Electronic Materials, Devices and Fabrication
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Lecture - 25
Optoelectronic devices: Solar cells

Last class we looked at photo detectors. So, in the case of photo detectors we had an incident light onto your device, which was converted in to an electrical signal.

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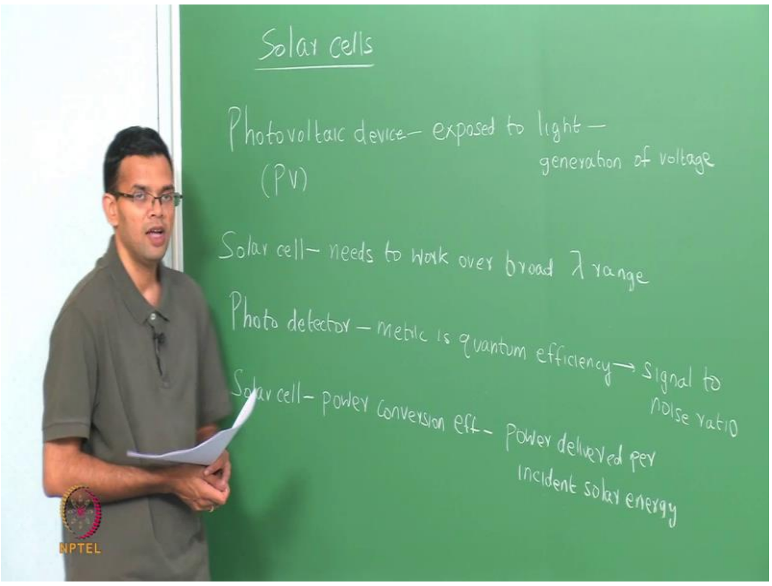

Today we are going to look at solar cells. A solar cells is an example of a photo voltaic device that is, it is a device were you have a generation a voltage when exposed to light. So, when it is exposed to light, leads to a generation of voltage. Photovoltaic's were first discovered by Henry Becquerel in 1838, but the first silicon based p n junction photovoltaic was invented by Ole in 1940. So, the principle of photo voltaic, let me just abbreviate this as PV is similar to the photo detector that we looked at last class, there are just a few crucial differences. So, in the case of a photo detector we saw that once such example was photo diode could be a simple p n junction or a p i n junction.

So, in that case a photo detector works over a narrow wavelength range, so the maximum wavelength dependent upon the energy of transition that was involved. So, there was a transition from the valance band to the conduction band the maximum wavelength is defined by the band gap of the material. The minimum wavelength range depended upon the absorbance of the material because as wavelength decreases observances increases so that light is only observed very close to the surface. In the case of a solar cell, we need the device work over a broad wavelength range and this wavelength range depends upon the solar spectrum.

So, that is the first crucial difference between a solar cell and photo detector, the wavelength range is imposed by this spectrum, also in the case of a photo detector, the metric is the quantum efficiency. So, we define quantum efficiency as the number of electron hole pairs or the current that is generated to the ratio of the number of photons that are incident on your sample. So, the quantum efficiency determines the signal to noise ratio. In the case of a solar cell, the metric that is normally used is the power conversion efficiency. This is the ratio or this is the power delivered per incident solar energy.

So, solar cells are usually wide area devices, because they need to capture as much as the incident solar energy, and then convert it in to electrical energy. So, to understand the solar cell the first need to take a look at the solar spectrum.

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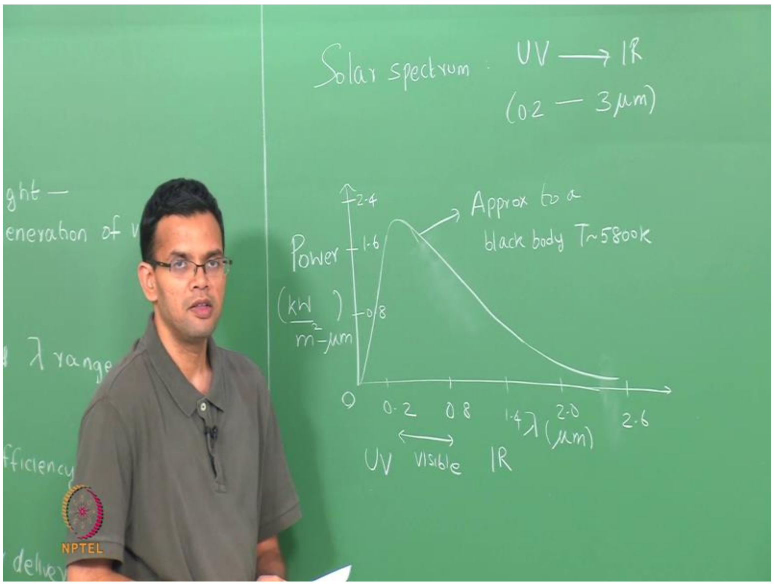

If you look at the solar spectrum, it primarily ranges from the use, UV to the IR regions. So, it encloses the visible regions to its goes from UV to IR the typical wavelength range goes from around 0.2 microns or 200 manometers to 3 microns, so 3 microns lies in the IR region 0.2 in the UV region. So, this encloses the visible region as well of course, the intensity of this radiation is not a constant, the intensity depends upon the wavelength. So, we can plot a power spectrum versus wavelength, so I have wavelength lambda on the x axis, this is in micrometers, then I plot the power and the unit is kilowatt meter square per micrometers.

So, this is your power spectrum 0.2, 0.8, 0.4, 2, let me extend the access a little bit 2.6, 0.8, 0.6, 2.4. So, the visible region lies some were between 0.2 and 0.8. So, it is visible, this is IR this is UV, so if you plot the power spectrum as a function of wavelength, we have a peak and then the intensity decreases at higher wavelengths. So, this sort of spectrum can be approximated to a black body whose temperature is around 6,000 Kelvin. So, it is approximated to a black body, the area under the curve gives the total intensity of the incoming solar radiation.

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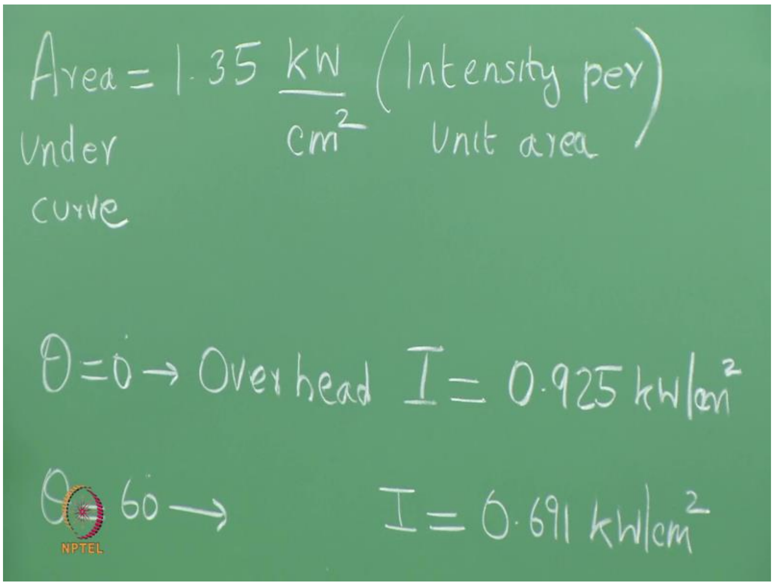

This area has a value of along 1.35 kilowatts per centimeter square, so this is the intensity of the solar radiation per unit area. Just to be clear, I will say this is area under the curve, of course, we should also take into account the fact if you have scattering of radiation by the earth atmosphere.

So, the atmosphere has ozone it also have some water molecules, so these can scatter the solar radiation. It also has dust particles, which can scatter radiation; the path length will also change the energy of the spectrum. For example, if you have solar light directly overhead, so when theta is 0. So, when we have this solar light directly over head, the intensity I is a along 0.925 kilowatts per centimeter square and when theta is 60, so there is some scattering and the path length is more, the intensity i is lower it is around 0.691.

So, there is an energy spread to the spectrum, which energy spread shown here and the spectrum or the actual intensity that is arriving at the earth is going to depend upon scattering from the atmosphere and also the incident angle of the radiation. So, this radiation needs to be observed by a device in order to produce electrical signal, so let us consider a simple design of a solar cell.

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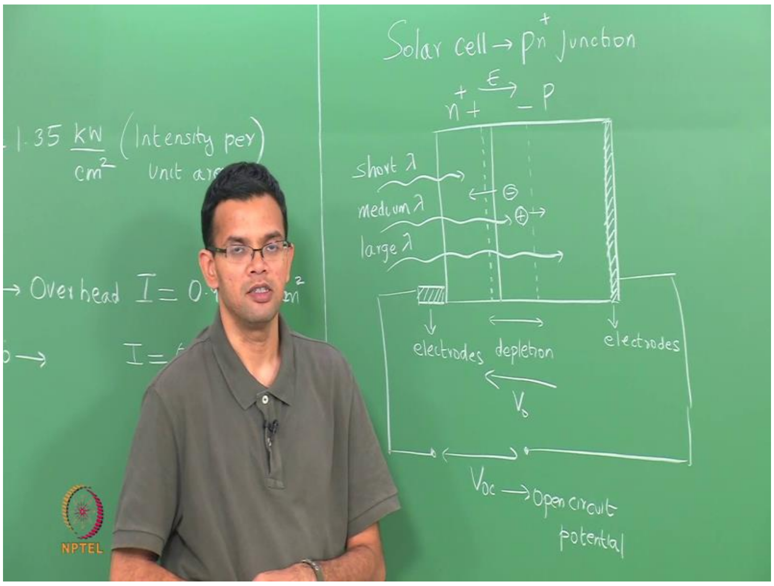

So, let us look at the solar cell that is based on a simple p n junction, so last class we saw that you photo detectors or based upon p n junction or p i n junction, so the basic principle is similar. So, we have a solar cell that is based on p n junction, the n region heavy doubt, so I will call p n plus and we also have a p n region because the light has to penetrate through the n region. So, if have to draw schematic of this, here is my solar cell, I have electrical contacts it on end, my light is incoming from this direction, so I also have electrodes at the other end, but these electrons do not cover the entire surface because the light has to penetrate through your device.

So, this is the interface between the n plus and the p region, so the n plus region is heavenly doubt in this case the depletion region will lie almost entirely on the p side. So, I have a very thin depletion region on the n side and it is lot more thicker on the p side. So, these are electrodes, so we have solar radiation coming from the left and falling on the n plus region, now your radiation can have both long wavelength medium and short wavelength.

So, shorter the wavelength higher the energy, short wavelength are usually observed by the n plus region because a absorption coefficient is large hence the penetration depth is small, whereas, the wavelength increases the penetration depth also increases. So, this just depicts three kinds a wavelength short, medium and large, when the wavelength of light gets absorbed, it generates and electrons hole pair. So, for example, the medium wavelength region generates an electron hole pair within the depletion region.

We have looked at the p n junction in equilibrium, we know that whenever we have a junction, we always have a contact potential. So, we have a plus and a minus, we saw this earlier when we talking about p n junctions, this is because we have electron and the holes recombining and getting annihilated to give you a depletion region. So, the electric field seen goes from positive to negative, which means there is built-in potential or a contact potential V naught. So, when the incoming variation generates an electron hole pair, the electron is accelerated towards the n sign because it c is the positive potential in a hole is accelerated towards the p side, this means were is now a potential the develops between the p and the n regions.

In the absence of any external load, this potential is called V OC, which is your open circuit potential. So, if you now make the connection between the p and the n so that instead of open circuit, you have a short circuit. You have a current that flows through the device and it flows true the outer circuit because of the electron an hole pairs, the generator, this current is called you short circuit current, so let us draw schematic of that.

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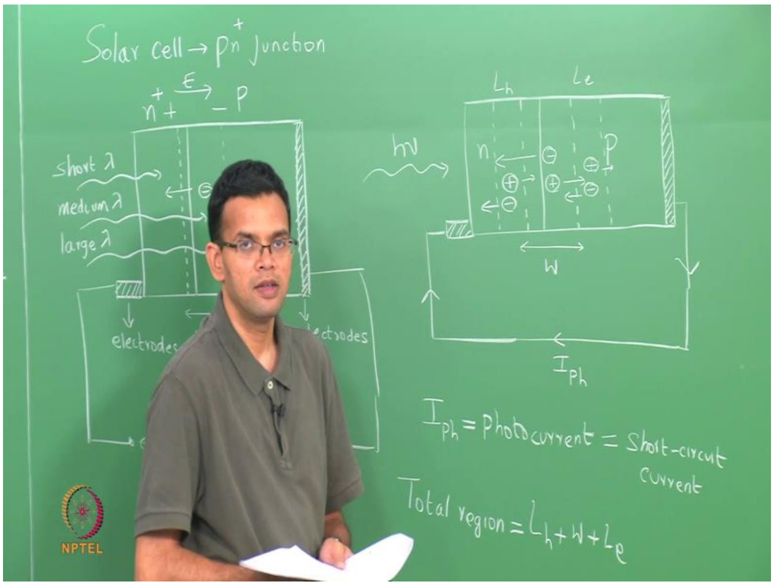

I have my n and the p and there is depletion region, so we have the electrodes on both sides and instead of having a open circuit, we make the electrical connection so that current can flow. So, in this particular case, once again you have solar radiation falling on your sample, an electron hole pair that is generator, the electrons accelerating towards the n side and holes accelerating towards the p side, so that the current flows from p to n.

This current is called your photo current, so it is a current that is generated because you have photo generated carriers. In the absence of any external load, it is also call the short circuit current. So, in this particular figure, let W be the width of the depletion region, so you electron hole pairs are also generated within this W by t. If you also look more closely, electron hole pair are also generated within the n and the p region because all of these regions observes the light. So, electron hole pairs are generated in all of them.

So, once again you can see that the holes will get accelerated towards the p side and the electrons get accelerated towards the n side. Why these electrons in holes are essentially minority carriers? So, they can only defuse with in a region which is defined by the diffusion width. So, l h is the dilution width of the wholes, which are the minority carriers on the n side an l e is the diffusion width other diffusion length of the electrons which are the minority carriers from the p side. So, the total region from which current is generated is l h plus w plus l e, so it not only comes from the depletion region, but also from the diffusion regions in both the n and the p side.

So, electron holes generated from this region contribute to the current, so let us now go ahead and calculate the IV characteristics of a solar cell, so let us look at the IV characteristics of a solar cell.

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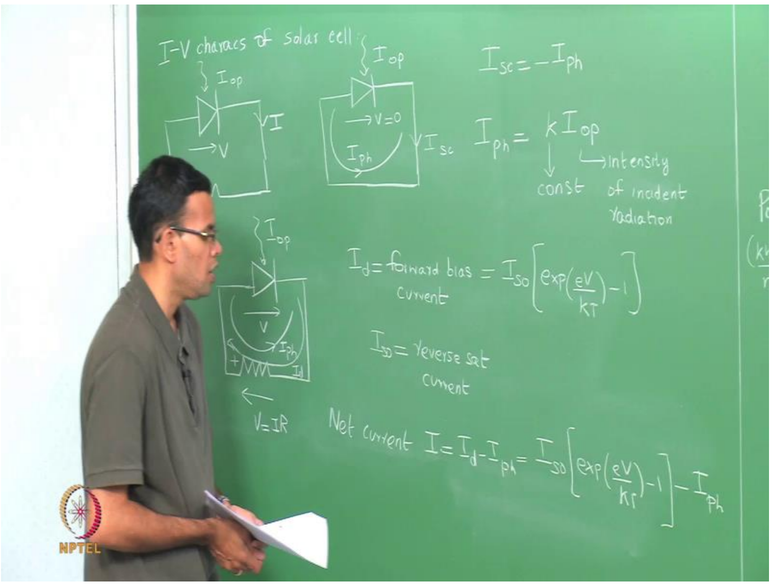

In this particular case, you are looking at a solar cell which is a simple p n junction that is connected to some external load. The external load is defined by a resistor R and you have some incident light of certain intensity is given by I op. So, in this particular case, there is a built in voltage with in a p n junction and also a current that flows through the device. So, this is the schematic representation of is solar cell and is connected to an external load. Now, in the absence of a load where the resistor 0, we saw that when you shine light, you have a photo current that is generated within.

In this case, the voltage are the voltage differences are 0 because you have photo current I p h if we define the conventional direction of current. The other way and called I s c which is a short circuit current, then I s c is nothing but minus I p h. So, I s c is a short circuit current, which is current flows through at the device when it is short circuits. So, when there is no external load and this interned depends upon the photo current I p h. Now, I p h depends upon the intensity of solar light that shining on you device.

So, I p h is usually some constant k times I o p, which is the intensity of solar radiation signing on the device. So, k here is a constant and this is the intensity of incident radiation, so we take this I now add on an external load in the form of a resistor.

So, when you have a potential now we have I op, so once again there is a photo current which is I p h, but this photo current generates a voltage of cross 0 resistor. This voltage across the resistor is IR and this voltage opposes the inbuilt voltage of a p n junction because any p n junction has inbuilt potential or in bit voltage. So, it is a contact potential and the photo current basically generates an external potential that opposes this. So, this is equivalent to saying that you forward biasing your p n junction so that now it is easier for the minority carrier is to defuse so that you have a forward bias current.

So, the forward bias current goes the other way call it id, so I d which is a forward bias current and you can write the standard for this I s naught, where I s not is a reverse saturation current exponential e v over k t minus 1. So, I s naught is a reverse saturation current, which way of seen earlier the context of a regular p n junction. So, we have a forward by is current that goes in one way we have a photo current due to the radiation that falls on your sample that goes the other way. So, the net current I is nothing but I d minus I p h I s not exponential e v k t minus 1 minus I ph. So, it is possible to draw an equivalent circuit for a solar cell is nothing but p n junction and elimination.

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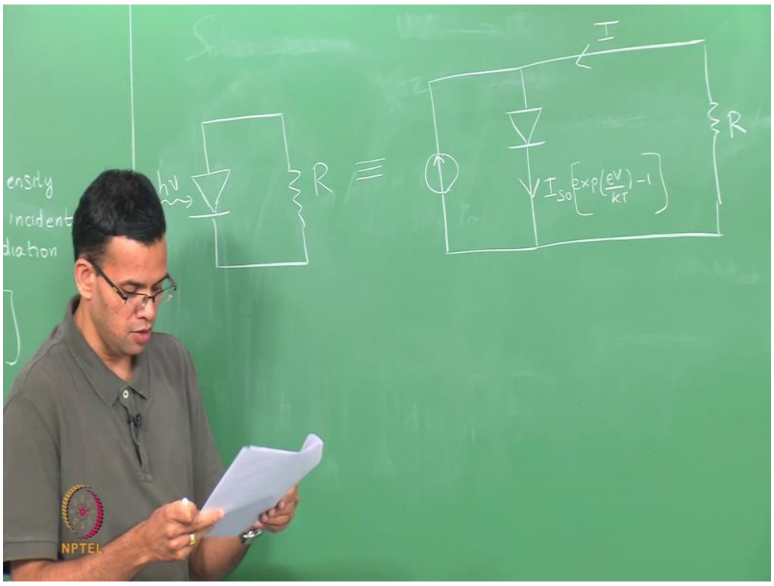

So, we have a solar cell connect to external load and you have incident radiation shining on it. So, it is possible to draw an equivalence circuit for that, so in that case you have a constant current source, which is you photo current generated because of the incident light you have a p n junction that is now under forward bias. So, there is a forward bias current I and this forward bias current oppose the constant current. So, all your photo current and then there is you resistor R.

So, the equivalent circuit solar cell is just a constant current source and p n junction under forward bias which oppose each other. So, we can also draw IV characteristic for the solar cell if there is no radiation. So, in the case of a dark solar cell, the IV characteristic will just resemble a p n junction under bias. So, we have the current which increase exponentially with the voltage just given by this expression. So, this is in the case of dark we found that when we shine light we have a photo current that opposes forward bias current.

So, the net current is I d minus I p h, so the effect of this is to shift here IV current below so that when you have some photo current shining, you no longer start at 0, but your shifted below because of the minus I p h. If you increase the value of the incident radiation intensity so that I o p is higher than I p h will be even higher than shifting this even further below. So, in this particular case we can calculate the voltage at which current is 0. So, when current I is equal to 0 the voltage is called open circuit voltage. So, in that case I, which is I s naught exponential e v o c over k t minus 1, this is 0. So, when the voltage e v o c, which refers to this point the current, is 0, so we can rearrange this expression to give v o c.

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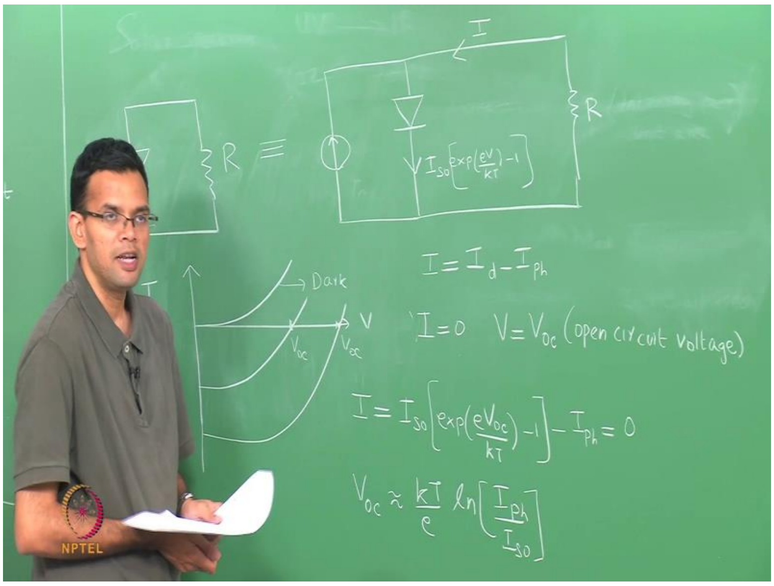

To be approximately equal, we can neglect this factor minus 1 to be k t over e 1 of I p h over I s o. So, let me rewrite this expression and we can look at the two parts of it.

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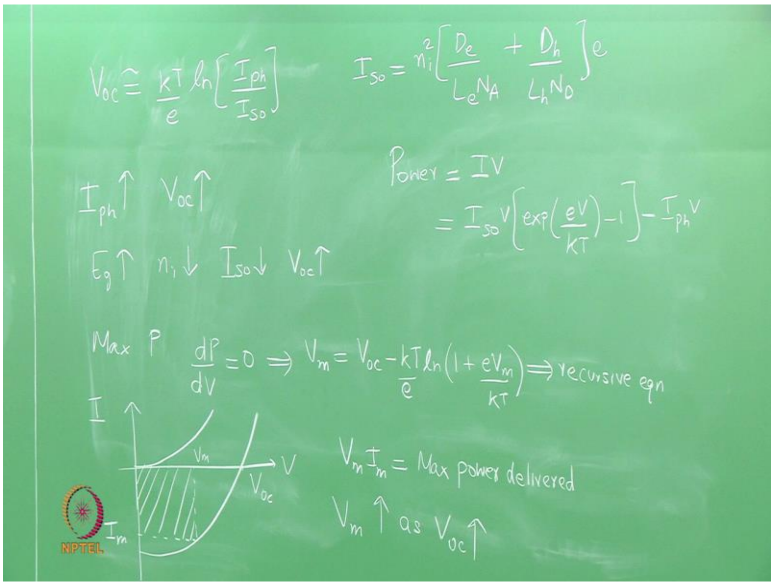

So, written down the expression for the open circuit voltage, we see approximately k t over e long of I p h over I s o, I p h is a photo current is depends upon the intensity of the light and I. So, is reverse auscultation current which depends upon the intense carrier concentration and I square and also on the diffusion coefficient diffusion length and the concentration of the p and the n region there is a term e here.

So, if you increase the value of photo current, so if I p h is higher, v o c will increase, similarly if you go for material with higher band gap. So, if e g is higher than n, I will be lower, so I will be lower and that will also increase v o c. So, in the case of solar cell, we saw the important per annum meter is the power conversion efficiency the power is nothing but I times the voltage which is I. So, v exponential e v over k t minus 1 minus I p h v, in order to have the maximum power, so for maximum power, d p over d v should be equal to 0. So, we are just differentiating this expression, so in that case the corresponding voltage is v m and we can write a recourse relationship that relates v m to v o c.

So, this is the recovers relationship because v m is on both side, but it can be solid in order to get the maximum voltage is the voltage corresponding to maximum power. So, once we know the value of v m we can plug in the expression and get the maximum power. So, let us once more look at your IV curve which a redraw this, so this is your dark current, this your current under elimination this point is V o c. So, we can calculate the v m which corresponds to the maximum power in also the i m. So, this is v m corresponds to I m, the area under the curve are the area between these two points gives is the maximum power that is delivered to this system.

So, V m times I m is the maximum power delivered if you do the calculation we find the V m will increase as V o c increases. So, higher your open circuit voltage, higher the value of V m. So, one way of increasing V o c is to increase the intensity of the radiation and the other way was to have p n junction with higher band gap. The draw back in that case is that as you band gap increases the region of the solar spectrum that is being observed will decreased because as e g increases the corresponding wavelength for the transition will decrease. So, there is the trade off on what material we choose in order to get the maximum value of the power. So, conventional silicon base solar cells have efficiencies over 1 percent.

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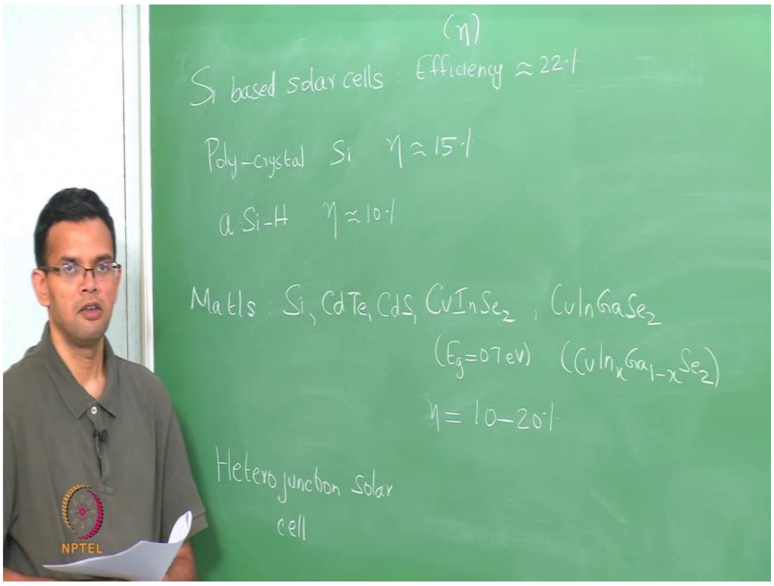

So, in this case these are single crystal silicon based devices instead of single crystal if you have a poly crystal and silicon your efficiency that we call this eta. The efficiency will be around 15 percent, you could also go for silicon base solar cells, and the advantage is that the cause is reduced, because you can directly deposit this and a glass light. So, you can have silicon base solar cell for the efficiency even drop even further, there are other materials the use for solar cells some of the typical materials.

We already saw silicon have cadmium telluride cadmium sulfide and then copper indium desalinate this is a material with a band gap of along 0.7 electron volts and the variation of this is copper indium gallium desalinate. So, as usual return S Cu INX gallium 1 minus XSE 2 the band gap in this case depends upon the value of x all of these have efficiency some were between 10 to 20 percent depending upon the processing route which is used in order to make this devices and also the quality of the films that are produced to solar cells. We have seen so far simple p n junction base solar cells, we could have also hetero junction solar cells, so in this case we can increase the efficiency was of the device.

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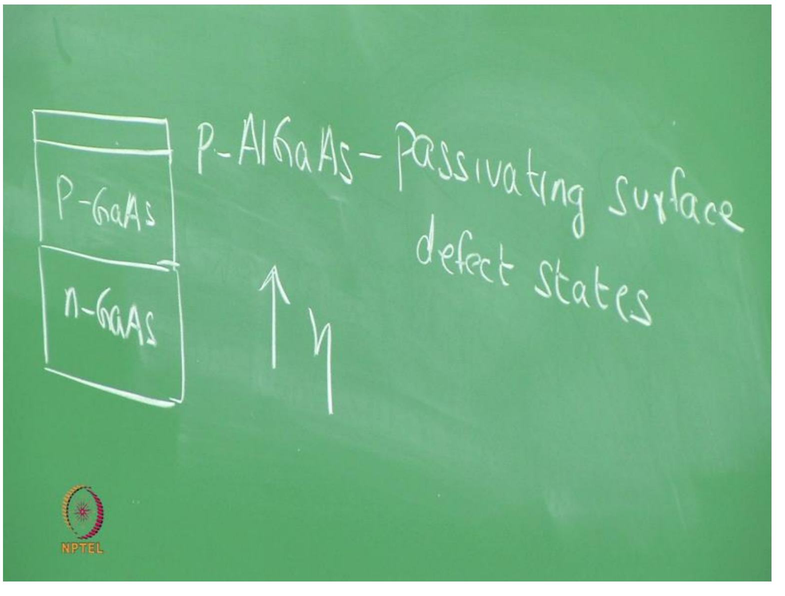

For example, consider a hetero junction that we have p aluminum gallium arsenide which chooses a thin layer that is deposited on top of p an n gallium arsenide. So, in this case, your p n junction is still between the same material by the aluminum gallium arsenide layer helps in passivating this of bands of the surface defect states. It also has the higher band gap then gallium arsenide so that it allows radiation to pass through weight and we observed by the gallium arsenide. So, this in turn needs to a higher efficiency, so you can also have other designs of p n junctions, so you can also have a p n junction between different materials.

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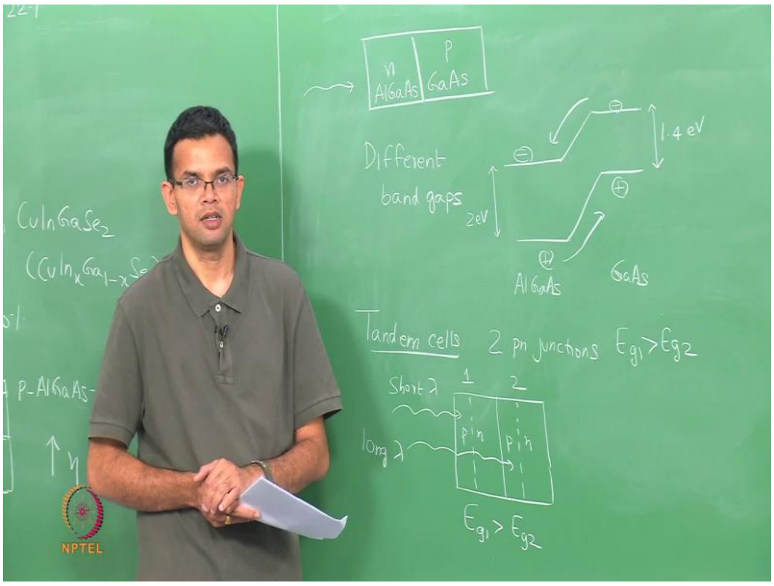

So, you have n aluminum gallium arsenide a p gallium arsenide, so aluminum gallium arsenide has a higher band gap. Once again x as the window in order to allow radiation to each the junction so that we no longer need the n layer to be really within the case of homo junction based p n junction. So, here you have different band gaps, so this again next carrier separation easy, so this is a gallium arsenide with a band gaps a 1.4 electron volts. This is aluminum gallium arsenide with two electron volts, so any electron volts pairs they are generated can be easily separated and this to a current you can have also solar cells that are in tandem, which means you have 1 solar cell on top of the other.

So, you have 2 p n junctions and you choose you material in such way the band gap of the first material is greater and the band gap of the second. So, if you look at the design, you have the first material which as p n junction and you have this again material with x p n junction. So, this has the band gap e g 1 is greater than g 2 the advantage of having this type of arrangement is that the shorter wave lengths will get absorbed by the first material. It has a lower absorption and distance or lower penetration distance while the long wavelength will get observe a material 2 the problem of course, is that making the devices more complex.

Although on 2, the processing cost and the processing complexity because if you have tandem cells like these and they to be grown with no defects between them, defects will again act as traps for carriers and will reduce efficiency of the device. So, these last few classes we have looked at electronic devices. So, we started with is simple metals a semiconductor junction, then we moved on to p n junction and then we looked at transistors we also looked at some examples of up to electronic devices like LED’s LASER’s photo detectors.

Then, losses, so in the last part of the course we are going to focus on fabrication of these devices we look at some of the terminology that are used. Some of the process that I used in fabrication, and also the challenges we are also look at some alternate methods of fabrication then your standard micro fabrication processing this currently being practiced.