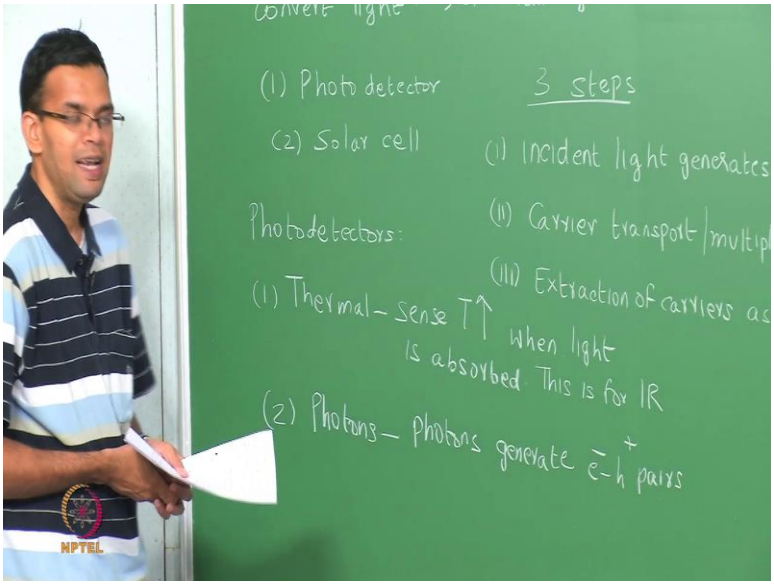
Metallurgical and Materials Engineering

Prof. Dr. S. Parasuraman.
Department of Metallurgical and Materials Engineering
Indian Institute 0f Technology, Madras

Lecture - 18
Optoelectronic devices: Photodetector

The last few classes we have been looking at optoelectronic devices. We first look at devices where, we have an input electrical current and convert that in to light. So, we looked at two of those devices: LEDs and Lasers; in both cases we have electrons in holes that are injected in to your semiconductor device at small typical example would be a p-n junction. And we found these electrons in holes can recombine in order to give you light. So, now we are going to into look at different class of devices where we shine light on to the device and then measure the electric current.

(Refer Slide Time: 01:04).



So, we are still looking at optoelectronic devices, but we are looking at devices where we are convert light into an electrical signal. We are going to look at 2 such devices: first 1 is Photodetector and then later we are going to look at Solar cell. So, today we will chart by looking at the Photodetector and as the name implies it basically detect incident photons or radiation and then tomorrow we will look at the Solar cell.

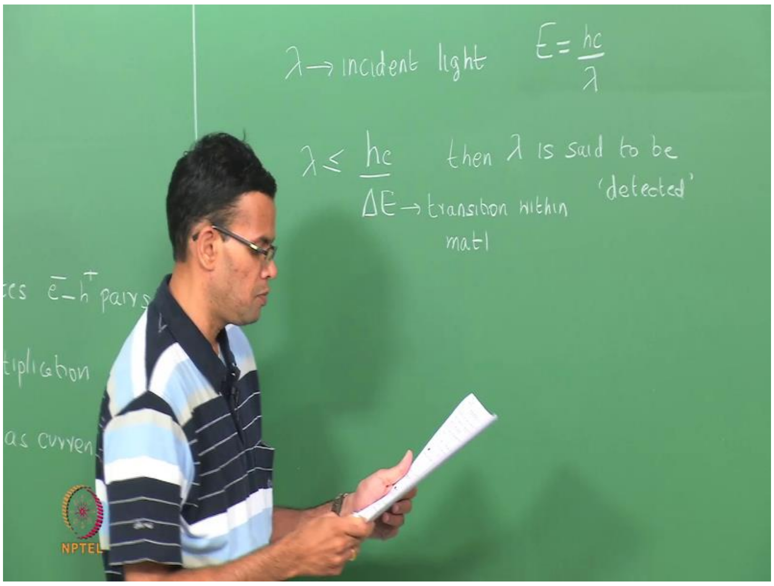
So, there are three steps involved when we think about shining light on to a device and then converting it into electrical current. So, in the first case your incident like generates carriers in the device. So, when we talk about carriers these are your electron hole pairs once this carriers are generated they need to be transported to the respective electrols some time 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 finally, these carriers are then extracted out of the device in the form of a current when we look at, Photodetector there normally 2 classes of Photodetector.

So, the first class are thermal detectors in this particular case you shine light on to the device or you shine light on the material, which leads to a temperature rise which is measured and the temperature rise directly proportional to the amount of light that is shining in. So, you sense a temperature rise when light is absorbed this is mainly used for detecting IR radiation or infrared radiation.

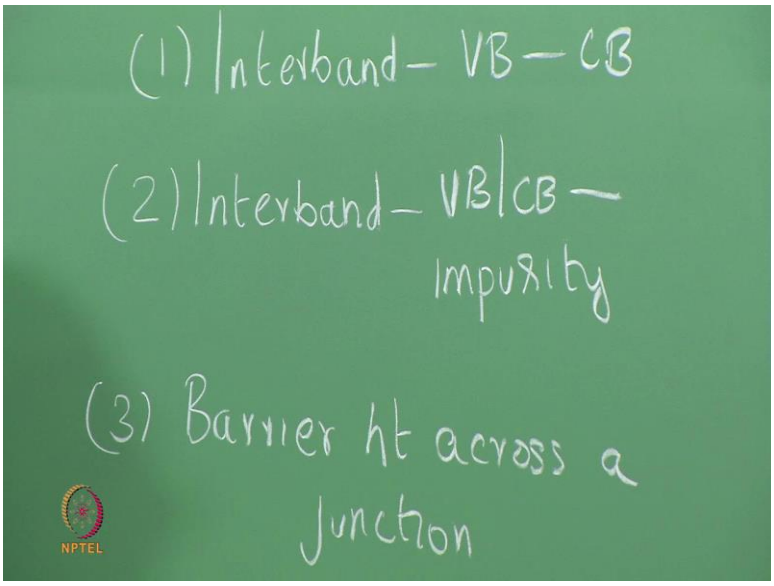
The other case is Photons, which is the traditional sense in that your photons generate electron hole pairs. Now, we will be mainly dealing with the second type of photo detectors where your Photons generate electron hole pairs.

(Refer Slide Time: 05:39).



So, consider incident light on your material of wave length lambda, the energy of this radiation off course you seen before is nothing, but hc over lambda. So, this light can be detected if this lambda corresponds to some sort of transition with in a martial. So, as long as lambda is less then equal to hc over delta E where, delta E is transition within the material then your light is said to be detected.

(Refer Slide Time: 06:55).



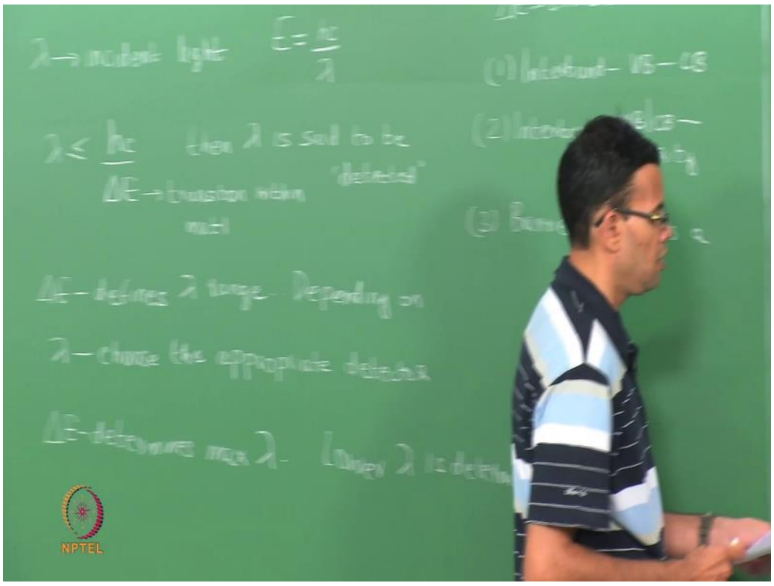
So, what are these different transitions that delta e can correspond to so, delta E which represents the transition in a device or transition in your material it could be an intern band transition so, it could be from the valence band to the conduction band that is the simplest and most common form of 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 bond. 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 generate impurity level in the band gap in this kind 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 a junction for example, later we will look at short key diode based Photodetector in which case your electrons or your light can have sufficient energy in order to excide the electrons from the metal to the semiconductor.

In which case, they will have to overcome the short key barriers. So, this delta E depends on variety of transitions and this defines the wave length range of your Photodetector.

(Refer Slide Time: 09:04).



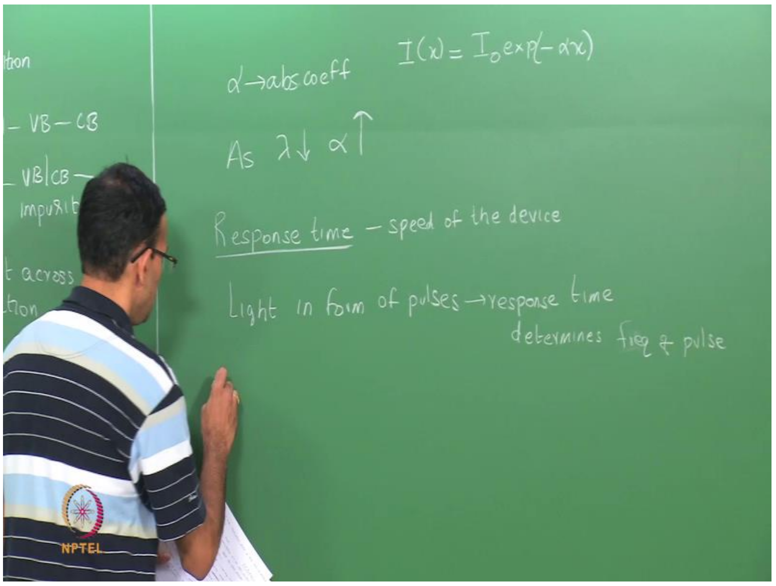
More specifically delta E determines the long wave length range that is possible or the minimum; the maximum wave lengths that is possible. Another way of saying this, is that depending upon the wave length range you are interested in you will choose the appropriate tied of Photodetector or the Photodetector material range. So, depending on lambda you can choose the appropriate detector.

So, the difference between a Photodetector here and in case of a solar cell is that in a solar cell the wave length range is sort of fixed because it depends upon the solar spectrum that has a specific wave length range. So, later when we look at the solar cell we will see the solar spectrum and what is the wave length spread. So, solar cell the wave length range is fixed.

So, we want choose materials which absorb, in that range the other hand in the case of a Photodetector depending upon the wave length range we will choose what material we want to use. So, the maximum wave length is determined by delta E so, any wave length that is larger than that determined by delta E will not be able to absorb or will not be able to produce your electron hole pairs and will not get absorbed.

So, there is also a lower wave length range that depends on the absorption proficient of your material. So, the lower wave length so, we have a maximum wave length which determined by delta E and the lower wave length is determined by alpha. So, we have looked at the concept of absorption coefficient before you find that

(Refer Slide Time: 11:54).



If alpha is the absorption co efficient then the intensity at a distance x with in the material was just I0 exponential minus alpha x. So, I0 is the intensity at the surface I of x is the intensity at some depth x and alpha is your absorption coefficient. You have seen earlier that as the wave length reduces alpha increases which means, the material gets absorbed at a lower depth.

So, this absorption co efficient determines the lower wave length regime. If alpha is very large then all of the lights gets absorbed then a layer very close to the surface and would not have sufficient electron in whole pairs in order to be able to detect. So, the highest wave length regime is determined by band gap of the transition or the energy of the transition and the lower wave length regime is determined by alpha.

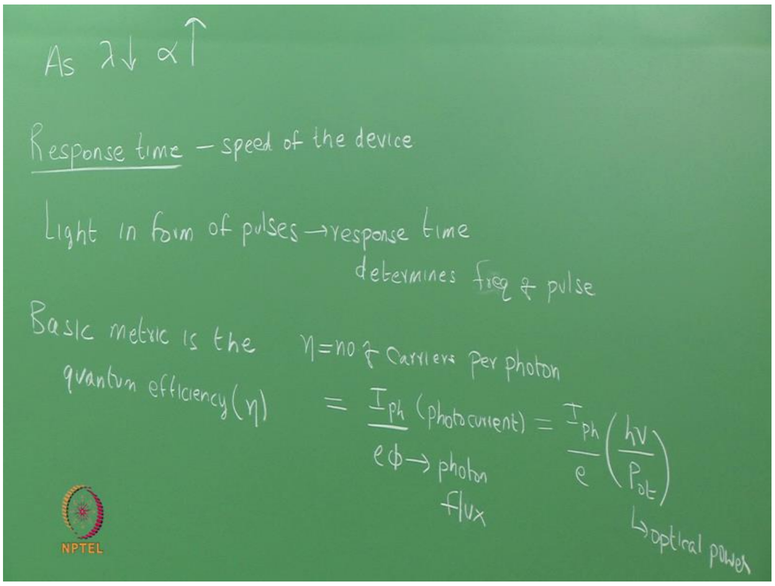
Another important factor in case of Photodetector is the Response time. So, this determines the speed of the device so, if we think of light arriving in the form of pulses response time determines how close these pulses are. So that, they can be individually detected. So, if you light in the form of pulses the response time determines the frequency of the pulses determined the speed or the frequency of the pulse.

So, the response time depends on the fact that you have electrons in holes that are generated and these must defused through the device, in order to reach the electrodes and then form your current. So, it’s depends upon the diffusion coefficient or the mobility of the electrons in the holes in the device.

If you have a Photodetector that is based upon a p-n junction with wide depletion region then, the distance electrons in holes have to travel is longer. Which means, correspondingly the response time is short and the other hand, have a thin depletion if you have a p-n junction with a wide depletion region in the distance the electrons in holes have to travel this large so that, the response time is also large.

On the other hand, if you have a p-n junction with a very short depletion region then distance the electrons in holes have to travel the small so that, the response time is fast. But the drawback is, the number of electrons in hole generated is small so that, you need a large amount of signal in order to form or in able to be detect the radiation. So, there different red offs depending upon the design of the device and the response time that is required.

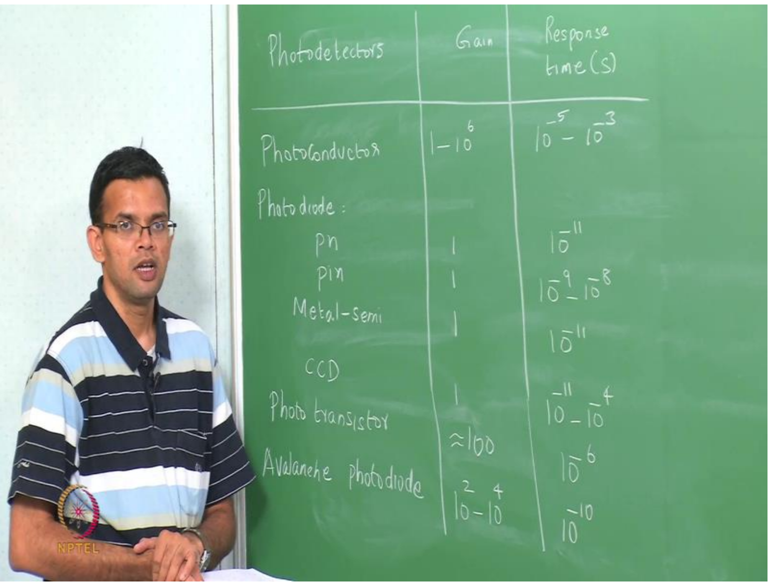
(Refer Slide Time: 16:02).



The basic metric of a Photodetector is called quantum efficiency. So, the quantum efficiency is defined as the number of carriers that are generated for per photon. So, this intern is related to the photo current divided by the flux of the photons. So, I ph is the photo current this term phi is the photon flux. Another way of writing this, set it is Iph over e and flux of the photons is depends upon the power of the incident radiation and the energy.

So, h mu is the energy of the radiation and P ot is the optical power. In the case of a Photodetector they could also be an internal gain mechanism. So that, even though we have a certain number of photons that are incident device the number of electron hole pairs are larger. So, we have both a gain and a response time that basically characterizes your Photodetector. Now, your different kinds of the detectors all having different values for gain and response time so let me, just tabulate some of these types of Photodetectors.

(Refer Slide Time: 18:35).



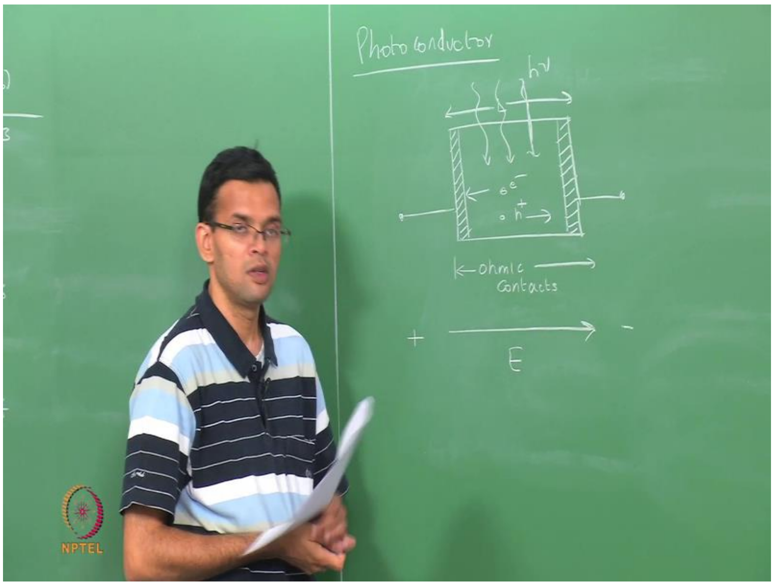
So, we look at some of the types of Photodetectors and then you will look at a comparison of the gain and the response time. Response time is given in seconds so, a simplest Photodetector is just Photoconductor depending upon the applied elective field and will talk about 2 minutes. You have different gain values and the response time is usually order of the milli seconds.

So, you could also, had photo diode this could be simple p-n junction p in stands for a p intrinsic and then n or it could be metal semiconductor. Because, all of these cases your gain is to typically 1 which means, all the lights that comes in gets converted into electron hole pairs. Response times of these devices are typically much better or much shorter around 10 to the minus 11.

So, we could also have charged couple devices this has wide range of response time these are all photo diodes. You could also, have photo transistors for us the advantages of a transistor is that, it 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 Avalanche photo diode which also has gain that is larger than unity cause that is paste Avalanche process and also very fast response time.

So, we have a wide variety of Photodetectors these depends upon the type of materials is you used and also on the junctions that are found. We will not look at all of these, but we look at some examples of the Photodetectors in order to better understand the mechanism. So, the first thing we look at is a Photo conductor.

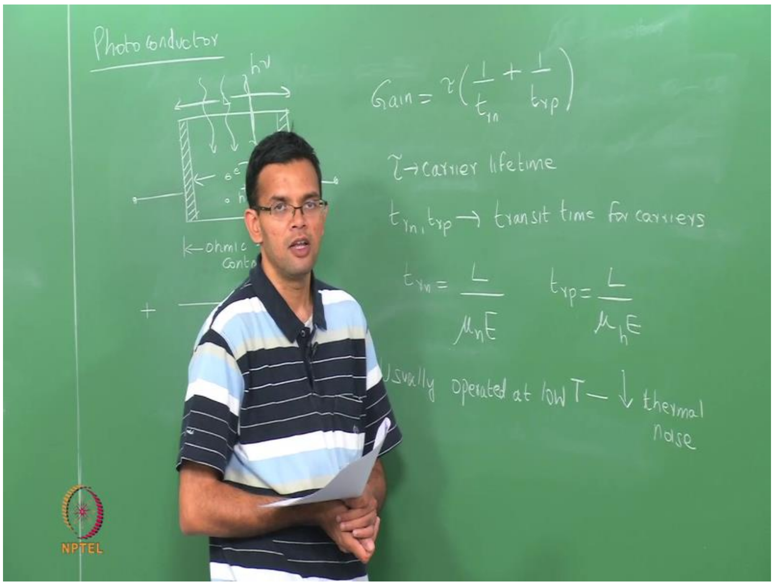
(Refer Slide Time: 22:29).



So, consider a simple slab of silicon we looking at a photo conductor. So, consider a simple slab of silicon with 2 electrodes on either ends so, these can be typically metals. So, they form an Ohmic Contact with silicon we want choose the materials in such a way that you have an Ohmic Contact. So, this is your central slab which 2 Ohmic Contacts. So, let L be the length of your slab so, we can have incident light for slab.

So, you have incident light of some energy which depends upon the wave length. So, h mu or hc over lambda and if these energy is sufficient it will generate electron hole pairs. If he now apply an electric field across this silicon by using your Ohmic Contacts we can basically extract the electrons in holes and then form a current which is your photo current. So, 1 of the terminals is connected to a positive side; the other is connected to a negative.

(Refer Slide Time: 24:23).



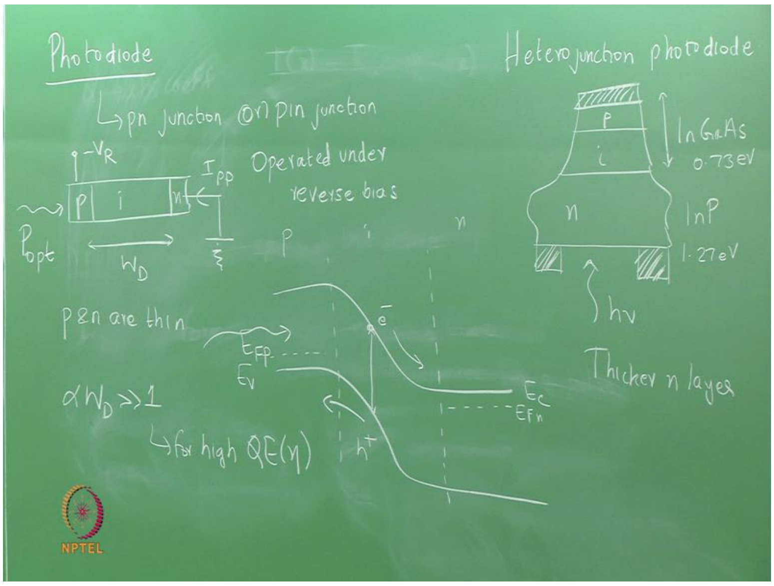
In this case there is an electric field so, the electrons in whole move in the opposite direction. So, the current in this device is directly proportional to the number of electron hole pairs that are generated, which intern depends upon the intensity of the light that falls on the material. In the case if a device, the gain is given by divided by the time for your holes for the electrons and 1 over time for the wholes.

So, tau refers to the life 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 r n and t r p they are the transit time for these carriers to the electrodes. This in turn depends upon the length of the device so, t r n depending upon the length it's depends upon the mobility of your electrons or holes so, mu and the applied electric field.

Similarly, t r p is just L over mu h times the electric field. So, higher the motilities per higher the electric fields shorter is the transit time and similarly, smaller the device smaller L shorter will be your transit time. Usually in the case of a simple photo conductor there will always be in thermal noise because, you always have in thermally generated electrons in holes.

So, these devices are usually operated at low temperatures so typically they are operated at liquid Nitrogen temperatures in order to minimize the thermal noise so, to reduce. So, the device we are going to look is a photo diode. So, here we are going to put 2 different materials: p n and n in order to form a junction. So, in the case of a simple photo conductor all we had was slab of a semiconductor material it could be silicon, it could be Gallium Arsenide and then just generated electron hole pairs.

(Refer Slide Time: 27:47).



In the case of a Photo diode we use a p and then n material so that, you form a junction. So, these can be a simple p-n junction or modification of that which is a 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 electron and hole pairs are then separated by applying a reverse bias to the junction.

So, that the electron goes towards the n side, holes go towards the p side and the you have a current. So, consider a simple pin kind of device. So, the intrinsic region is typically wide and the p and n regions are short these devices are usually operated under reverse bias. So, that a negative charge is apply to the p side this particular example the n side is just grounded.

We have some incident light shining on this pin device that is just optical radiation. So, we want to make the p and the n region 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, p were to draw the energy band diagram for this under reverse bias have my p, I have intrinsic, I have n this refers to your conduction band, this refers to the valence band this is e f p this is e f n.

So, in this particular case there is a reverse bias; the reverse bias voltage depends upon the difference in the Fermi levels. So, now we had incident light falls on your material. So, that generates electrons in the conduction band and holes in the valance band because of reverse bias these electrons in holes are separated and they contribute to the current.

In the absence of the light, there will be a small current which is your reverse saturation current 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. So, in the case of these devices p and n are really short so that, most the absorption take place within the intrinsic region.

If alpha is absorption co efficient in wD is the width of the intrinsic region ideally we want alpha times wD to be much greater than 1 so, this for high quantum efficiency. Another way of saying that is that 1 over alpha is a penetration depth so that, we want the width of the region to be larger than the penetration depth of wave length of interest. So, these cases whether you have a simple p-n junction or a pin you could have them of same material.

Another way to do that is to have a Heterostructure based device so that, you can have a hetero junction photo diode. So, let me draw a simple symmetric of such structure presence the contact it is my 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 my p and intrinsic regions are made of Indium Gallium Arsenide.

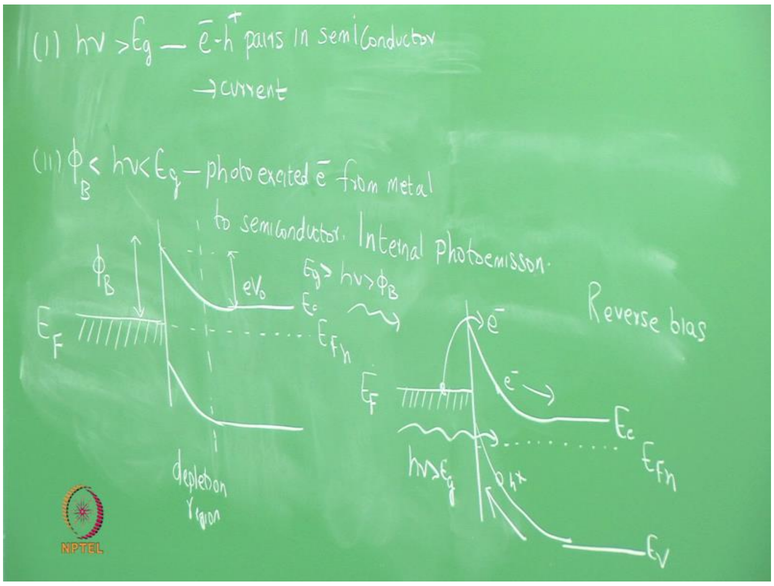
So, Indium phosphide has a higher band gap 17 eV and Indium gallium arsenide has a band gap of 0.73 eV. The advantage of the hetero junction device is that in the case of a regular pin the p and the n region should be really short in order to not to absorb the light. But here since Indium phosphide has a higher band gap wave length whose energy is less then this will have very little absorption in the Indium phosphide.

So that, the thickness of the n layer does not have to depend upon the wave length of the light we can have thicker n layer in what you normally have in regular pin device. So, in this case light shines from below so that, you can have a thicker n layer. So that, all the wave length 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 wave length that you would not want.

For example, if you do not want to look at wave length above 1.27 by having a thick n region those wave lengths or those energies can be absorbed. So, that only wave length of certain range can be detected by the Photodetector. So, the hetero junction photo diode it works on the same principle as a regular p n or pin but added functionality because of the difference in band gaps.

1 we act is we have 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.

(Refer Slide Time: 36:22).



We had 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 photo diode we want a depletion region so that, we can generate electron whole pairs. Now, the Schottky junction is the 1 that has a depletion region. So, we use a Schottky junction to form your photo diode.

So, there 2 modes of operation of metal semiconductor diode and the reason we have 2 modes is because, we now a barrier between the metal and the semi conductor this is your Schottky barrier. So, in the first case if the energy of the photon is more than the band gap g then it behaves like your regular photo diode electron hole pairs have created these are created in your semiconductor and they contribute towards current.

So, 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 barrier height in this case it is Schottky barrier. So, 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 photo emission and this electron can contribute to the current.

So, you can have photo excited electron from the metal crossing over the Schottky barrier in to semiconductor this process called an internal photo emission. So, consider the example of a Schottky junction in equilibrium. So, 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.

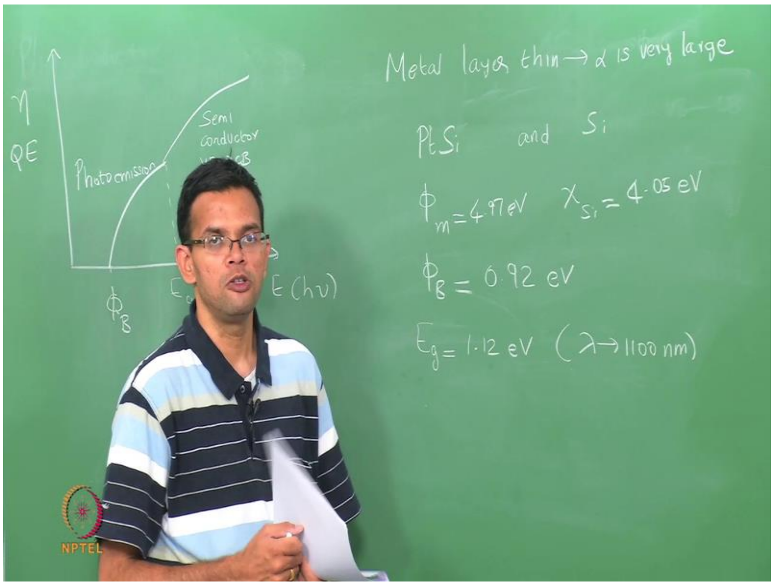
So, have depletion region so, my semiconductor is entail that my Fermi energy I have any conduction band Ec and then have my valence band. So, that you have a depletion region on the semiconductor side there is a built in potential which is eV0 and there is Schottky barrier height phi B. The Schottky barrier height depends upon the difference between the work function of the metal and electron affinity of the semiconductor.

So, when we apply a reverse bias to this junction its semiconductor potential shifts metal is still the same semiconductor shifts Ec Ev EF EFn perverse bias. So, if we have light of energy greater than the band gap so, h mu greater then Eg then you will generate your electron hole pairs electron have a hole which will travel in opposite direction in order to give me may correct.

In the other hand, we have light energy greater then Schottky barrier, but less than the band gap then you can take an electron from the Fermi level of the metal then take it above the Schottky barrier and that can also give use current. So, by using a metal Schottky junction you can increase the wave length range that you want inter a gate with your Photodetector.

You're no longer limited by the band gap of the material, but you can extend further depending upon the Schottky barrier. So, few were to draw the quantum efficiency of this device verses the energy.

(Refer Slide Time: 43:01)



So, is a eta quantum efficiency QE verses energy E of the light so that just h mu. You have 1 term that corresponds to Eg then there is phi B which is the barrier. So, anything below the barrier will not get absorbed among the barrier you have some gain because of the internal photo emission process and our Eg your gain is higher because you now have the transition with in the semi conductor.

So, this is conductor valence band conduction band. Usually instead of using metals we can also, use silicides for example, if you have platinum you could have platinum silicide forming junction with silicon that can be used as a Photodetector. So, in the case of a metal semiconductor Photodetector metal layer should be really thin because, metals usually have very high absorption co efficiency.

So, 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 of 4.97 eV silicon has an electronic affinity of 4.05. So, the Schottky barrier phi B is just the difference between these 2 so, is 0.92 eV. The band gap of silicon Eg is 1.12 electron Volts this corresponds to wave length of approximately 1100 nanometers.

So, as long as your wave length is below 1100 or energy is above Eg then the light will be absorbed by the silicon, but if your energy between 1.12 and the Schottky barrier and a light will be absorbed by the platinum silicide layer in a internal photo emission process. So, we looked at 3 examples of photo diodes so, you have 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 bi polar junction transistor, which we have seen before it has in a amatol base in the collector. So, in this particular case you modify your simple bipolar junction transistor to have larger base. So, that electron hole pairs generated within that and this intern get separated and forms your current. You could also have a hetero junction based device from your transistor in order to improve the gain.

So, you looked at different examples of Photodetectors in all of these cases the wave length range that can be scanned depends upon the type of material that you have. The next class you’re going look at a solar cell, which works in a similar way to Photodetector. But the wave length range is fixed depends upon the solar spectrum that is incoming on to the sample. So, we look at the working of a solar cell and also some of the different materials and efficiencies when we use them in the solar cell.