve, very often we use M value 1.5 in most of the cases even in the photovoltaic devices when we characterize the photovoltaic devices we keep the simulator or solar simulator at a value of artificial sunlight M 1.5.

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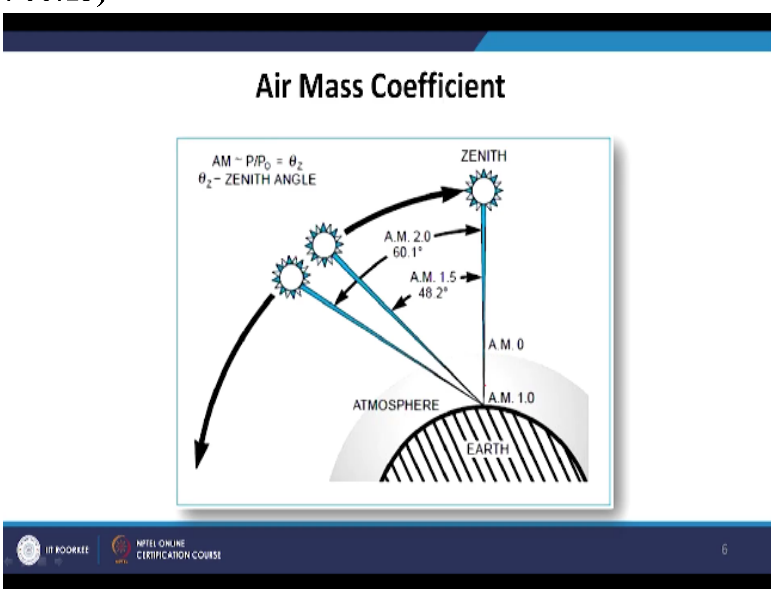

In this picture we explain this thing in a more clear way, you see when sun is on the genitor on the top of the earth's surface it is here, but over the day sun moves around on the earth's surface let us say at a certain instant of time the sun is at here and this angle from the zenith to the point where the sun is theta. For this particular case here this angle is 60.1 degree and we call that M

2.0. M 0 is that when the sun is just above the earth surface and it hits in 0 degree angle and here we are showing the atmosphere.

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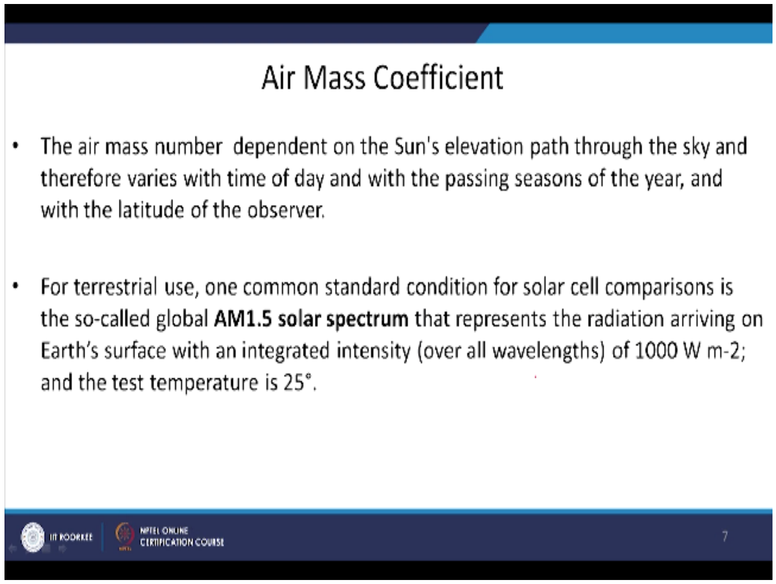

So the air mass coefficient or air mass number depending on the sun's elevation path through the sky and therefore varies with time of the day and with the passing seasons of the year and with the latitude of the observer. For terrestrial use one common standard condition for solar cell comparisons is the so-called global AM 1.5 solar spectrum that represents the radiation arriving on earth's surface with an integrated intensity over all wavelengths of 1000 watt/meter square.

And the test atmosphere is 25 degree Celsius, so whenever we mentioned about AM 1.5 spectrum we mean an intensity of 1000 watt/meter square and at the temperature of 25 degree Celsius.

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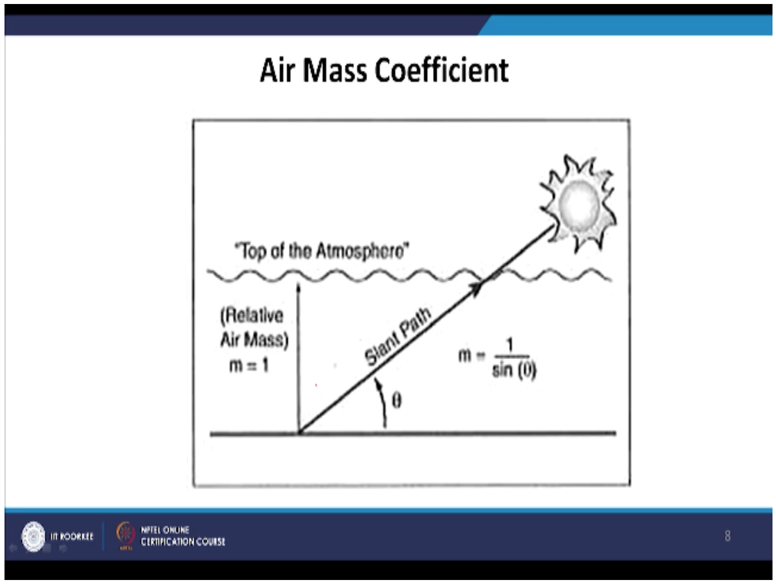

And in this picture we are showing the AM 1.5, so as you can say AM is 1/sin theta, so if AM 1.5, so that corresponds to a particular value of the angle theta.

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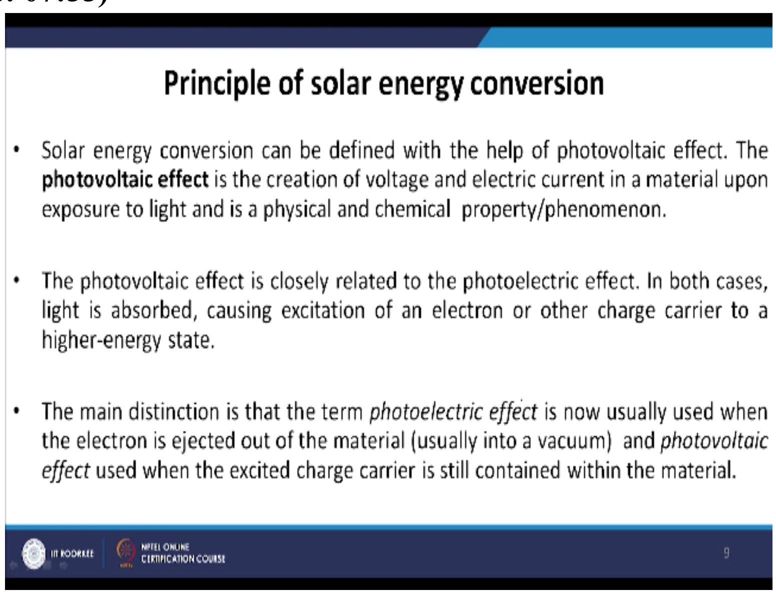

So what is the principle behind the solar energy conversion, solar energy conversion can be defined with the help of photovoltaic effect. The photovoltaic effect is the creation of photo voltage and electric current in a material upon exposure to the light and it is a physical and chemical property and phenomena. So the material absorbs the light which is nothing but a beam of photon if we consider light as a quantized particle.

And that creates some electrons hole pair and that electron hole pair participated in the charge carrier conduction and we get a current and voltage in the external circuit and that we call as a photovoltaic effect. The photovoltaic effect is closely related to the photoelectric effect, if you remember photoelectric effect was discovered by Einstein and he explained this effect with the help of the particle nature of light.

In both these cases whether it is photovoltaic effect or it is photoelectric effect light is absorbed causing excitations of an electron or other charge carrier to a high energy state. So if the light is absorbed electron absorbs this light and it goes from the ground state to the excited state. The main distinction is that the term photovoltaic effect stands for photo means light and voltage mean voltage, whereas the photoelectric effect is now usually used when the electron is ejected out of the material usually into a vacuum.

And photovoltaic effect is used when excited charge carrier is still contended within the material. So photoelectric effect electron is ejected but it is ejected outside the material, but in photovoltaic effect electron is still ejected but it is elected N side the material.

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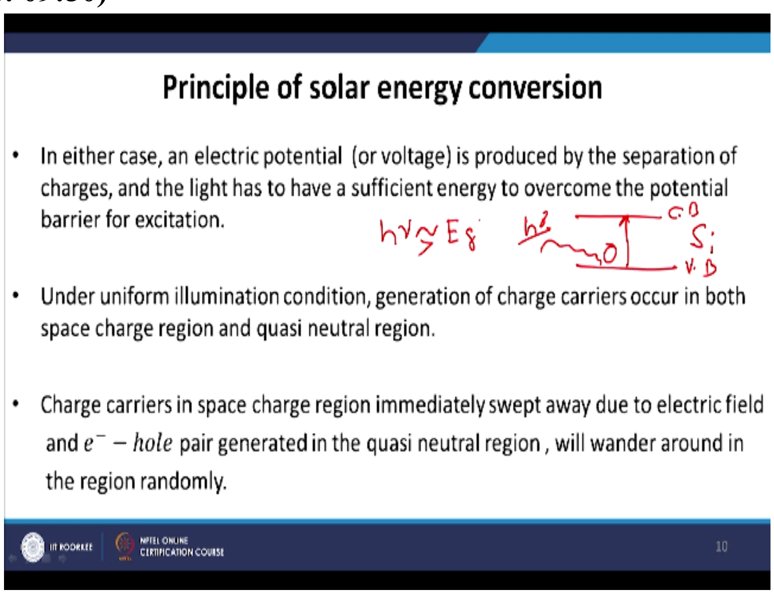

In either case an electric potential or voltage is developed by the separation of the charge carriers and the light has to have a sufficient energy to overcome the potential barrier for excitations, what does it mean, let us say we have an arbitrary material silicon, this is the valence band and this is the conduction band of the silicon. So when light falls on this material electrons will absorb this energy H nu.

And it will absorb that much amount of energy which is sufficient for this electron to bring it from the valence band to that conduction band or the energy H nu should be equal or slightly greater than the band gap energy Eg. So the energy of the incident light has to be sufficient to overcome the potential barrier of the excitation. Under uniform illumination condition generation of charge carriers occur in both space charge region and in quasi neutral region.

We have seen earlier that in a PN Junction diode there are 2 regions, one is the depletion regions which is devoid of any mobile charge carriers or in other words which consists of immobile ions and the other region is called quasi neutral region. In the photovoltaic devices the generation of charge carrier occurs both in space charge region and in quasi neutral region. Charge carrier in the space charge region they immediately swept.

Why because in the space charge region there is an already existing building electric field. So the already existing electric field that sweeps the charge carrier which have been generated in the depletion region and in the quasi neutral region the charge carriers wanders and those electrons or holes which has sufficient thermal velocity or which has sufficient kinetic motion due to the diffusion they only can come and overcome the potential barrier.

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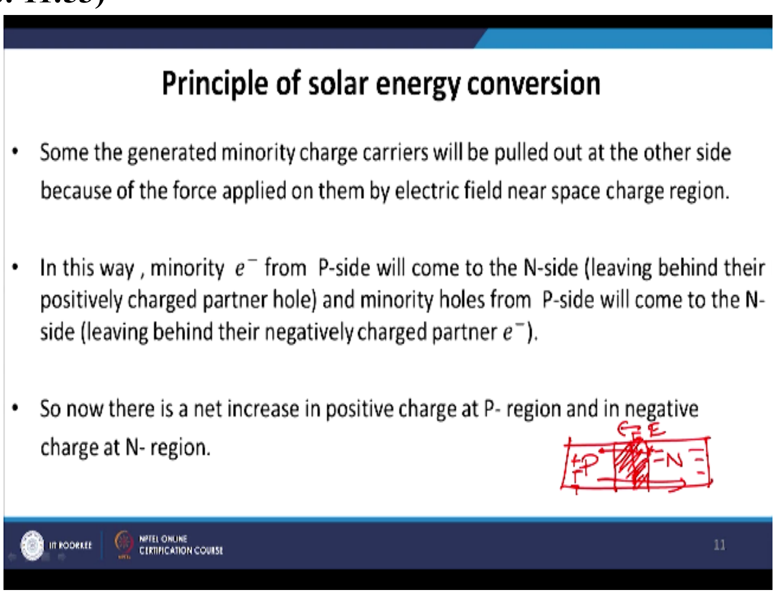

The generated minority charge carriers will be pulled out at the other side because of the force applied to them by electric field near space charge region. So the point is that if I draw a PN junction semiconductor diode like this, this side is my P side and this side is my N side and we know that in between there is a depletion region. Now whatever the charge carrier which have been generated in this shaded region that will be swept out by the already existing electric field e.

So there is an electric field exist here that is e in this depletion regions. So this electric field sweeps the charge carrier which have been created in the shaded regions, but what about the charge carrier which have been created here. So those charge carrier will only able to come to this depletion region by the diffusion motions, once that comes by the diffusion motion then the drift motion by the electric field will switch them around to the other side.

And once they go to the other side they becomes a minority charge carrier. In this way minority electrons from P side will come to the N side, leaving behind a positively charged hole in the P side and minority holes in the P side will come to the N side leaving behind it negatively but not charged E-. So now there is a net increase in potential or you can say that there is a net increase in the positive charge at the P side.

And there is a net increase in the negative charge in the N side, we can also understand this by a animation which will show you in the next slide.

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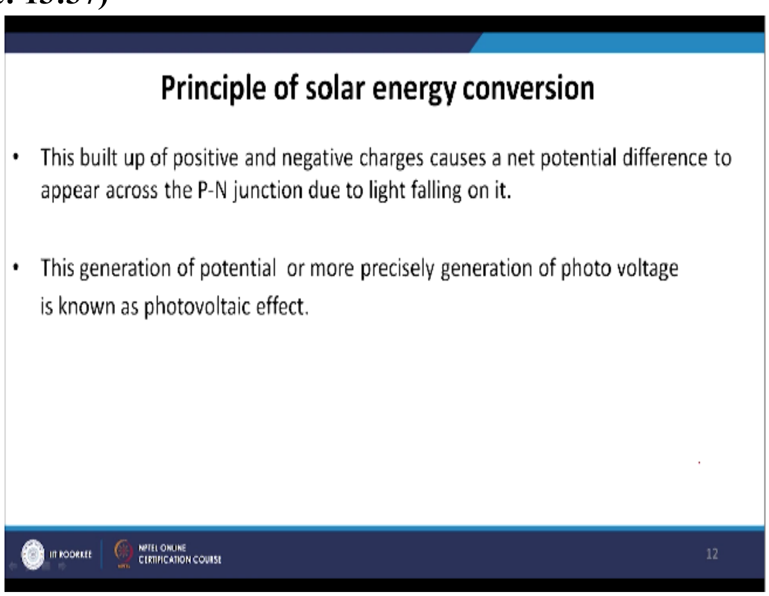

So this buildup of the positive and negative charge that cause a potential difference which appears across the PN Junction due to the light falling on it. So basically the photo voltage is generated due to the light falling on it. This generation of potential or more precisely generation of photo voltage is known as the photovoltaic effect.

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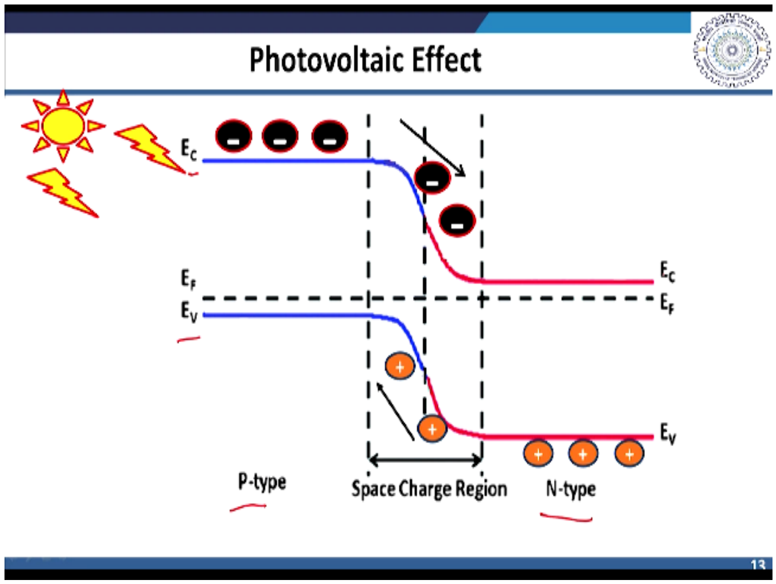

You look at this animation, so we have this 2 different portion here, one is the P-site on the left hand side and another is the N side on the right hand side. So electrons are the minority carriers on the P side and holes are the minority carriers on the N side. Ev stands for the valence band, Ec stands for the conduction band. These types of PN Junction diode with the band alignment we have already discussed in our last class and we have seen that the Fermi level positions itself in such a way that it is close to valence band in the case of P type semiconductor and it is close to conduction band in the case of N type semiconductor.

Now what happens when light falls on it, so we have this negative charge electrons at the conduction band on the Ec at the P-type semiconductor. So this Ec will start falling up and go to the Ec of the N side.

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So the next electrons will move, so once the electron goes from the Ec of this P side to the Ec of the n-type, so what has created on the E side, the absence of the electron because now 3 electron has moved, this absence of the electron has created a hole or positive charge on the left hand side. Similarly the holes which are minority carriers in the N side they can now write this uphill and go to the left side or the P side.

So the holes are moving here as you can see from this diagram and it comes to the valence band of the P side from the N side. So once holes leaves from the N side it has created a negative charge gradient on the n-type side. So finally we left out with a positive charge carrier on the left hand side and negative charge carrier on the right hand side and this positive charge carrier on the left hand side and negative charge carrier on the right hand side has developed a potential difference.

And that potential difference appears across the junction. Now what happens to the space charge region, space charge region whatever the electrons and hole has been created they are swept out by the building electric field. So the electron moves from the valance conduction band up the p-site to the conduction band of the n-type site by using this potential heel as drawn here and the holes rise from the valence band of the n side to the valence band of the p-side by using this potential hill.

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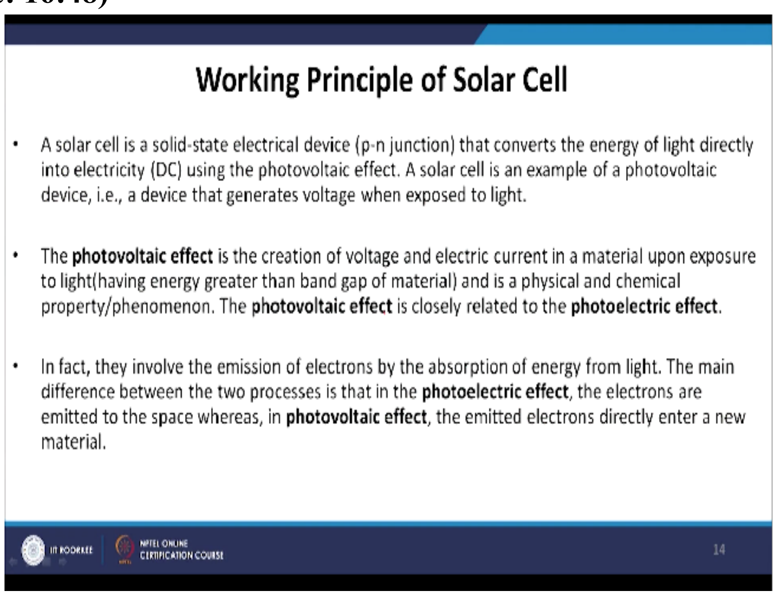

So basically a solar cell is nothing but a solid-state device or a PN Junction diode that converts the energy of light directly into the electricity, but this electricity is the DC electricity using the photovoltaic effect. A solar cell is an example of a photovoltaic device that is the device that generates voltage when exposed to light. So remember a photovoltaic device is a device which generates photo voltage when light is exposed on that.

And solar cell is also an electrical device that converts the energy of the light directly into the DC electricity by using the photovoltaic effect. The photovoltaic effect is the creation of voltage and electric current in a material upon exposure to light having energy greater than the band gap of the material and is a physical and chemical property or phenomena. The photovoltaic effect is close to related to the photoelectric effect.

In fact they invoke the emission of electrons by the absorb the energy from light, in both case light is absorbed and electron is ejected, in the case of photoelectric effect the electrons has to overcome a certain work function of the metal to eject it out. The main difference between the 2 process is that in the photoelectric effect the electrons are emitted to the space where the photovoltaic effect the emitted electron lies inside the material.

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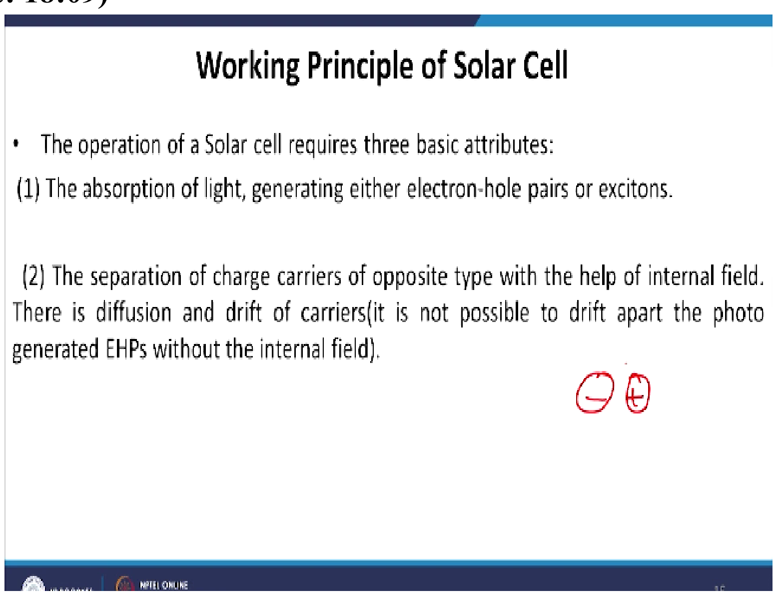

Now the working principle a solar cell can be broadly distinguished into 3 basic attributes, first is that the absorption of the light, if there is no absorption of the light there is no charge carrier generation. So the first important process in a photovoltaic devices or in a solar cell devices is the absorption of the light followed by generations of electron hole pairs. Now we mentioned that in a semiconducting material there are 2 different types of charge carrier exist namely electrons and holes.

And they are bound and these bound electron hole pairs are called exciters, the second process is that the separation of the charge carriers of opposite type with the help of the internal field. Now once this electron which is negatively charged and hole that is positively charged that has been created they are bound by an electrostatic force and that is force is called the excitonic binding force. Now we need to provide an energy to dissociate the excitonic binding energy.

So that the exciton now dissociate to free charge carriers and electrons and hole can participate in the charge conduction. In this process 2 different types of mechanism is involved one is diffusion another is drift. Drift is due to the internal electric field and diffusion is due to the mobility of the charge carrier. Now it is not possible to happen the drift apart the photo generated electron hole pairs without the internal field. If we do not have any internal field there is no drift.

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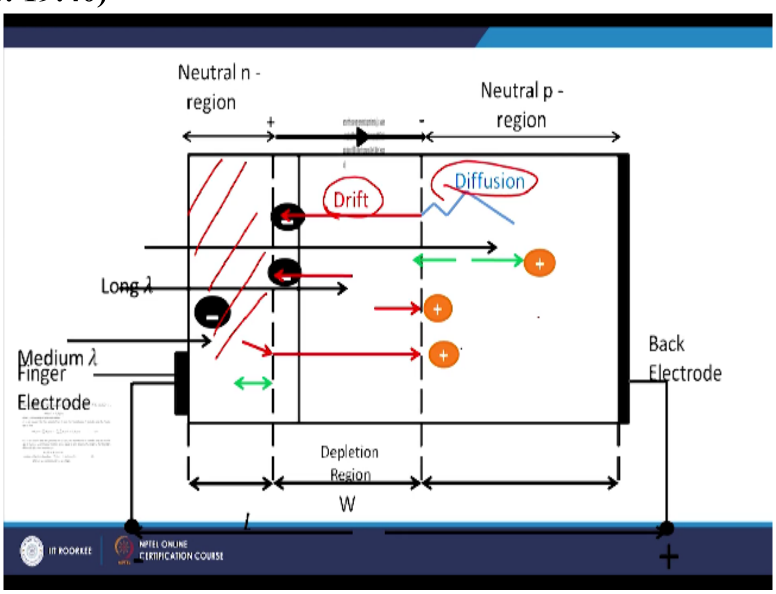

In this figure we are showing how this drift and diffusion happen, so a typical solar cell is a very narrow and heavily doped N side region and has a very wide P-side region. Since N side region is narrow and heavily doped the depletion region extends to the P-type site and you see that in the depletion regions there is an internal electric field is there. Now for simplicity we are considering that there are 3 different wavelengths of the light is falling on this material.

One is the long wavelength lambda who is coming and penetrating towards the depletion region, another is medium wavelength lambda and other is the short wavelength lambda. Now because of the drift whatever the charge carrier what has been created at the depletion regions they will immediately swept out to the other side. So electrons will go to the N side and the holes will go to the P side due to the directions of the electric field.

Now there are some charge carriers also has been created at the neutral P region and neutral N regions, they can move only due to the diffusion. So that is why there are 2 different mechanisms one is drift another is diffusions. Once this negative charge carriers comes to the depletion regions so they immediately swept by the internal electric field to the N side. Similarly the electron which have been created at the depletion region their drift apart due to the internal electric field to the N side.

Same thing happens for the hole which have been created at the depletion regions that is drift out to the P side and the hole switch is in the neutral N regions that first diffused to the depletion region once it comes to the depletion region then it gets drift out to the neutral P regions. So now we have electrons in the N side and holes in the P side.

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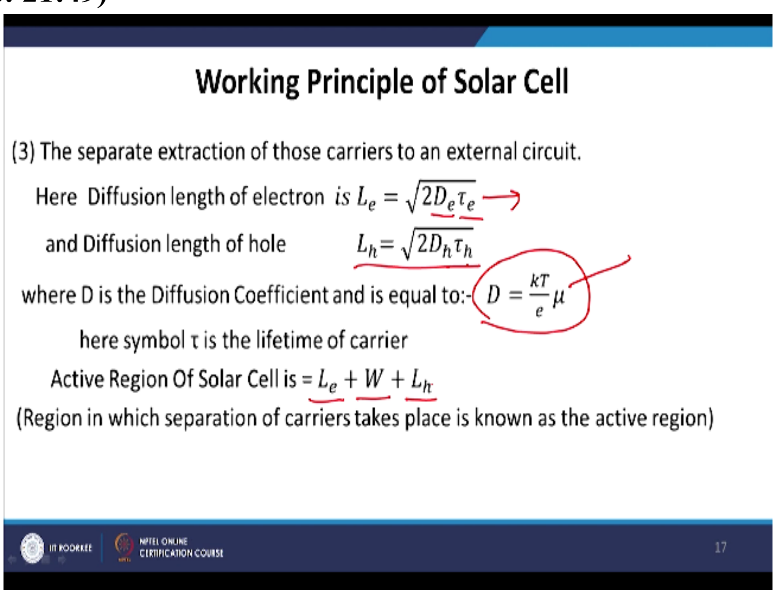

So the third process involving in this solar cells is that the separation of the extraction of the charge carriers to the external circuit. Now I have separated the charge carrier but this charge carrier has to move to the electrode. So that carrier can reach to the electrode and we can collect that charge carriers, it depends upon the diffusion length of the charge carrier. Now the whole diffusion length and the electron diffusion length is different in a semiconductor.

The diffusion length of an electron is defined as Le = square root of 2 into diffusion coefficient of the electrons into the life times tau and the whole diffusion length is defined as square root of 2 times d diffusion coefficient of the whole times that life time of the hole. Now this value of Le and Lh is different. D is the diffusion coefficient and it is given by D = KT/ E times mu where mu is the mobility of the charge carrier.

And tau these symbols that actually tells about the lifetime of the charge carrier. So the active region of a solar cell is the depletion regions plus the diffusion length to the both side one due to the electron and another due to the hole. Let us comes back to the previous slide, so if the depletion region we see W, so this is the W and the diffusion length of the electron let us say this is Le and the diffusion length of the hole let us say that is Lh.

So the active region which generates the charge carrier is W + Le + Lh, thus we have written here active region of the solar cell is Le, the diffusion length of the electron plus the width of the depletion regions plus the diffusion length due to the hole. So this is called the active region where that charge carrier separation happens.

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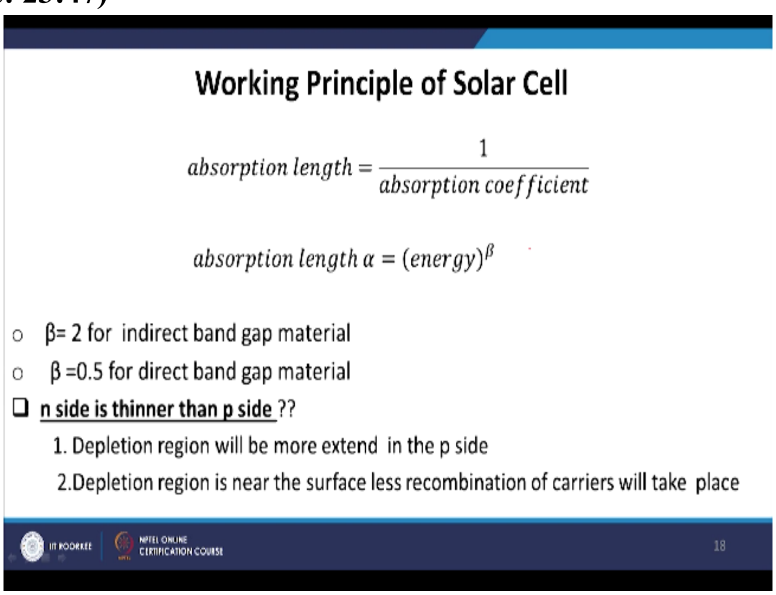

In this context we also define the absorption length, now the absorption lengths is defined as 1 over absorption coefficient where the absorption length alpha can also be defined as energy to the power beta, this beta has a value of 2 for an indirect band semiconductor and beta has a value of 0.5 for a direct band gap material. So for a silicon which is an indirect band gap material beta is 2, for gallium arsenide which is a direct band gap material the value of beta is 0.5.

So if we can know the energy we can find out the absorptions length depending upon whether it is a direct band gap semiconductor or whether it is an indirect band gap semiconductor. Now you might ask the questions I mentioned that whenever we make a solar cell devices, so we make the N side very narrow and heavily doped, what is the reason behind that why N side is thinner than P side well.

The first point is that once we make the ends is very narrow and thin that depletion regions will be extended more towards the P sides. Now in the depletion regions when it extends to the P side the second part will be that depletion regions near the surface has less recombination of the charge carriers, then which is far away from the surface.

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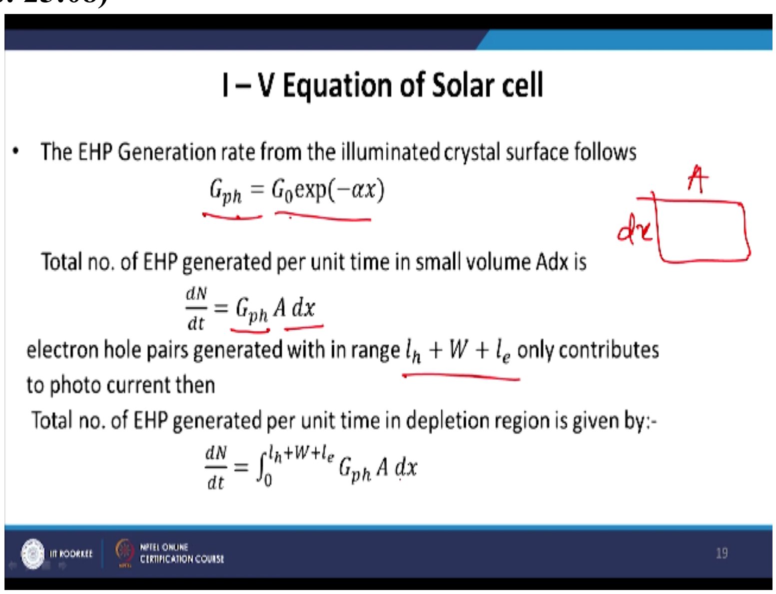

We can also find out an expression of the charge carrier generated in a solar cells which will eventually lead to the I-V equation of a solar cell, the electron hole pair generation rate from an illuminated crystal surface that follows the rule Gph = G0 exponential minus alpha X. Here Gph stands for the charge carrier generation rate or photo generated charge carrier and G0 is the charge carrier generation rate at X = 0.

Nd it falls up with exponential minus alpha X where alpha is the absorption coefficient. So total number of hp or electron hole pair generated per unit time in a small volume adx is dN dX = Gph A dx. So let us consider there is a volume this is A, the area is A and the width is dx, so this volume is A dx, so the total number which will be produced per unit time is dN dT is the charge carrier generation rate per unit volume times the volume A dx.

Electron hole pairs generated in a range lh + w + le which is the active region which participate in the charge carrier generation in solar cell that only contributes to the photo current that you already know, then total number of the electron hole pairs generated per unit time in represent regions is given by dN dts integration 0 to l h + w + le Gph times A dx.

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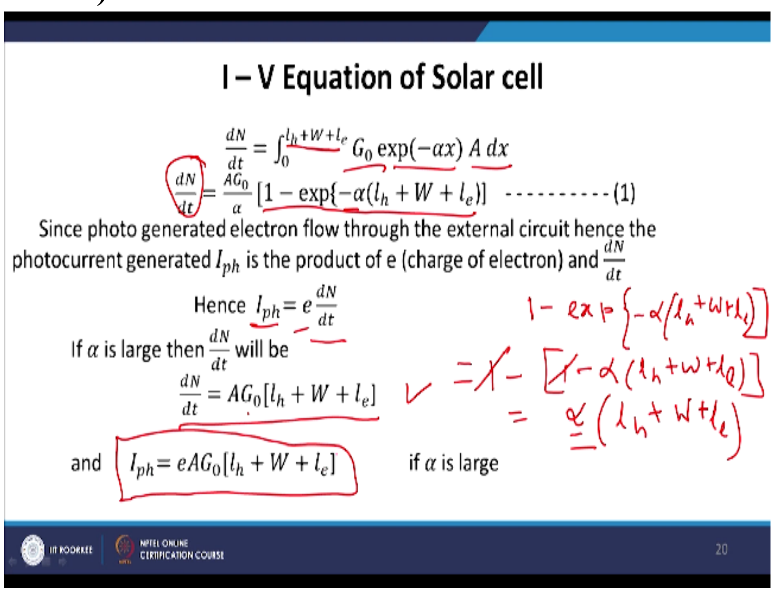

Or dn dt = integration 0 to l h + w + le why we have integrated from 0 to l h + w + le because we have taken this upper limit that is the width of the active layer which contributes to the generation of the charge carrier that is why the integration limits goes from 0 to l h + w + le and then the g0 which is actually the charge carrier generations add the interface or add the surface where x = 0 times exponential - alpha x into the A dx.

Now A is a constant you can take it outside the integral and G0 is also a constant you can take it outside the integral, so basically we need to integrate exponential -alpha X dx or integration exponential - -alpha X Dx. So if you do the integration what we will get dN dt A0 AG 0/ alpha into 1- exponential -alpha lh + w _ le. Since photo generator charge carriers or electrons flow through an external circuit hence the photo current generated Iph is the product of e charge up the electron and dN dt.

So dN dt gives the charge carrier generation rate if we multiply it with the charge carrier the amount of the charge carrier will get the current, so the current Iph is the product of the charge carrier generation rate times the electron charge e. Now if alpha is large then the dN dt will be we can approximate this equations as the dN dts G0 * lh + w + le. So for alpha is equal to large we can approximate the equation 1 like the following equations.

Because you can expand the exponential in terms of 1 + lh + w + le and once and 1 cancels out giving you the only the terms lh + w + le and that terms alpha, let us do this so that it will be more clear so if we expand only the terms behind the inside the bracket for alpha large value 1 - exponential - alpha lh + w + le right. So if alpha is large we can expand this exponential - alpha into some quantity in a binomial expressions.

And that will give us 1 - 1 - alpha lh + w + le right, so this 1 and this 1 cancels out, this minus and minus plus giving you alpha lh + w + le and this alpha cancels out with the alpha the denominator giving you A G0 times lh + w + le, that exactly what you have written in this expressions and in this particular case if the alpha is very large if we consider the value of dN dt is the following then the charge carrier generation rate times the electron charge e will give my the photocurrent.

The photocurrent expression is given by the following terms alpha ph = e AG0 times l h + W + le, if alpha is large, what is alpha, alpha is the objection coefficient, so when the objections coefficient is very large for that kind of material that proto charge carrier generation rate times the charge e that will gives me my photo current.

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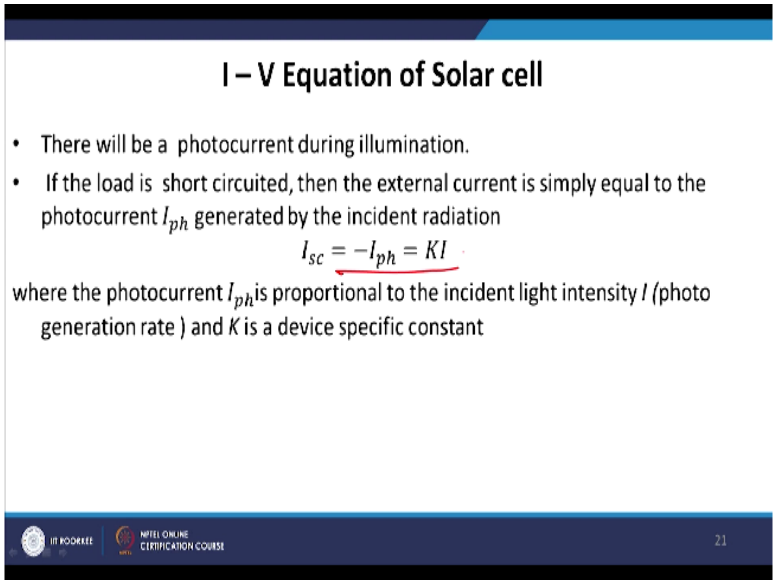

Now there will be a photo current during in luminescent, if the load is short circuited then the external current is simply equal to the photo current Iph generated by the incident radiations. So I sort circuit that is equal to the - I photo current and that is proportional to the intensity so ki where the photo current Iph is proportional to the incident light intensity I, photo generation rate and k is the device specific constant.

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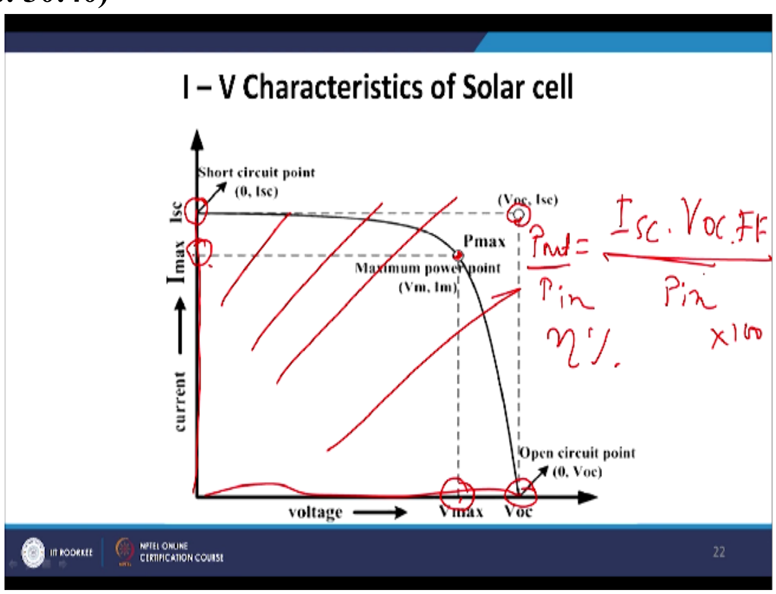

So if we plot the IV characteristics of a solar cell that looks like this, this curve has been plotted in the fourth quadrant because a fourth quadrant we can deliver the power. So as you can see that y-axis is the current and x-axis is the voltage. Now from this diagram we can plot you can see also this dotted line and where this dotted line intercepts the y-axis this gives my I maximum or maximum current.

And where this dotted line intercepts the x-axis that gives the V maximum or the maximum voltage, whereas the solid line where it intercepts the y-axis we called as a short-circuit current and the solid line when it intercepts at the x-axis we call it as a open circuit voltage. Now to operate these solar cells, so it has to operate a particular point, so when you operate these solar cells at a point like P we get maximum current and maximum voltage. So at this point P max I max times B max gives the maximum power.

But very often we don't get the maximum power, what we get is a more realistic case which is not this point but this point and this point is actually the area under this rectangle and what is the area under this rectangle ISC times VOC. So the power output from this IV curve we can calculate from this rectangular area. So we have to multiply the value here ISC times the VOC that gives you the area under this curve.

And that is your power output but that is for a realistic solar cell in an ideal solar cell I should get IM times VM, so this deviation is expressed by a quality factor in solar cell and that quality factor is called a fill factor and fill factor actually represents how good is your solar cell device. If you have too much resistance in your circuit or if you have too much series resistance in your devices then your fill factor will be bad.

If you have a very small series resistance then your fill factor will be good, so fill factor is a quality factor which tells us about how good a solar cell is or how good one experimentalist is. So it tells us about the deviation of a real solar cell from an ideal solar cell. So to get the power output for a real solar cell I have to multiply the current times voltage with a quality factor called the fill factor.

So this terms gives me the total power output or you can write it as P output. Now if I divide by P input then what does it give it gives us P output divided by P input, this is nothing but the efficiency of a solar cells if we multiply it by 100. So the efficiency of a solar cell is ISC short-circuit current times the open circuit voltage times the field factor divided by the input voltage.

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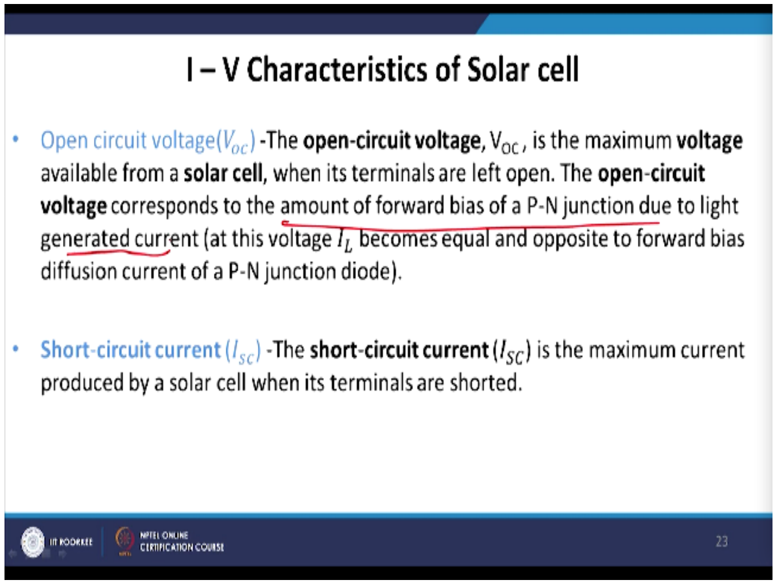

Let us define this terms one by one, so open circuit voltage or Voc, is the maximum voltage available from a solar cell, when its terminals are left open as the name suggests it Is an open circuit. So the terminals are left open and the maximum voltage we get in that condition is the open circuit voltage. The open circuit voltage corresponds to the amount of forward bias of a PN Junction due to the light generated current at this voltage il becomes equal and opposite to forward bias diffusion current of a PN Junction diode.

So the open circuit voltage corresponds to the amount of forward bias of a PN Junction due to the light generated current. At these voltage the load current becomes equal and opposite to the forward bias diffusion current of a PN Junction diode, what is short-circuit current ISC, the short-circuit current is the maximum current produced by a solar cell when its terminals are sorted.

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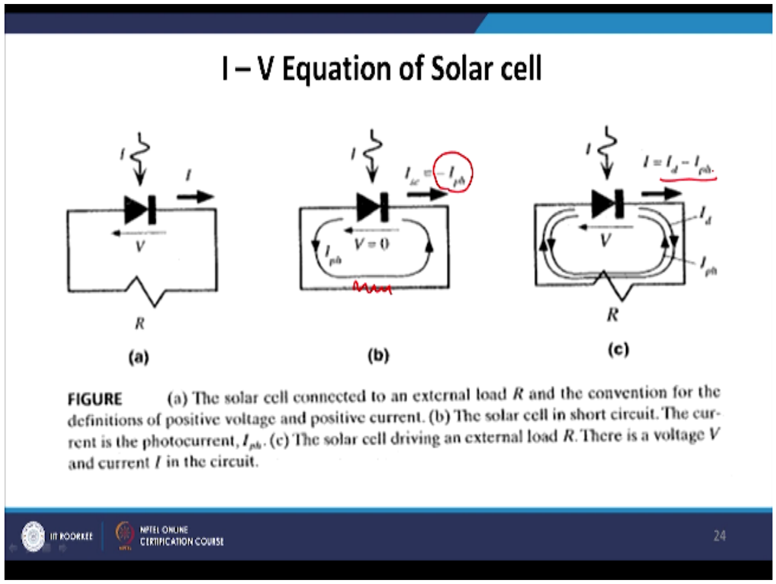

In the figure number A the solar cell is connected to an external load R and the convention for the positive current is shown by this arrow and the voltage is shown by the arrow which is moving to the left hand side and solar cell is usually represented by a diode like that and light is falling on these solar cells. Figure number B that Is the solar cell in a short circuit conditions and the current the photo current is Iph and short-circuit current is equal to the - I photo current.

And the current which have been generated is due to the photo current or due to the exposure of the light and voltage is 0 here in short circuit condition ok, in open circuit voltage this is the opposite condition, now the third figure the solar cell driving an external load R there is a voltage V and current I in the circuit. You see that when now I add a load in the figure B it gives the figure C.

So in the case of figure B we have only the short-circuit current or the photocurrent but when I apply a load in the external circuit I have a diode current also. So the total current is the diode current minus the photo current.

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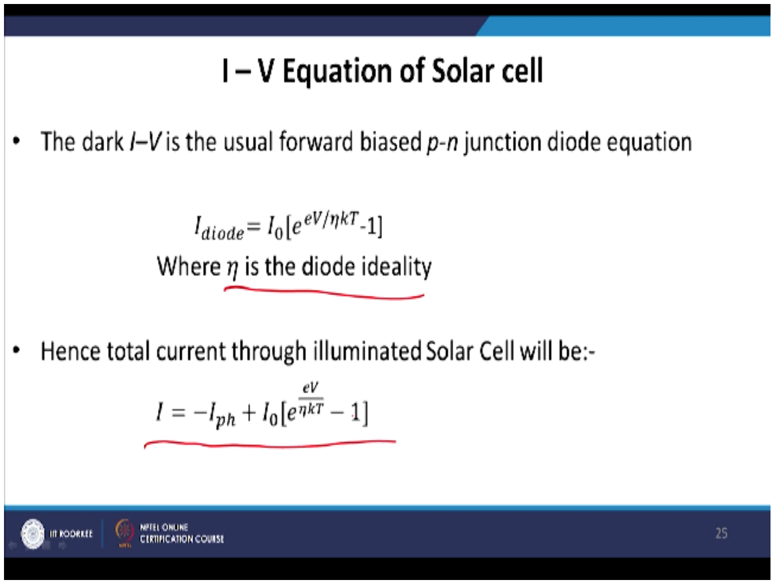

The dark I-V the usual forward bias PN Junction diode is given by I diode is I0 e to the power ev/ eta KT -1 where eta is the diode ideality factor, that we have learned earlier it comes from the sub equation if you add the recombination current then you get the diode current and that is equal to I times IO that is the saturation current times e to the power ev the externally applied voltage divided by eta KT where it is a diode ideality factor whose values can be 1 to 2 depending upon the material of the choice K is the Boltzmann constant, T is the temperature.

So the total current in a solar cell will be I is -I photocurrent + I0 times e to the power ev/ eta KT -1. Now this photo current dependence on the intensity of the light.

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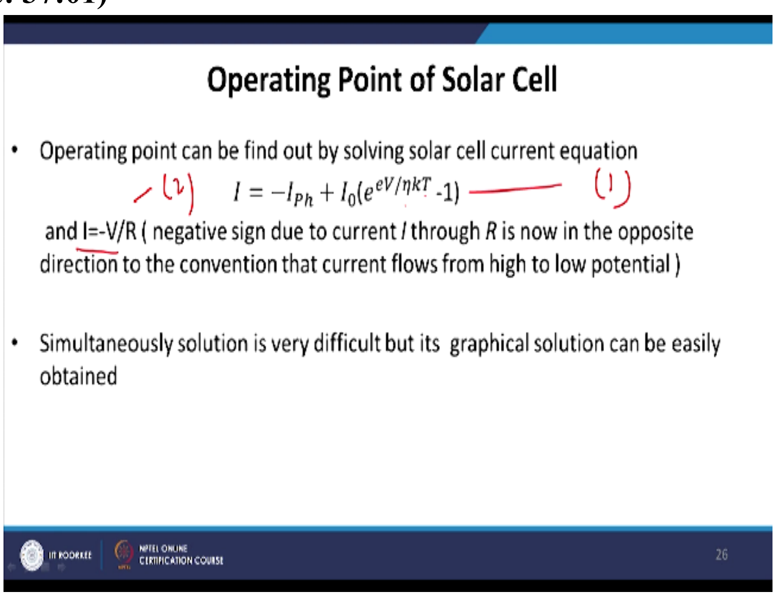

Operating point can we find out by solving the solar cell current equation I is I my I = - Iph + I0 e to the power ev/ eta KT -1. So from this graph or from this equation if we call this as equation 1 and if we take the load equation which is I = - P/R negative sign due to the current I is flowing now in the opposite directions. If we take these 2 equation if we call it as equation 2 and if we sort these 2 equations.

So we will get the operating point of a solar cell, simultaneous solution is very difficult and usually it is done by graphical way as we have done earlier.

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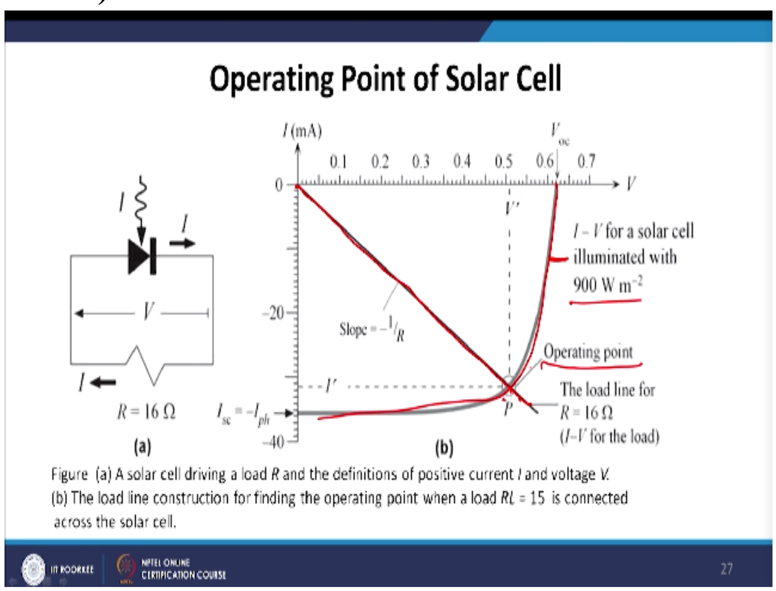

So if we plot the IV characteristics of a solar cell so this is given by this curve and the load line the load curve which is V = - IR is given by this, this kind of construction is called a load line constructions. Now both this curve intersects at the point P, so point P is the operating point of these devices. So here we have said that this curve is the IV curve for a solar cell illuminated with 900 watt per meter square.

And the straight line curve is the load line for R = 16 Ohm, where the intersects is gives the operating point of the device. So today we have introduced the concept of how a solar cell device works, what is the basic device physics behind the silicon solar cell or behind the inorganic solar cell.

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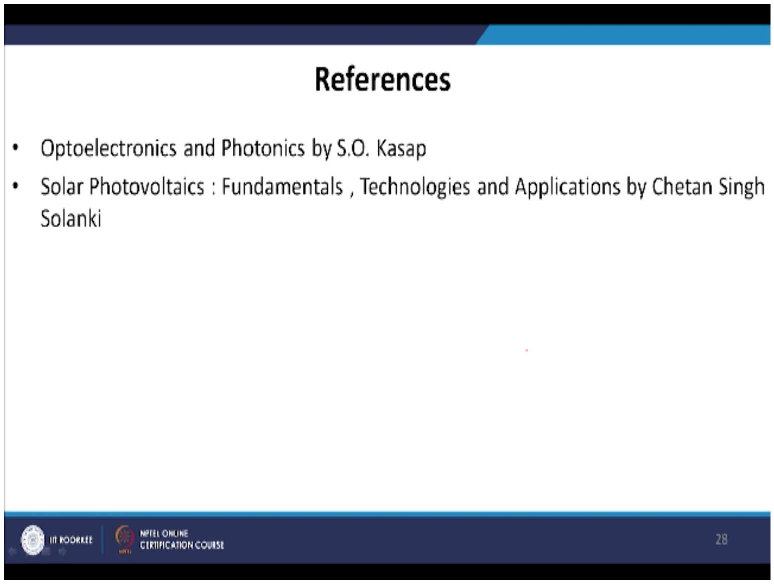

For a more understanding of this concept you can refer to the optoelectronics and photonics book by S. O Kasap and the solar photovoltaics fundamental and technology book by Chetan Singh Solanki, thank you.