Fundamentals of electronic materials, devices and fabrication

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Lecture - 18

Optoelectronic devices: Photodetector

The last few classes we have been looking at Optoelectronic devices. We first looked at devices where we have an input electrical current and convert that into light. So, we looked at 2 of those devices LED's and LASERs.

In both cases, we have electrons and holes that are injected into a semiconductor device. A small a typical example would be a p-n junction and we found that these electrons and holes can recombine in order to give you light. Now, we are going to look at a different class of devices where we shine light on to the device and then measure the electric current.

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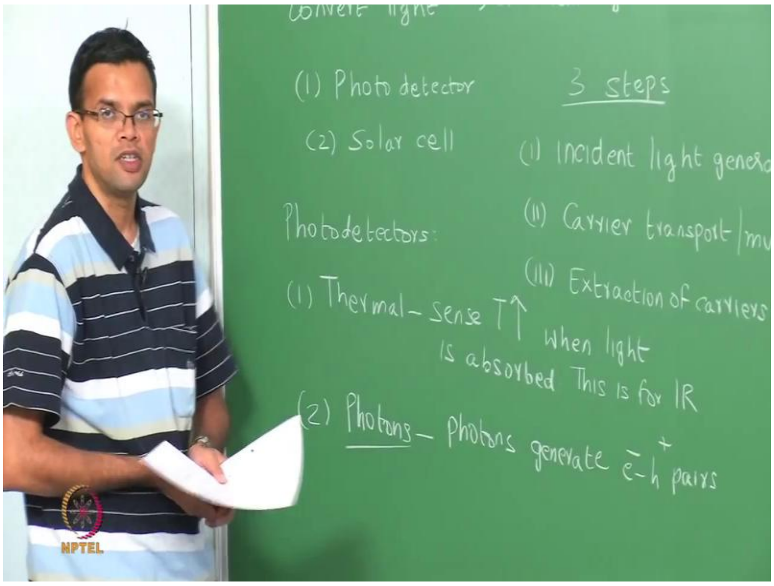

We are still looking at Optoelectronic devices, but we are looking devices where we convert light into an electrical signal. We are going to look at 2 such devices, the first one is the Photo detector and then later we are going look at a Solar cell. So, today we will start by looking at the Photo detector and as the name implies it basically detects incidence photons or radiation, and then tomorrow we will look at Solar cell.

So, There are 3 steps involved, when we think about shining light on to a device and then converting it into a electrical current. So, In the first case your incident light generates carriers in the device. So, when we talk about carriers these are all your electron hole pairs. Once these carriers are generated they need to be transported to the respective electrodes sometimes some sort of carrier multiplication is also possible. So, You have both carrier transport and multiplication. Multiplication is usually called the gain will see gain in the minute and then finally these carriers are then extracted out of the device in the form of a current. When we look at a photo detector, they are normally 2 classes of photo detectors. The first class are Thermal detectors. In this particular case, you shine light on to the device or you shine light on to the material which leads to a temperature raise which is measured and the temperature raise is directly proportional to the amount of light that is shining in. So, you sense a temperature raise when light is absorbed. This is mainly used for detecting I R radiation or infrared radiation.

The other case is your photons, which is the traditional sense in that your photons generate electron hole pairs. Now we will be mainly dealing with the second type of photo detectors, where your photons generate electron hole pairs.

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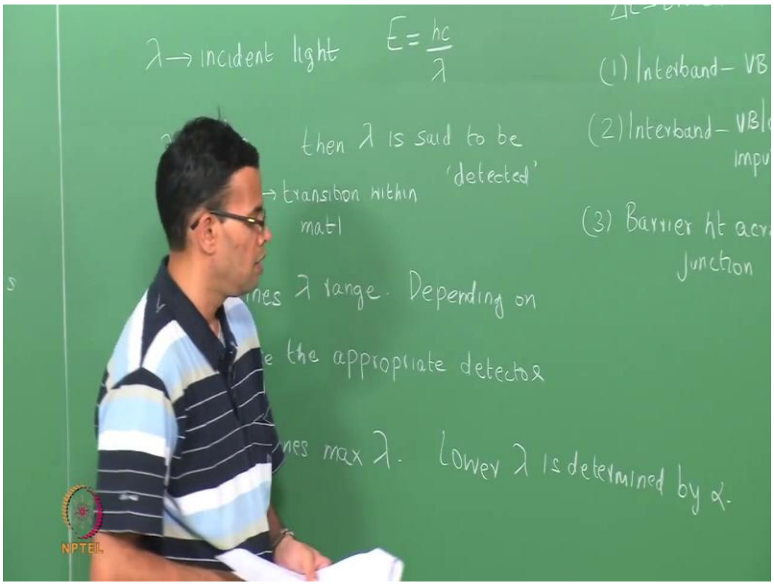

So, consider incident light on your material of wavelength lambda, the energy of this radiation of course you have seen before is nothing but $\frac{hc}{\lambda}$.

This light can be detected if this lambda corresponds to some sort of transition within your material. So, as long as λ is less than equal to $\frac{hc}{\Delta E}$, where ΔE is a transition within the material, then your light is said to be detected. So, what are these different transitions that ΔE can correspond to? So, ΔE which represents the transition in your device or transition in your material it could be an inter band transition, so it could be from the valence band to the conduction band. That is the simplest and most common form of transition. So for example, if your material is gallium arsenide then you will absorb light of energy greater than the band gap so that an electron gets excited from the valence band to the conduction band. You could also have an inter band transition, but instead of going from the valence band to the conduction band you could have impurity levels within your band gap, so a transition is from either the valence band or the conduction band to some impurity level.

So, Typically, if you dope a material, so that it generates impurity levels in the band gap then these kinds of transitions are possible. If you have junctions then you have barriers at the junction, so that your transition could be across a barrier. So, This could correspond to a barrier height across the junction. For example, later we will look at some schottky diode based photo detectors, in which case your electrons or your light can have sufficient energy in order to excite the electrons from the metal to the semiconductor, in which case they will have to overcome the schottky barrier. So, this delta E depends on a variety of transitions and this defines the wavelength range of your photo detector. More especially ΔE determines the long wavelength range that is possible or the minimum or the maximum wavelength that is possible.

Another way of saying this is that depending upon the wavelength range your interested in you will choose the appropriate type of photo detector or the photo detector material range. Depending on λ you can choose the appropriate detector. So, The difference between a photo detector here and in the case of a solar cell is that in a solar cell the wavelength range is sort of fixed because it depends upon the solar spectrum that has a specific wavelength range. So, later when we look at the solar cell we will see that solar spectrum and what is the wavelength spread. So, Solar cell the wavelength range is fixed, so we want to choose materials which absorb in that range. The other hand in the case of a photo detector depending upon the wavelength range we will choose what material we want to use.

So, The maximum wavelength is determined by ΔE, so any wavelength that is larger than that determine by ΔE will not be able absorb or will not be able to produce your electron hole pairs and will not get absorbed. There is also a lower wavelength regime and that depends upon the absorption coefficient of your material. So, The lower wavelength, so we have a maximum wavelength which determined by ΔE and the lower wavelength is determined by α.

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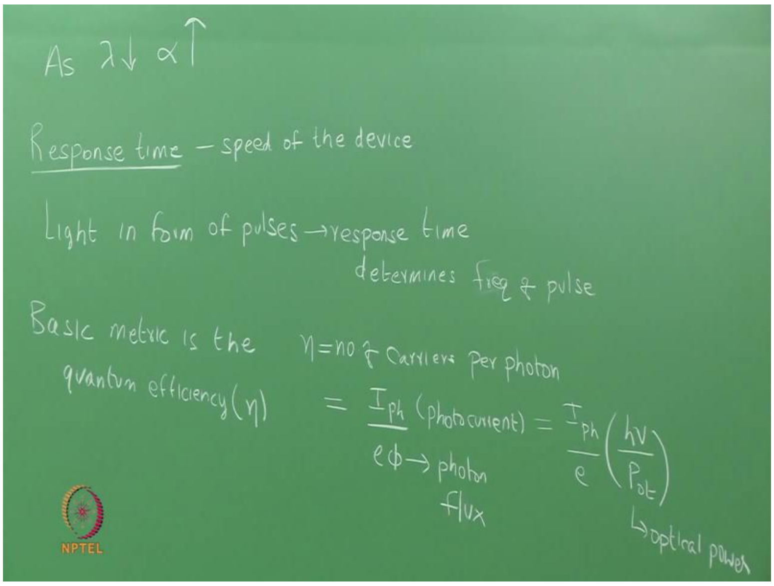

We have looked at the concept of absorption coefficient before, we find that if α is the absorption coefficient then the intensity at a distance x within the material was just $I_o \exp(-\alpha x)$. So, I_o is the intensity at the surface, I(x) is the intensity at some depth x and α is your absorption coefficient. You have seen earlier that as the wavelength reduces alpha increases, which means the material gets absorbed at a lower depth. So, This absorption coefficient determines the lower wavelength regime. If α is very large then all of the light get absorbed within a layer very close to the surface and would not have sufficient electron in hole pairs in order to be able to detect it. So, the higher wavelength regime is determined by the band gap of the transition or the energy of the transition and the lower wavelength regime is determined by α.

Another important factor in the case of a photo detector is the Response time. This determines the speed of the device. So, If we think of light arriving in the form of pulses the response time determines how close these pulses are so that they can be individually detected. If you have light in the form of pulses, the response time determines the frequency of these pulses, determines the speed or the frequency of the pulse. So the response time depends on the fact that you have electrons and holes that are generated and these must defused through the device in order to reach the electrodes and then form your current. It depends upon the diffusion coefficient or the mobility of the electrons and holes in the device. If you have a photo detector that is based upon a p-n junction with a wide depletion region then the distance the electrons in holes have to travel is longer which means correspondingly the response time is short.

On the other hand, if you have a thin depletion region, the response time is I am sorry, if you have a p-n junction with a wide depletion region then the distance the electrons in holes have to travel is large, so that the response time is also large. On the other hand, if we have a p-n junction with the very short depletion region then the distance the electrons and holes have to travel is small, so that the response time is fast. But the drawback is the number of electrons and holes generated are small so that you need a large amount of signal in order to form or in order to be able to detect the radiation. So, they are different tradeoffs depending upon the design of the device and the response time that is required. The basic metric of a photo detector is called the Quantum efficiency.

So, The quantum efficiency is defined as the number of carriers that are generated per photon. So, This in turn is related to the photo current divided by the flux of the photons, so I_{ph} is the photo current; this term φ is the photon flux. Another way of writing this is that it is $\frac{I_{ph}}{e}$ and the flux of the photons is depends upon the power of the incident radiation and the energy. So, $h\upsilon$ is the energy of the radiation and P_{ot} is the optical power. In the case of a photo detector, they could also be an internal gain mechanism, so that even though we have a certain number of photons that are incident on your device, the numbers of electron hole pairs are larger. We have both a gain and a response time that basically characterizes your photo detector. Now, there are different kinds of these detectors all having different values for gain and response time. So, let me just tabulate some of these types a photo detectors.

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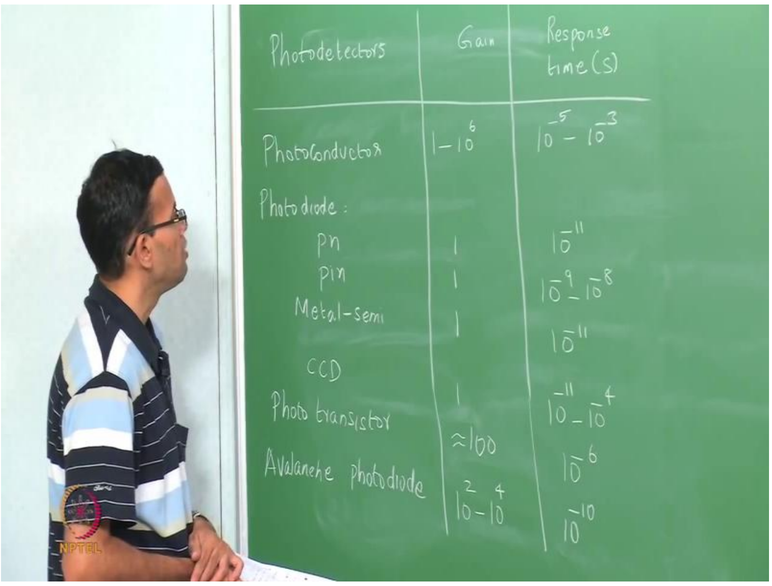

So, we look at some of the types of photo detectors and then you will look at a comparison of their gain and the response time, Response time is given in seconds. So, a simplest photo detector is just a photo conductor, depending upon the applied electric field and will talk about it in a minute, you can have a different gain values. And the response time is usually of the order of milliseconds. Could also have photo diodes, this could be a simple p-n junction a pin stands for, a p and intrinsic and n or it could be a metal semiconductor. Instead, all of these cases your gain is typically 1 which means all the light that comes in just gets converted into electron hole pairs. Response time of these devices are typically much better or much shorter, this is around 10^{-11}.

You could also have charged coupled devices. This has a wide range of response times, these are all photo diodes. You could also have a photo transistor. One of the advantages of a transistor is that it is always possible to have some gain, and your response time is of the order of micro seconds. Another type of a photo detector is based on an Avalanche photo diode, which also has a gain that is larger than unity because it is based on avalanche process and also very response time. We have a wide variety of photo detectors these depend upon the type of materials you use and also on the junctions that are found. We will not look at all of these, but we look at some examples of these photo detectors in order to better understand the mechanism. So, the first thing we look at is a photo conductor.

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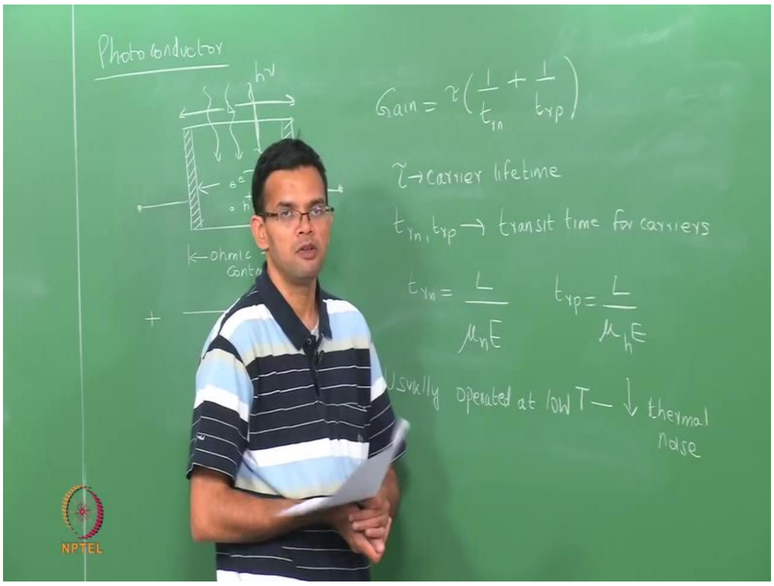

So, consider a simple slab of silicon, we are looking at a Photo conductor. So, consider a simple slab of silicon with 2 electrodes on either ends, these can be typically metals. They form a ohmic contact with silicon you want to choose the materials in such a way, that you have an ohmic contact. This is your central slab it is 2 ohmic contacts.

Let L be the length of your slab. So, we can have incident light fall on to your slab. You have incident light which of some energy which depends upon the wavelength, so it is $h\upsilon$ or $\frac{hc}{\lambda}$ and if this energy is sufficient it will generate electron hole pairs. If we now apply an electric field across the silicon we're using your ohmic contacts, we can basically extract the electrons in holes and then form a current which your photo current. So, one of the terminals is connected to a positive side the other is connected to a negative. In this case, there is an electric field, so the electrons and holes move in the opposite direction.

So, The current in this device is directly proportional to the number of electrons hole pairs that are generated, which in turn depends upon the intensity of the light that falls on the material. In this case of a device, the gain is given by τ divided by the time for your holes for the electrons and 1 over time for the holes. So, τ refers to the life time of the carriers because once your electrons in holes are generated they will like to recombine. So, The recombination is determined by the carrier life time. T_{rn} and T_{rp} they are the transit time for these carriers to the electrodes, this in turn depends upon the length of the device, so T_{rn} is depending upon the length. It depends upon the mobility of your electrons or holes, so mu n and the applied electric field. Similarly, T_{rp} is just $\frac{L}{\upsilon h}$ times the electric field. So, higher the mobilities or higher the electric field shorter is the transit time and similarly smaller the device, so smaller L shorter will be your transit times.

Usually, in the case of a simple photo conductor there will always be some thermal noise, because you will always have some thermally generated electrons and holes. These devices are usually operated at low temperatures. Typically, there are operated at liquid nitrogen temperatures in order to minimize the thermal noise, so to reduce. So, The next device we are going to look is a photo diode. Here, you are going to put 2 different materials over p n and n in order to form a junction. In the case of a simple photo conductor all we had was a slab of a semiconductor material, so it could silicon, it could gallium arsenide and in that just generated electron hole pairs.

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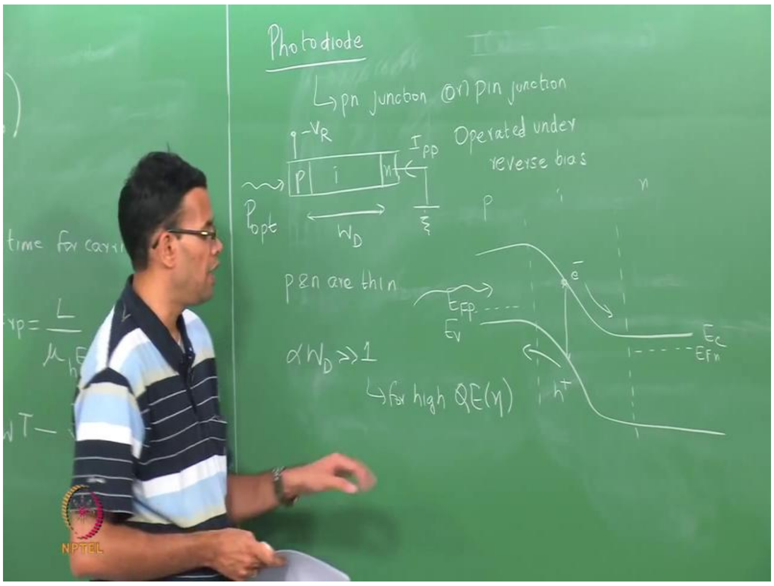

In the case of a photo diode, we use a p and n material so that you form a junction. This can a simple p-n junction or modification of that which is your pin junction. So, Electron hole pairs are generated either in the depletion region of the p-n junction or they generated in the intrinsic region. These electrons and hole pairs are then separated by applying a reserve bias to the junction, so that the electrons go towards the n side, holes go towards the p side and then you have a current. So, consider a simple pin kind of device. The intrinsic region is typically wide and the p_{nn} regions are short, these devices are usually operated under reverse bias, so that a negative charge is applied to the p side. In this particular example the n side is just grounded.

We have some incident light shining on this pin device that is just your optical radiation. We want to make the p and the n regions short so that the light can shine through. And then most of the electron hole pairs are generated in the intrinsic region. So, p and n are typically thin. So, If you were to draw the energy band diagram for this under reverse bias, have my p_i have intrinsic I have n. This refer to your conduction band, this refers to the valence band, this is E_{Fp} this is E_{Fn}. So, in this particular case there is a reverse bias, the reverse bias voltage depends upon the difference in the Fermi levels. Now, we have incident light that falls on your material, so that generates electrons in the conduction band and holes in the valence band, because of a reverse bias these electrons in holes are separated and they contribute to the current. In the absence of any light there will be a small current which is your reverse saturation current, which is similar to any p-n junction under reverse bias. When we shine light this current is enhanced because we now have an additional photo current due to the electrons in holes that are generated.

In the case of these devices p and n are really short, so that most of the absorption takes place within the intrinsic region. If alpha is the absorption coefficient in W_D, is the width of the intrinsic region and ideally we want alpha times W_D to be much greater then 1, this is for high quantum efficiency. Another way of saying that is that $\frac{1}{\alpha}$ is your penetration depth, so that we want the width of the region to be much larger than the penetration depth of the wavelength of interest. So, These cases whether you have a simple p-n junction or a pin you could have them of the same material. Another way to do that is to have a hetero structure based device. So, that you can have a hetero junction photo diode.

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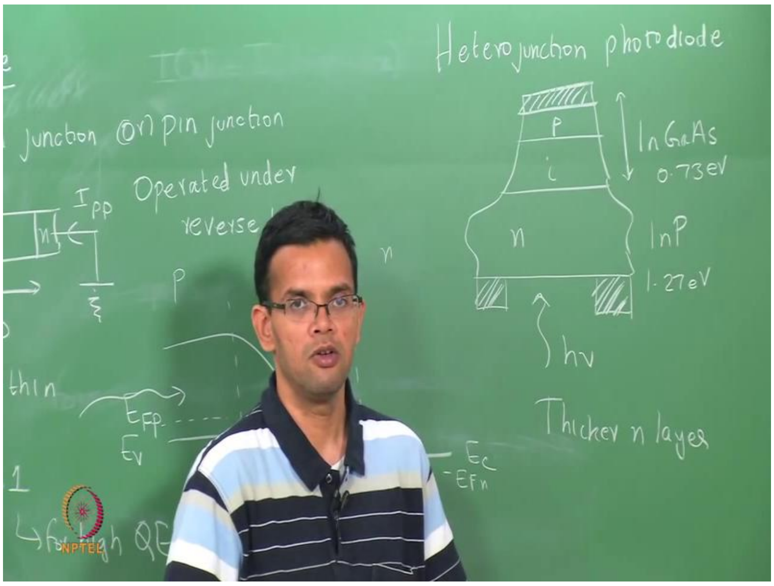

So, Let me draw a simple schematic of such a structure, represents the contact, it is my p region, that is the intrinsic region, then I have the n region. So, my n region is made of indium phosphide and my p and the intrinsic regions are made of indium gallium arsenide. Indium phosphide has a higher band gap 1.27 e v and indium gallium arsenide has a band of 0.73 e v. The advantage of the hetero junction device is that, in the case of a regular pin the p and the n region should be really short in order to not to absorb the light. But here since indium phosphide has a higher band gap, wavelength whose energy is less then this will have a very little absorption in the indium phosphide. So, that the thickness of the n layer does not have to depend upon the wavelength of the light, you can have a thicker n layer then what you normally have in a regular pin device.

So, In this case light shines from below, so that you can have a thicker n layer, so that all the wavelength whose energy is below 1.27 will get absorbed. Another advantage of the hetero junction photo diode is that we can cut off certain portions of the wavelength that you would not want. For example, if you do not want to look at wavelength above 1.27 by having a thick n region those wavelengths or those energies can be absorbed, so that only wavelength of a certain range can be detected by the photo detector. So, The hetero junction photo diode it works on the same principle as a regular p-n or a pin, but offers added functionality because of the difference in the band gaps. The 1 caveat is we have to grow different materials, so growing these materials with good epitaxial contact is very important. We can also have a photo diode based on Metal semiconductor junctions.

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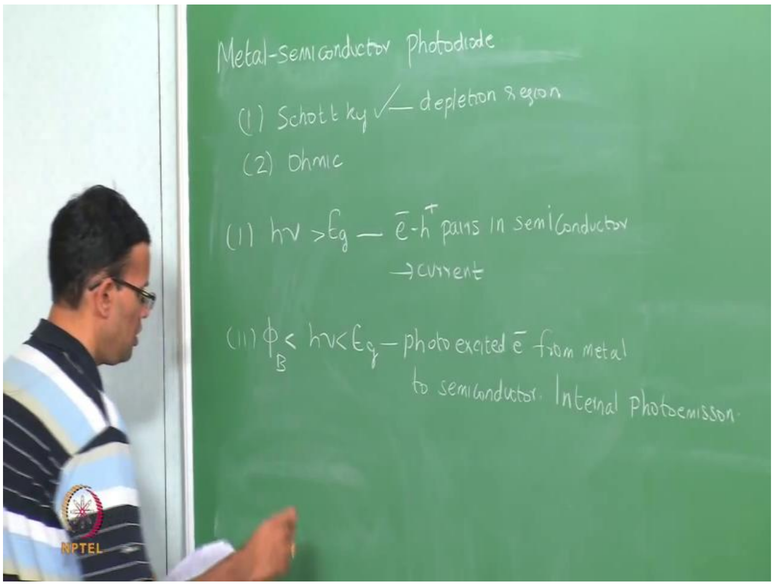

We have seen earlier that there essentially 2 kinds of metal semiconductor junctions, 1 is your Schottky junction, the other is the Ohmic junction. So, In the case of a photo diode we want a depletion region, so that we can generate electron hole pairs. Now the schottky junction is a one that has a depletion region, so we use a schottky junction to form your photo diode. So, There are 2 modes of operation of a metal semiconductor diode and the reason we have 2 modes is because we now have a barrier between the metal and the semiconductor, this is your schottky barrier. So, in the first case, if the energy of the photon is more than the band gap E_g, then it behaves like your regular photo diode, electron hole pairs are created. These are created in your semiconductor and they contribute towards current. You have electron hole pairs in the semiconductor that lead to current. On the other hand, if you have light of energy less than the band gap, but more than the barriers height, in this case it is your schottky barrier. The energy is more than the barrier height, so you can excite an electron from the metal and take it above the schottky barrier. In this case, it is called Internal Photoemission and this electron can contribute to the current. We can have a photo excited electron from the metal crossing over the schottky barrier into the semiconductor. This process is called an Internal Photoemission.

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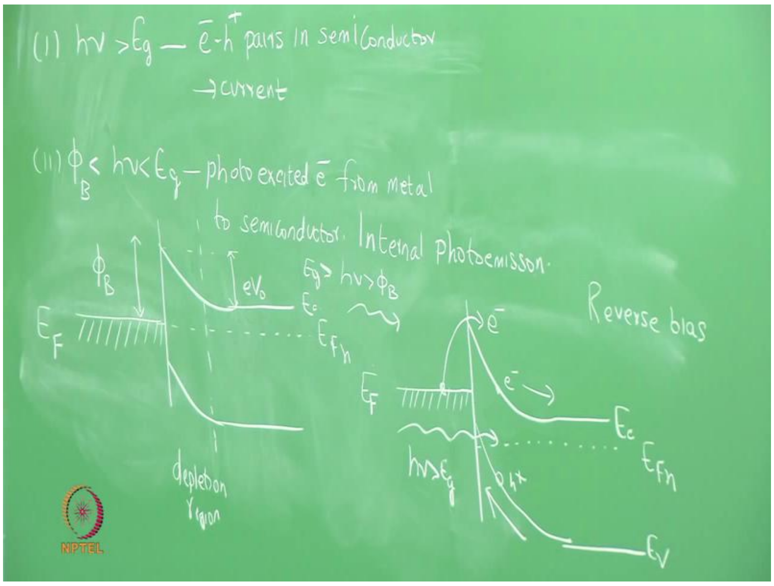

So, consider the example of a schottky junction in equilibrium. This is my metal side E_F. You have seen earlier that a schottky junction is formed, when the work function of the metal is greater than the work function of the semiconductor. Have a depletion region, so my semiconductor is n-type that is my Fermi energy. I have my conduction band E_c and then I have my valence band, so that you have a depletion region on the semiconductor side. There is a built-in potential which is ev_o and there is a schottky barrier height φ_B. The schottky barrier height depends upon the difference between the work function of the metal and the electron affinity of the semiconductor. So, When we apply a reverse bias to this junction a semiconductor potential shifts, so the metal is still the same, semiconductor shifts E_c, E_v, E_F, E_{Fn} for reverse bias. If you have light of energy greater than the band gap, so $h\upsilon > E_g$ then you will generate your electron hole pairs, electron I have a hole which will travel in opposite directions in order to give me my current. The other hand if you have light energy greater than the schottky barrier, but less than the band gap, then you can take an electron from the Fermi level of the metal and then take it above the schottky barrier and that can also give you current. So, by using a metal schottky junction you can increase the wavelength range that you want to interrogate with your photo detector. You are no longer limited by the band gap of the material, but you can extend it further depending upon the schottky barrier.

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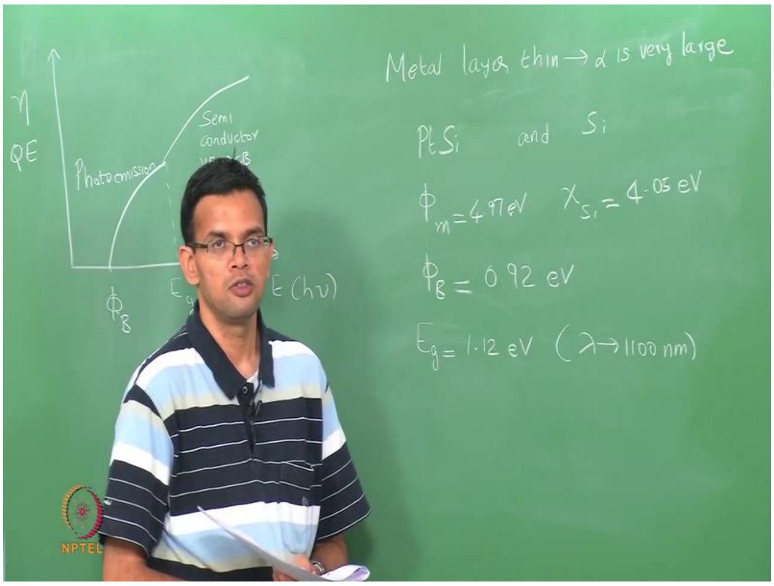

So, you were to draw the quantum efficiency of this device versus the energy. So, η is your quantum efficiency QE versus energy E of the light, so that just $h\upsilon$. You have 1 term that corresponds to E_g then, there is φ_B which is the barrier. So, anything below the barrier will not get absorbed, above the barrier you have some gain because of the internal photo emission process and above E_g your gain is higher because you now have the transition with in the semiconductor. This is conductor valence band to conduction band.

Usually, instead of using metals we can also silicides. For example, if we have platinum. You could have platinum silicide forming a junction with silicon and that can use as a photo detector. So, In the case of metal semiconductor photo detector, the caveats, the metal layer should be really thin because metals usually have very high absorption coefficients. So, the metal layer should be thin because alpha is very large. For example, if you have platinum silicide and silicon. So, platinum has a work function a 4.97 ev, silicon has an electron affinity of 4.05. So, the schottky barrier φ_B is just the difference between these 2 so it is 0.92 ev.

The band gap of silicon E_g is 1.12 electron holes. This corresponds to a wavelength of approximately 1100 nanometers. So, As long as your wavelength is below 1100 or energy is above E_g then the light will be absorbed by the silicon, but if your energy is between 1.12 and the schottky barrier, then light will be absorbed by the platinum silicide layer in the internal photoemission process. So, We have looked at 3 examples photo diodes, so you have a simple p-n junction or a pin or a metal semiconductor. You could also have a photo transistor. In this case, you have a regular bipolar junction transistor which we have seen before it has an emitter base and the collector. So, in this particular case you modify your simple by Bipolar Junction Transistor to have a larger base, so that electron hole pairs are generated within that and this in turn get separated and forms your current. You could also have a hetero junction base device from your transistor in order to improve the gain.

So, We have looked at different examples of photo detectors, in all of these cases the wavelength range that can be scanned depends upon the type of material that you have. In the next class, we are going to look at a solar cell which works in a similar way to a photo detector, but the wavelength range is fixed it depends upon the solar spectrum that is incoming on to the sample.

So, we will look at the working of a solar cell and also some of different materials and efficiencies when we use them in the solar cell.