Fundamentals of electronic materials, devices and fabrication
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Lecture - 19
Optoelectronic devices: Solar cells

Last class we looked at Photo detectors, so in the case of Photo detectors we had an incident light on to your device which was converted into an electrical signal.

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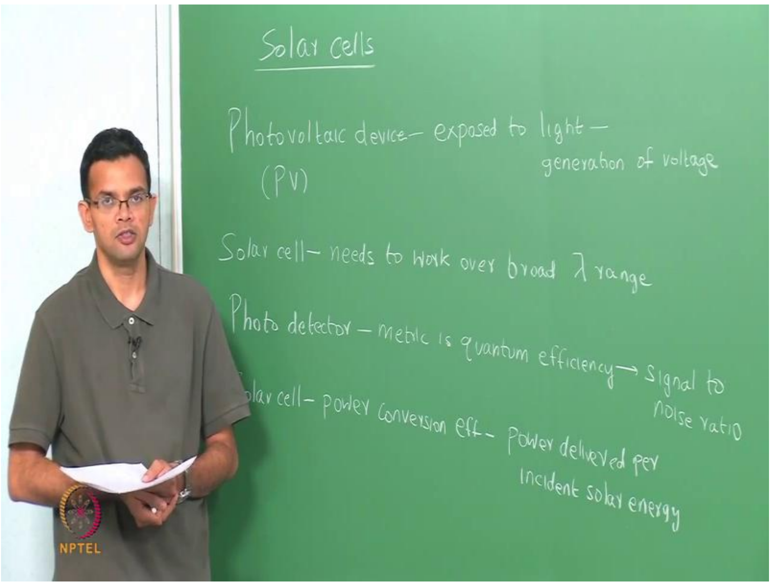

Today, we are going to look at solar cells. A solar cell is an example of a photovoltaic device; that is it is a device where you have a generation of voltage when expose to light. So, when expose to light leads to a generation of voltage. Photovoltaic were first discovered by Henri Becquerel in 1839, but the first silicon based p-n junction photovoltaic was invented by Ohl in 1940.

The principle of a photovoltaic, let me just abbreviate this as P V, is similar to the Photo detector that we looked at last class, they are just a few crucial differences. So, in the case of a photo detector we saw that one such example was a photodiode, could be a simple p-n junction or a pin junction. So in that case, a photo detector works over a narrow wavelength range. So, The maximum wavelength depended upon the energy of the transition that was involved. So, if there was a transition from the valence band to the conduction band, the maximum wavelength was defined by the band gap of the material. The minimum wavelength range depended upon the observance of the material because as wavelength decreases absorbance increases so that light is only absorbed very close to the surface.

In the case of a solar cell, we need the device to 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 a photo detector, the wavelength range is imposed by the 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. 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.

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

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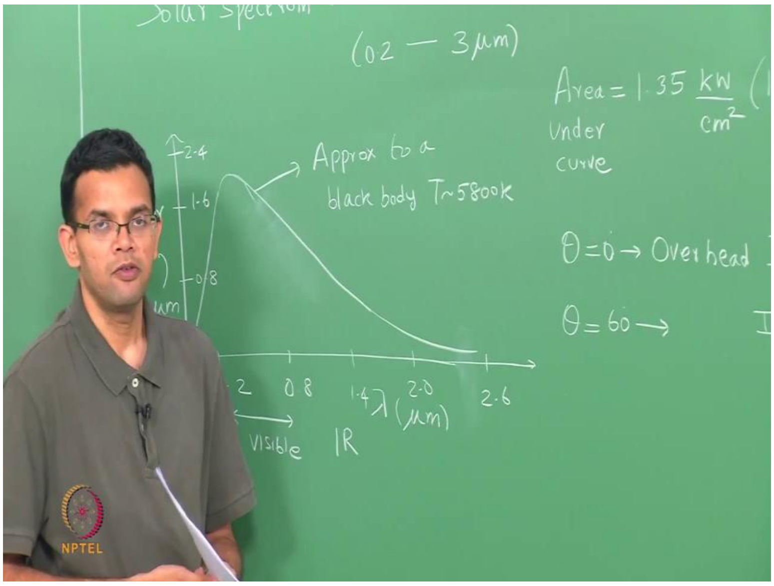

If we look at the solar spectrum it primarily ranges from the UV to the IR region so it encloses the visible region, so it goes from UV to IR. The typical wavelength range goes from around 0.2 microns or 200 nanometers to 3 microns. So, 3 microns lies in the IR region 0.2 in the UV region, so this encloses the visible region as well. Of course, the intensity of this radiation is not too constant; the intensity depends upon the wavelength.

We can plot a power spectrum verses wavelength, so I have wavelength lambda on my x-axis this is in micrometers, then I will plot the power and the unit is kilowatt meter square per micrometer. So, this is your power spectrum, this is 0.2, 0.8, 0.4, 2 let me extend the axis a bit, 2.6, 0, 0.8, 0.6, 2.4. So, the visible region lies somewhere between 0.2 and 0.8, so is visible this IR, this is UV. So, If we 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 6000 kelvin, so it is approximated to a black body. The area under the curve gives the total intensity of the incoming solar radiation; this area has a value of around 1.35 $kWcm^2$ 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 that you have scattering of radiation by the earth's atmosphere. So, The atmosphere has ozone; it also has some water molecules so these can scatter the solar radiation. They also have 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 over head so when θ is 0. So, when we have the solar light directly over head, the intensity I is around 0.925 kilowatts per centimeter square and when θ 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, this energy spread is 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 your device in order to produce an electrical signal. Let us consider a simple design of a solar cell

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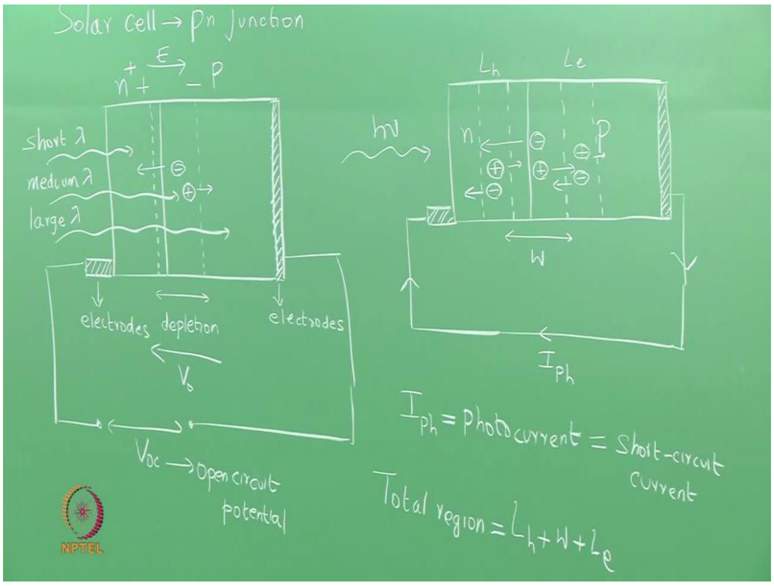

Let us look at a solar cell that is based on a simple p-n junction. So, last class we saw that your photo detectors are also based upon a p-n junction or a pin junction so the basic principle is similar. I have a solar cell that is based on p-n junction, the n region is heavily doped so I will call it pn^+ and we also have a thin n region because the light has to penetrate through the n region. So, if I were to draw a schematic of this here, is my solar cell I have electrical contacts at one end, my light is incoming from this direction. So, I also have electrodes on the other end, but these electrodes do not cover the entire surface because the light has to penetrate through your device.

This is the interface between the n^+ and the p region so the n^+ region is heavily doped. In this case the depletion region will lie almost entirely on the p side. I have a very thin depletion region on the n side and it is lot more thicker on p the side, so these are electrodes. So, We have solar radiation coming from the left and falling on the n^+ region so now your radiation can have both long wavelength medium and short wavelength. Shorter the wavelength higher the energy, the short wavelengths are usually absorbed by the n^+ region because the absorption coefficient is large.

Hence, the penetration depth is small. Whereas the wavelength increases the penetration depth also increases. This just a picks 3 kinds of wavelength short, medium and large, when the wavelength of light gets absorbed it generates an electron hole pair. So, For example, the medium wavelength region generates an electron hole pair within the depletion region.

We have looked at a p-n junction in equilibrium, we know that whenever we have a junction we always have a contact potential. We have a + and the - we saw this earlier when we were talking about p-n junctions. This arises because you have the electrons and the holes recombining and getting annihilated to give you a depletion region. So, the electric field goes from positive to negative which means there is a built-in potential or a contact potential V_o. So, When the incoming radiation generates an electron hole pair, the electron is accelerated towards the n-side because it sees the positive potential in a hole is accelerated towards the p-side. This means there is now a potential that 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 a open circuit you have a short circuit, you have a current that flows through the device and it flows through the outer circuit because of the electron in hole pairs that are generated, this current is called your short circuit current. Let us draw schematic of that, main I have my n and the p and there a depletion region. So, we have the electrodes on both sides and instead of having open circuit, we make the electrical connections 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 generated, the electron accelerating towards the n side and the holes accelerating towards the p side so that the current flows from p to n, this current is called your photocurrent. So, it is the current that is generated because you have photo generated careers.

In the absence of any external load, it is also called the short circuit current. So, In this particular figure, let w be the width of the depletion region so your electron hole pairs are generated within this width W. But if you also look more closely electron hole pairs are also generated within the n and the p regions because all of these regions absorb 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, but these electrons and holes are essentially minority careers.

So, They can only defuse within a region which is define by the diffusion width so L_h is the diffusion width of the holes, which are the minority careers on the n-side and L_e is the diffusion width or the diffusion length of the electrons, which are the minority careers from the p-side. So, The total region from which current is generated is $L_h + W + L_h$. 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 I-V characteristics of a solar cell.

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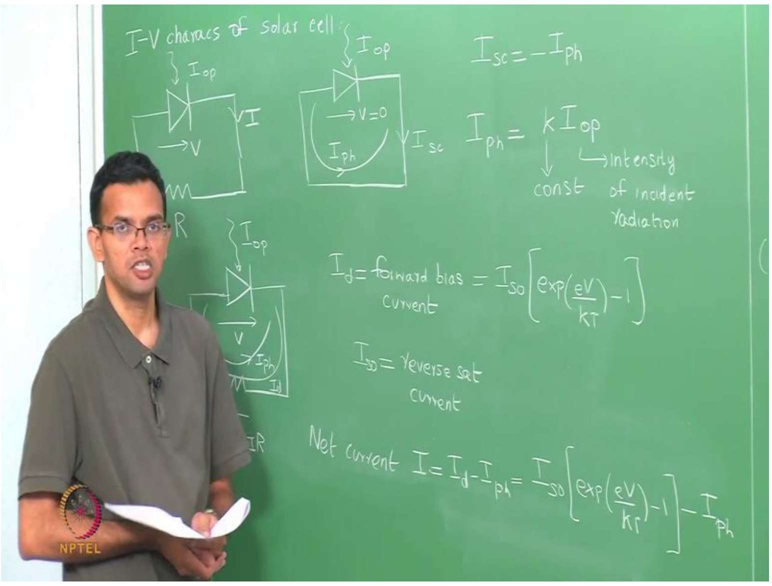

So, Let us look at the I-V characteristics of a solar cell. In this particular case, you are looking at a solar cell which is a simple p-n junction that is connected to some external load, the external load is defined by a resistor r and you have some incident light of certain intensity which is given by I_{op}. In this particular case, there is a built-in voltage within your p-n junction and also a current that flows through the device. This is a schematic representation of a solar cell that is connected to an external load.

Now in the absence of a load, where the resistor is 0, we saw that when you shine light you have a photocurrent that is generated within. In this case the voltage or the voltage difference is 0 because you have a photocurrent; I_{ph}. If you define the conventional direction of current the other way and call it I_{se}, which is your short circuit current then i s e is nothing but minus of I_{ph}. So, I_{se} is the short circuit current which is the current that flows through at the device when it is short circuited, when there is no external load and this intern depends upon the photo current I_{ph}. Now, I_{ph} depends upon the intensity of solar light that is shining on your device. So, I_{ph} is usually some constant K times I_{op} which is the intensity of the solar radiation signing on the device so K here is a constant and this is the intensity of incident radiation.

So, We take this and now add on an external load in the form of a resistor. Again, you have a potential now you have I_{op}. So, once again there is a photocurrent which is I_{ph}, but this photocurrent generates a voltage across the resistor, this voltage across the resistor is I R and this voltage opposes the inbuilt voltage of your p-n junction. Because any p-n junction has an inbuilt potential or an inbuilt voltage, which is your contact potential and the photocurrent basically generates external potential that opposes this. So, This is equivalent to saying that your forward biasing your p-n junction so that now it is easier for the minority careers to defuse so that you have a forward biased current. So, The forward bias current goes the other way, you going to call it I_d so I_d which is your forward bias current and you can write the standard diode equation for this is I_{so}, where I_{so} is the reverse saturation current $exp\left(\frac{E_v}{kT}-1\right)$. So, I_{so} is your reverse saturation current which we have seen earlier in the context of a regular p-n junction.

We have a forward bias current that goes in one way, we have a photocurrent due to the radiation that falls on your sample that goes the other way so the net current I, is nothing but I_d - I_{ph} which is just $I_{so}\left[\exp\left(\frac{ev}{kT}\right)-1\right]-I_{ph}$. So, it is possible to draw an equivalent circuit for your solar cell which is nothing, but a p-n junction under illumination.

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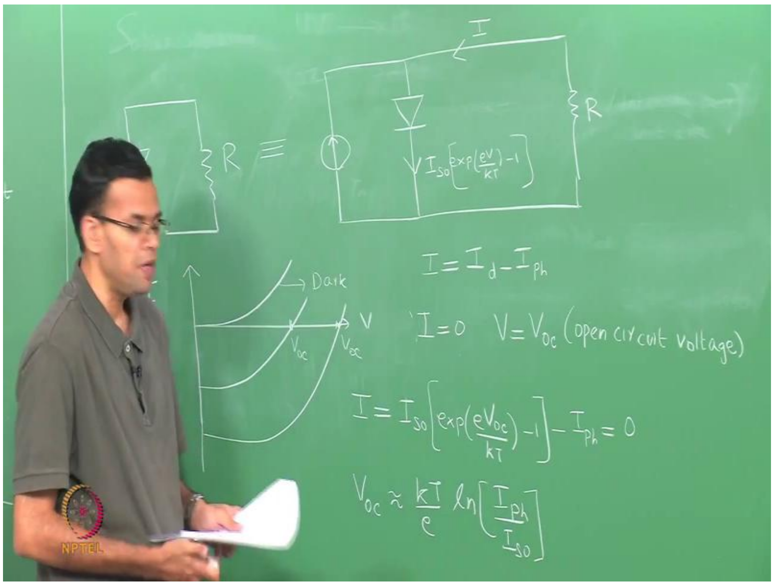

We have a solar cell connected to an external load and you have some incident radiation shining on it so it is possible to draw an equivalent circuit for that. In that case, you have a constant current source which is your photocurrent generated because of the incident light you have your p-n junction that is now under forward bias so that there is a forward bias current I_{so} and this forward bias current opposes the constant current source or your photocurrent and then there is your resistor R.

So, The equivalent circuit for a solar cell is just a constant current source and a p-n junction under forward bias which oppose each other. We can also draw an I-V characteristic for the solar cell, if there is no radiation. In the case of a dark solar cell the I V characteristic will just resemble a p-n junction under bias. So, we have the current which increases exponentially with the voltage, just given by this expression. This in the case of dark we found that when we shine light, we have a photocurrent that opposes the forward bias current so that the net current is $I_d - I_{ph}$. So, The affect of this is to shift your I-V current below so that when you have some photocurrent shining you no longer start at 0, but you are shifted below because of the $-I_{ph}$. If you increase the value of the incident radiation intensity so that I_{op} is higher then I_{ph} will be even higher and then you are 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 your open circuit voltage. In that case, I which is $I_{so}\left[\exp\left(\frac{eV_{oc}}{kT}\right)-1\right]$ this is 0. When the voltage is V_{oc} which refers to this point the current is 0, so we can rearrange this expression to give you V_{oc} to be approximately equal you can neglect this factor -1 to be $\frac{kT}{e}\ln\left(\frac{I_{ph}}{I_{so}}\right)$. Let me rewrite this expression and we can look at the 2 parts of it.

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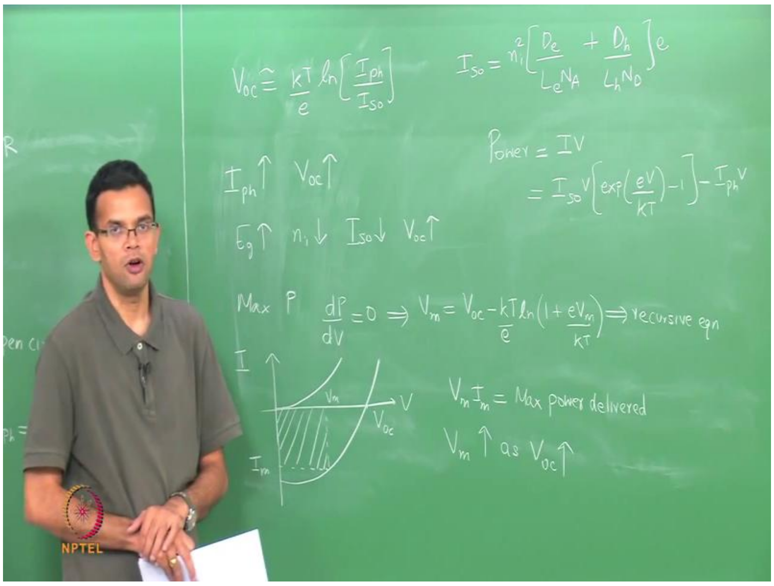

So, We have written down the expression for the open circuit voltage, V_{oc}approximately $\frac{kT}{e}\ln\left(\frac{I_{ph}}{I_{so}}\right)$; I_{ph} is your photocurrent which depends upon the intensity of the light and I_{so} is your reverse saturation current, which depends upon the intrinsic career concentration n_i^2 and also on the diffusion coefficients, diffusion lengths and the concentration of p and the n regions there is a term e here.

So, If you increase the value of photocurrent, so if I_{ph} is higher, V_{oc} will increase. Similarly, if go for a material with the higher band gap so if E_g is higher then n_i will be lower, so I_{so} will be lower and that will also increase V_{oc}. So, In the case of a solar cell, we saw that the important parameter was the power conversion efficiency. The power is nothing, but I times the voltage which is I_{so} v $\left[\exp\left(\frac{ev}{kT}\right)-1\right]-I_{ph}v$. In order to have the maximum power so for maximum power $\frac{dP}{dV}$ 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 recursive relationship that relates V_m to V_{oc}. So, this is a recursive relationship because V_m is on both sides, but it can be solved in order to get the maximum voltage or the voltage corresponding to maximum power. Once we know the value of V_m we can plug in this expression and get the maximum power.

Let us once more look at your I-V curve, you just redraw this so this is your dark current, this is your current under illumination, this point is V_{oc}. So, we can calculate the V_m which corresponds to the maximum power and also the I_m, so this is V_m corresponds to I_m. The area under the curve or the area between these two points gives you the maximum power that is delivered to this system so V_m x I_m see maximum power delivered. If you do the calculation, we find that V_m will increase as V_{oc} increases. So, higher your open circuit voltage, higher the value of V_m. So, One way of increasing V_{oc} is to increase the intensity of the radiation and the other way we saw, was to have a p-n junction with a higher band gap. The drawback in that case is that as your band gap increases, the region of the solar spectrum that is being absorbed will decrease because as E_g increases, the corresponding wavelength for the transition will decrease. So, there is a trade off on what material you choose in order to get the maximum value of the power.

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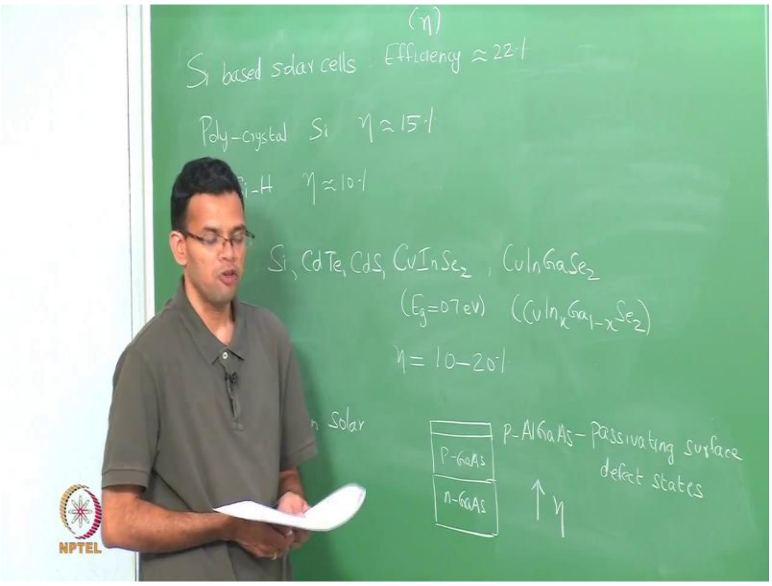

Conventional silicon based solar cells have efficiencies of around 22 percent, so in this case these are single crystal silicon based devices. Instead of single crystal if you have a polycrystalline silicon, your efficiency let me just call this eta, your efficiency will be around 15 percent. You could also go for amorphous silicon base solar cells; the advantage is that the cost is reduced because you can directly deposit these on a glass slide. So, you can have amorphous silicon base solar cells, but the efficiency will drop even further. There are other materials that are used for solar cells some of the typical materials we already saw, silicon have cadmium telluride, cadmium sulphide and then copper indium diselenide. This is a material with a band gap of around 0.7 electrons volts and a variation of this which is copper indium gallium diselenide. So, it is usually written as Cu_{inx} Ga_{1-x} Se_2. The band gap in this case depends upon the value of x, all of these have efficiency some where between 10 to 20 percent depending upon the processing root which is used in order to make this devices and also the quality of the films that are produced.

The solar cells you have seen so far are simple p-n junction based solar cells. You could also have a hetero junction solar cell, so in this case you can increase the efficiency of the device. For example, consider a hetero junction where we have p aluminum gallium arsenide which is a thin layer that is deposited on top of p and n gallium arsenide. So, in this case your p-n junction is still between the same materials. But the aluminum gallium arsenide layer helps in passivating the surface bonds or the surface defects states, it also has a higher band gap then gallium arsenide so that it allows the radiation to pass through it and be absorbed by the gallium arsenide, this intern leads to a higher efficiency.

So, You can also have other designs for p-n junctions; So, you can also have a p-n junction between different materials.

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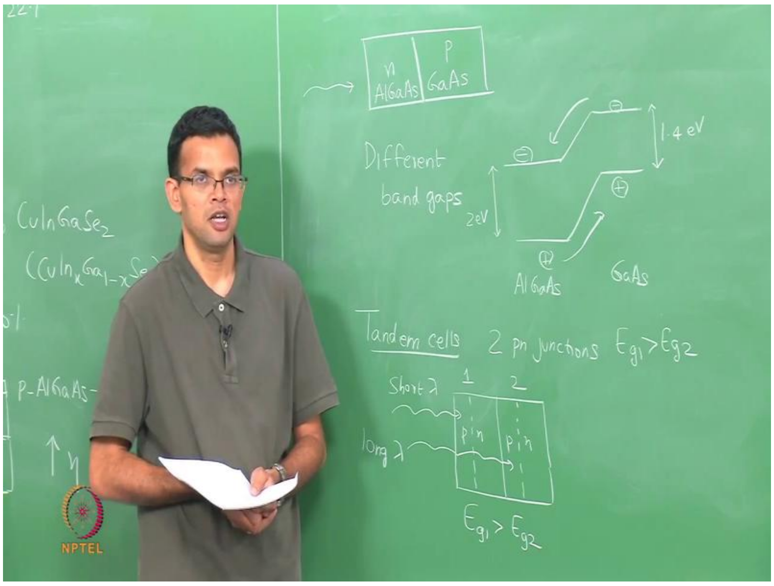

So, You have n aluminum gallium arsenide and p gallium arsenide, so aluminum gallium arsenide has a higher band gap once again it acts as a window in order to allow the radiation to reach the junction. So, that we no longer need the n layer to be really thin as in the case of a homo junction based p-n junction. Here you have different band gaps so this again makes carrier separation easy. So, This is your gallium arsenide with the band gap of 1.4 electron volts; this is aluminum gallium arsenide with 2 electrons volts. So, any electron hole pairs that are generated can be easily separated and this gives rise to a current. You can have also solar cells that are in tandem, which means you have one solar cell on top of the other. So, you have two p-n junctions and you choose your material in such a way that the band gap of the first material is greater than the band gap of the second.

If you look at the design you have the first material which has it is p-n junction and you have the second material with it is p-n junction, this has a band gap E_{g1} which is greater than E_{g2}. The advantage of having this type of arrangement is that the shorter wavelengths will get absorbed by the first material because it has a lower absorption distance or a lower penetration distance, while the longer wavelength will get absorbed by material through.

The problem of course, is that making the devices more complex also adds on to the processing cost and the processing complexity because if you have tandem cells like these then have to be grown with no defects between them because defects will again act as straps for carriers and will reduce the efficiency of the device. So, These last few classes we have looked at electronic devices so we started with a simple metal semiconductor junction then we moved on to a p-n junction and then we looked at transistors. We also looked at some examples of optoelectronic devices like LEDs, lasers, photo detectors and then solar cells.

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 processes that are used in fabrication and also the challenges. We also look at some alternate methods of fabrication then your standard micro fabrication processing that is currently being practiced.