Semiconductor Optoelectronics
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Lecture - 45
Other Photo detectors

Welcome to this lecture, this is the lecture number 45. We are coming to the nearing the end of this course. Today, in the last two classes we have seen primarily in the photo detectors, photo diodes, pin photo diodes and APDs which are widely used in optoelectronics and optical communication. In this class, I would like to discuss some of the other detectors, miscellaneous detectors, other detectors – other photo detectors refer to miscellaneous photo detectors. Some of them are very important, although not from the point of your optical communication.

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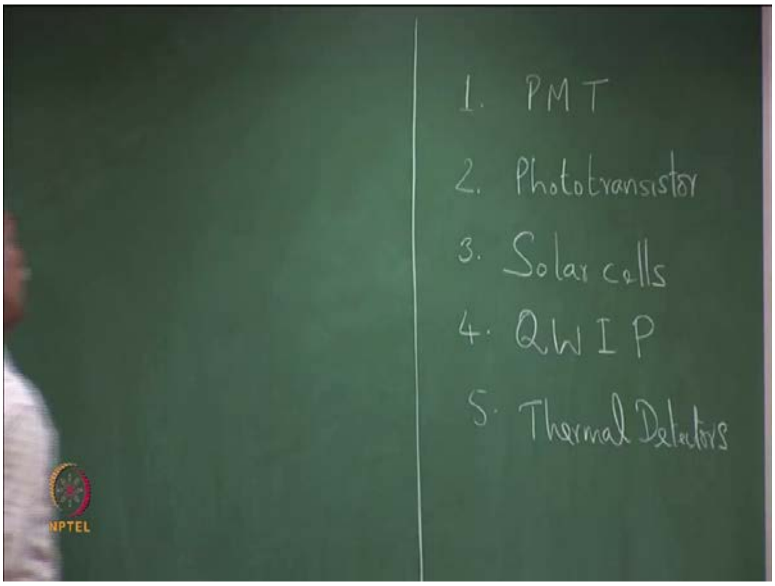

So, the first of these let me list some of the important photo detectors here. So, the photo multiplied tube - PMT, the Photo Multiplier Tube. We also have photo transistors and then we will briefly discuss solar cells. We will discuss solar cells, because it is basically a photo detector which is operated in the photo voltaic mode of operation as we will see. Then we will briefly touch upon quantum well - QWIP, quantum well infrared photo detectors and if time permits, we will also discuss little bit about thermal detectors. Thermal detectors are basically a class of detectors, thermal detectors.

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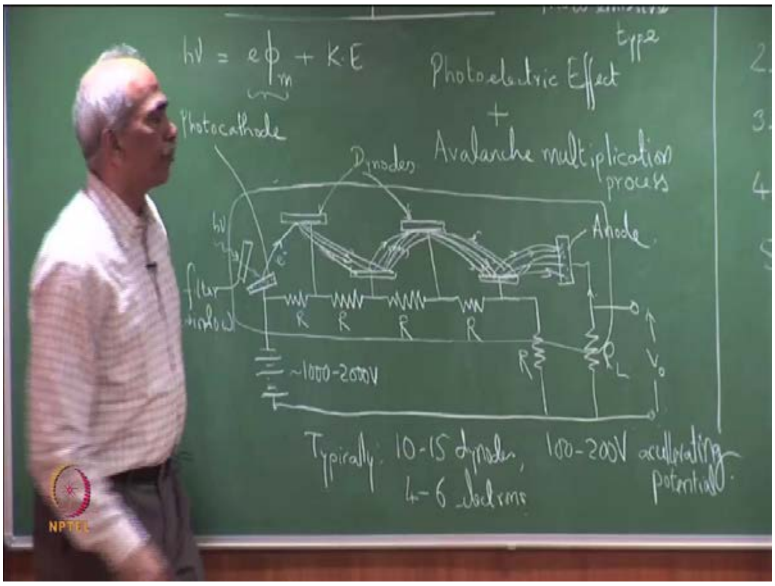

So, let me start with PMT, because it is widely used photo detector photomultiplier tube. The basic principle of operation is first, photoelectric effect. This is the photo emissive type of detector which is followed by an avalanche multiplication process, the photoelectric effect plus avalanche multiplication process. So, let me illustrate the simple, the basic schematic of a PMT and then we will discuss in detail. So, this is the photo cathode. Photon is incident through a filter here, filter or a window. Now, I will explain it and it will become clear from one side. Explain these.

The photo cathode here, this is the photo cathode. The light to be detected is incident on photocathode here. The photocathode releases an electron, the photo electron. As you can see these are the dynodes, this is an anode. These are resistances, all equal resistances are RRRR. So, these are the dynodes. This is the schematic representing the operation of a PMT. The incident photon releases a photo electron provided the photo cathode, the work function of the photo cathode is smaller than the photon energy or this is basic equation of the photo electric effect here. So, h new is equal to E times phi m or w. So, this is the work function plus kinetic energy, so the kinetic energy of the electrons. If h new is the energy of photons which are incident on the photo cathode, if h new is greater than the work functions, then an electron with this much of kinetic energy is released.

Now, as we see here, this is that high negative potential, typically 1000 to 2000 volt, a power supply and the subsequent dynodes are at lower potential or positive potential with respect to this and therefore, they immediately get attracted towards the dynode, the dynodes here, the dynode, the electron gains enough energy or a large kinetic energy, because of the accelerating potential between them that this leads to release of additional electrons. The electrons which are released here reach to next dynodes, move towards the next dynodes because there is a potential difference between this. There is a resistance here and therefore, they hit this dynode with certain kinetic energy and they lead to further avalanche multiplication.

So, we started with one photon incident, releasing one electron which in turn releases further electrons which leads to release of more and more electrons and this kind of avalanche process takes place. Depending on the number of dynodes, we have an avalanche that takes place. Let me illustrate further that avalanche is taking place. These are all electrons released which are finally collected. As you can see, this is the certain potential and this is connected to ground or the common line here and therefore, this is again at the same potential related at potential difference as same as this one. Therefore, these are collected at the anode, so that the electrons from the last dynodes are collected at the anode. This leads to a photo current.

So, this leads to a photo current and the voltage across. So, this is the load resistance RL and this leads to an output voltage, O here. So, a single photon incident leads to creation of an avalanche of electrons, typically in the entire thing. Of course, the entire thing is housed in a tube like this. Let me show you another diagram, but the basic principle is illustrated here and typically PMT, the tube contains 10 to 15 dynodes. An accelerating potential difference of 100 to 200 volts between adjacent dynodes, so typically 100 to 200 volt accelerating potential, and typically 4 to 6 electrons, secondary electrons. So, secondary electrons per electron per primary electron which releases 4 to 6 electron which further multiplies 4 to 6 times and therefore, the current gain due to one photon incident here, the current gain if we let us say, so what will be the current gain? How do you calculate the current gain?

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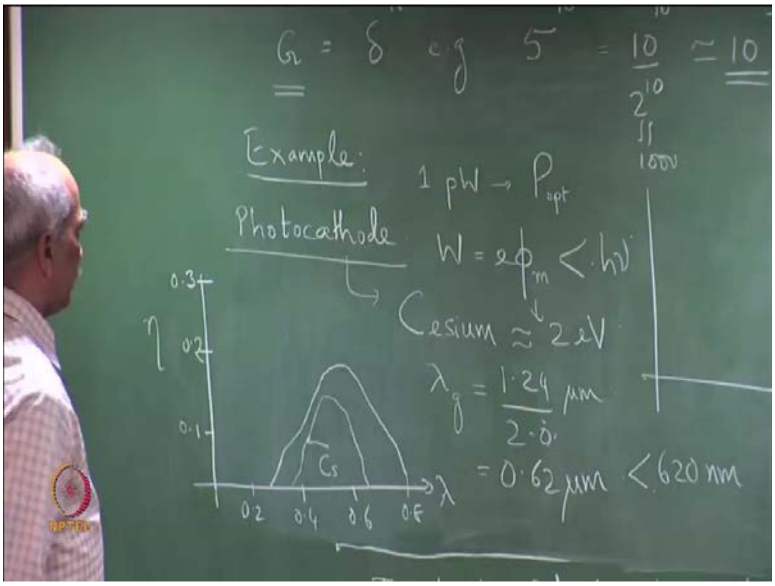

So, we have typically 4 to 6 let us call that as delta equal to and this is n equal to the number of dynodes. Then the gain, the carrier gain will be equal to delta to the power n. So, if delta for example, delta is equal to 5, if I assume, so typically 4 to 6 electrons per primary electron is released 5 and if it is 10 to 15 dynodes, so let me assume is equal to 10. So, this is 5 to the power of 10 is the gain because 1 releases 5 and each 5 releases 5. So, it is 5 to the power of n number of dynodes. So, this is nothing but 10 to the power of 10 divided by 2 to the power of 10. So, that is approximately 10 to the power of 7 to the power of 10 is 32 approximately. So, this is approximately 10 to the power of 3 and therefore, this is 10 to the power of 7. So, the current gain g, this is approximately 10 to the power of 7 which means we have a large current gain. So, how as this number manifest in terms of the detection power. We can take an example and see. Let me erase this diagram here and let me take an example that is schematic illustration. So, let me take an example.

So, example. Let us say 1 pico watt. The incident power is 1 pico watt. P optical incident is 1 pico watt. So, how to calculate? What is the output across the load resistance? So, the typical response of the photo cathode material. So, let me, before I continue the example, let me talk about the photo cathode materials. A photo cathode must have work function. W or E phi m should be less than h new. So, if generally one uses cesium which has a work function of approximately 2 E v. That means up to 2 E v photons efficiency to E v or more than 2 Ev are able to create electrons leads to photo electric effect. So, cesium is 2 Ev that means the wavelength corresponding to this is 1.24 divided by 2.0 Ev. So, which means this is 0.62 Ev.

This means light with wavelength 0.62 micrometers is 620 nanometers or less can be detected in this. So, if we see the quantum efficiency eta, this is wave length, so these typically have 0.2, 0.4, 0.6, 0.8. So, lambda verses eta, a typical numbers are and the numbers here are about 0.1 point tau 0.2, 0.3 eta. The quantum efficiency of the detector, quantum efficiency is of this order here. So, this is for cesium. It is cesium.

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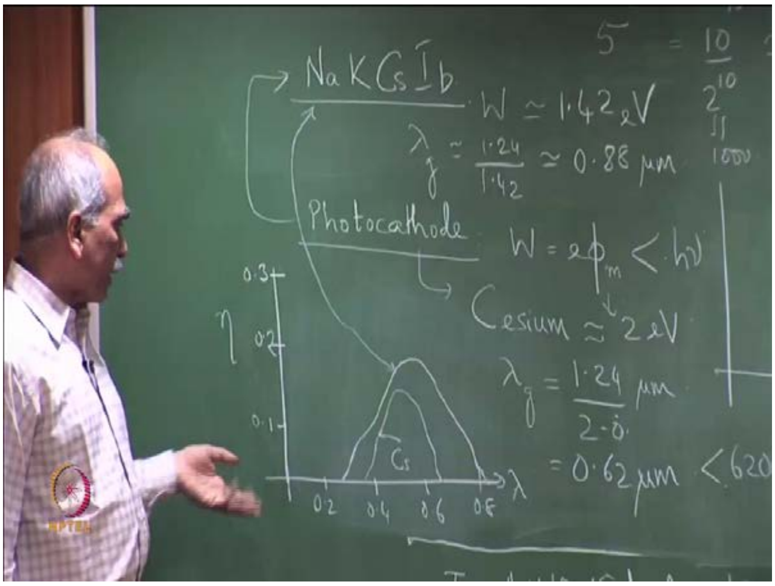

There are other materials for example, one of the materials which is aneroid, a compound of sodium potassium cesium antimonite. This is a very, this adds a work function 3 phi m. So, w is nearly equal to 1.4 2 E v 1 of the same as the band gap of gallium assonate, but this is the work function. So, a photo cathode material, this is about 1.42 E v. This means the lambda g is nearly equal to 1.24 divided by 1.42, that is nearly equal to 0.88 micrometer which means it can go to about 0.8 or a little bit beyond 0.8. So, this is for this material. This is for cesium and the curve which have shown here is for this material photocathode materials, but the important point to recognize is that the quantum efficiency is finite and usable quantum efficiencies are in the range of, in the visible range, primarily in the visible range. It is very difficult to find materials which have a quantum efficiency non-zero quantum efficiency beyond one micron.

So, this is in fact one of the primary limitations of a photo multiplied tubes. This is the range of detection wavelengths are limited to visible or a near ultra violet are very close to infra violet. So, let me come back to this because I wanted to show you what kind of numbers are in practice, what kind of numbers that we have for the quantum efficiency and once we know the quantum efficiency, we can come back to this example now. So, I come back to the example. The example of what kind of voltage is generated at the output if one pico watt of a optical power is incident.

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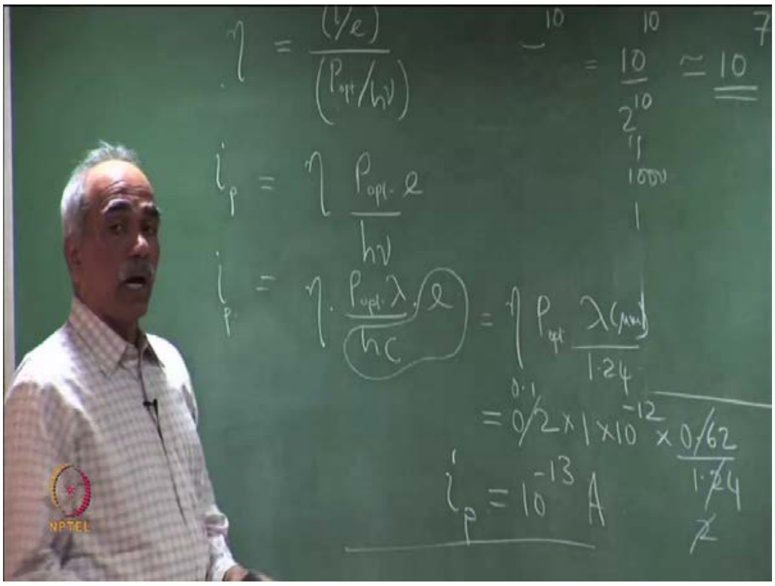

So, I go by the definition of quantum efficiency is equal to electron flux. So, I divided by E divided by incident photon flux that is p optical divided by h new, incident photon flux and therefore, this is the photo, current primary photo generated with this eta here. Therefore, we have I, the photo current, the primary photo current is equal to we have eta in to p of divided by h new into e. So, that is equal to eta into p of divided by h into c by lambda into E and we know this quantity here h c by E is 1.24 if lambda is in micrometer. So, this is equal to eta into p of into lambda in micron meters now divided by 1.24. So, for an incident optical power of p of, you can find out what is the primary current generated by the photo cathode primary generated by the photo cathode.

So, if you look at the previous curve, so these are typically 0.1 to 0.2. So, let me assume 0.2 eta is equal to 0.2 incident optical power is 1 Pico watt, so 1 into 10 power minus 12, 1 pico watt and the wave length. So, let me assume the wave length is as 0.6 or 0.62 divided by 1.24. So, this is the primary photo current generated. So, this is nothing by 2 and 2 goes here 2.1. That means this is so approximately 10 to the power of minus 13. So, ip is equal to 10 to the power of minus 13 ampere, the primary current photo generated.

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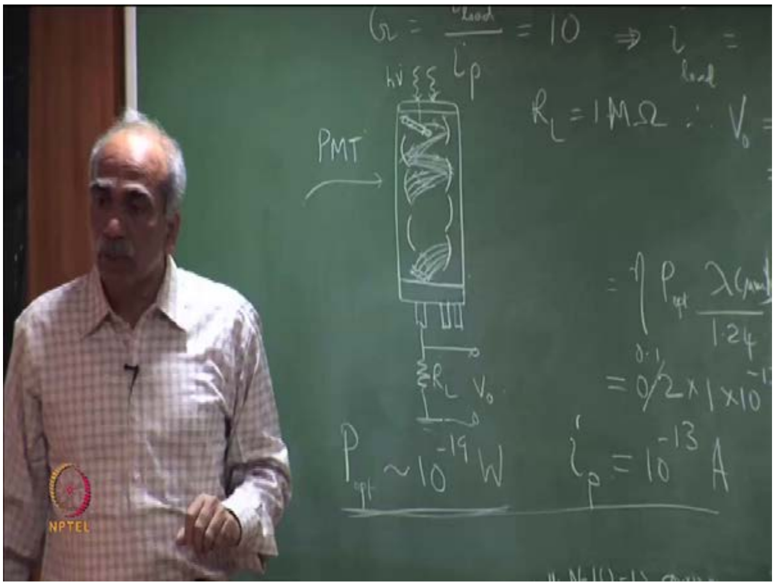

However, the current which comes out at a output, so we have a gain of 10 to the power of 7. So, gain which is equal to I at the load resistance output current divided by I primary. This is equal to 10 to the power of 7. I assume 10 to the power of 7, the number at which is calculated here and therefore, the current generated, this implies high load is equal to IP is 10 to the power of minus 13. So, this is simply 10 power minus 6 and amperes, I load is equal to 10 power minus 6 amperes.

So, recall that we have a tube. The pmt normally looks like this. There is the tube and a window that of for photon that is to incident. Photons is the tube is the pmt schematic of a pmt nab. So, as soon as it is incident, there are that photo cathode here. I am not showing the electrical connections, but then there is a dynode here. So, it is a set of dynodes and then the final anode. So, just recall that the incident photon generates an electron which then multiplies and get attracted to this dynode. From here, it gets further multiplied to this dynode and there, it is further multiplied to this dynode. We have an avalanche of electrons which are coming and finally, the last avalanche of electrons reach the anode and this is the anode which is connected. So, normally there are terminals which connects the power supply and the cathode current. So, this is passing through the load resistance RL and here, we have the output and one can even measure the photo current which is coming out or the voltage generated here. For example, if I take RL is equal to 1 mega ohm, so therefore, the voltage v out is equal to 10 power minus 6 into 10 power 6.

One volt is the very large output to measure. So, 1 pico watt can be easily detected by measuring the output voltage here. So, 1 pico watt incident hereby typically considered by a typical number, we have calculated 1 pico watt incident here generates a photo current, a primary photo current of 0.1 pico ampere and then the current because of the current gain, we have the current at the load of the 1 micro ampere and across the load resistance, we have about 1 volt. We need one can easily detect power. I mentioned this that output power at the order of 10 power minus 19 watts. We have already this calculations for 1 pico watt 10 power minus 12 watt and one can calculate one can detect powers as low as 10 power minus 19 watts using a pmt.

It is a various sensitive detector, but as I mentioned, the primary limitation of the photo, a photo multiplier tube is the material for photo cathode tube. Find the material for the photo cathode which can respond to infrared radiation. Work function of material of sufficient low work function of materials which is difficult to find and therefore, these are primarily used to detect very low levels of light intensity, very low level of light power in the visible region and the spectroscopic in the visible region.

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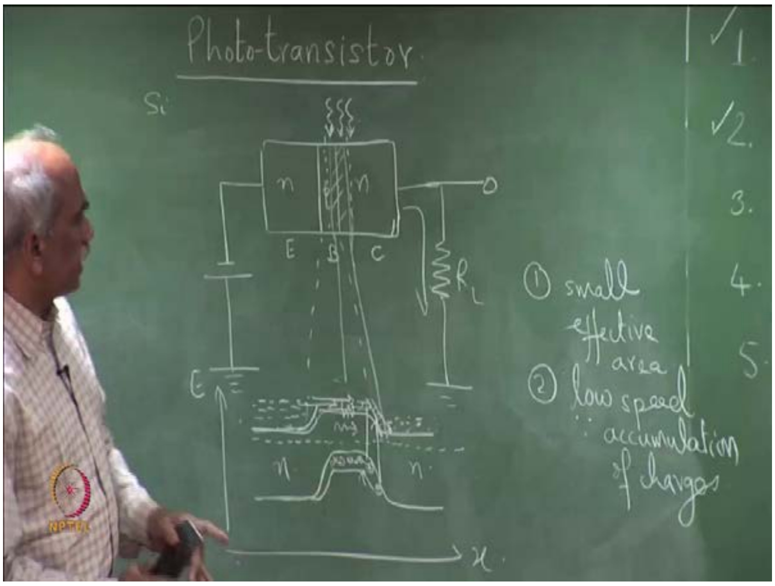

So, let me quickly go to the next one, photo transistors. Photo transistor basically is a transistor let me considered in npn transistor, let say silicon npn transistor. The incident light is incident at this junction, the light incident at other junctions do not really contribute at the current and therefore, the active junction is this. Well, this is an npn transistor and this is an emitter. This is the base and collector.

So, usually this and this are forward biased and a photo transistor normally, this is the load resistance. Normally, the base is not connected because the incident photon flux does the same job as the base current. The base current has to achieve the transistor action, where we get a current gain because of the base current is achieved by an incident photon flux. So, this can be understood more clearly if you will look at the energy band diagram of these npn junction. So, let me provide the energy band diagram. So, this is a npn junction, so pn in reverse.

So, we have this is the p region and the n region and we also have this is the energy band diagram E verses x. Now, x is this mentioned here. So, the preemie function this is the n side. So, the primary level is this you applied any bias. The primary level is constant all around and there is the study state, the net carrier which is traveling in this direction is equal to the carrier flux traveling in the opposite directions. So, there is the no net connect, but when you bias here. So, this is forward biasing this end. So, this moves up here, this end goes up and this end comes down. So, this is relative bias. So, you have plenty of electron here. So, plenty of electron there are holes here. So, holes and again there are plenty of electrons because this is n side. So, this is n, this is p and this is n, the photon flux which is incident on this junction here that is that as look at this junction. So, this is corresponds to this, this is the active area that is the base emitter base collector junction pn junction a photon which is incident here creates an electron hole here. So, an electron makes an upward transition here, so the incident photons.

Let me show the photon incident h new. So, in this region creates an electron hole pair. The electron which is here comes down the slope electrons flows down the slop here of the potential slope. The hole which is generated here, the positive hole here, this moves up. We have all holes here. So, there are more holes coming here. There are more holes added. Electrons going here. More holes coming to the base region means this region becomes more positive or the potential energy is lowered.

The potential energy is lowered which means this barrier is lowered. When the barrier is lower, let me show it schematically. Let me show the barrier lowering, the u diagram would or may be, let me show here, itself the barrier getting lowered. So, this comes down here. Similarly, the barrier is getting lowered. When the barrier is getting lowered, there is electrons which rush from here. Now, let me erase the earlier barrier. So, we can see now that the barrier has been lowered because of holes accumulating in the p region, the electrons is flowing down the n region, but the lowering of the barrier leads to an electron surge from the emitter side to the collector side. Normally in an electronic transistor, this job is done by the basic current. When you forward bias the emitter base junction, the barrier is lowered and consequently, large current flows from n sides from the emitter to the collector that is carrier moves over the barrier which has been lowered because of the base current. It is the same action which is taking place here when because of the incident photon flux, there are holes which are accumulated here and electrons moving here and consequently, this p region becomes more positive or the potential energy is lowered or the barrier is lowered.

Consequently, large number of electrons move from this side to this side. So, the current in the external circuit here, so the current which is flowing, the current is depends on the incident photon flux, but the current is not just the primary current because of the two electrons which are generated or two holes which are moving. If two photons were as incident generating a pair of hole and electron, then the primary current will be very low, but because of the lowering of the potential barrier, large electron, large number of carriers moves from the emitter to the collector leading to the current gain, and this is the primary working principle of a photo transistor. So, in the last class, we discussed about the avalanche photo diodes which has the current gain. Because of the avalanche process, exactly like that we see that the first two detectors which have listed here, other detectors, the photomultiplier tube has the large gain.

Again due to avalanche process is not a semiconductor pn junction, but it is a photo multiplier tube which works on the principle of photoelectric effect and avalanche process and the photo transistor which works on the transistor action which provides gain, also provides a overall gain to the photo current. Typical gains, current gains h f E is the order of 200 to 500. The current gain is the order of 200 to 500 in photo transistors. Phototransistors are used in certain simple applications where you have a sufficient amount of light incident, because one of the primary difficulties or demerits of a photo transistor is that the junction area, the catchment area here is very small because it is at the base collector junction which is the active region through the area here. This is very small area photo detector.

So, it is normally required focus to the incident light on to the junction and secondly, it is a relatively slow device compared to pin diodes. Pin diodes are very fast reverse biased pin diodes because there is accumulation of charge in the base region. So, these are the two merits, the two demerits. One is small active area, small effective area and two, slows lower speed. Low speed device low speed because of accumulation of charges in the base region. So, this is the device which is used for many simpler applications primarily due to the photo current gain which is available photo transistors.

So, let me go to the next detector here, solar cell. Solar cell is not used as detector. Normally, it is used for power generation as all of us are aware, but its proximities to the photo detector operation that we have discussed, proximities of solar cell operation to the principle that we have already discussed in the operation of pin photo diodes is what makes it very interesting.

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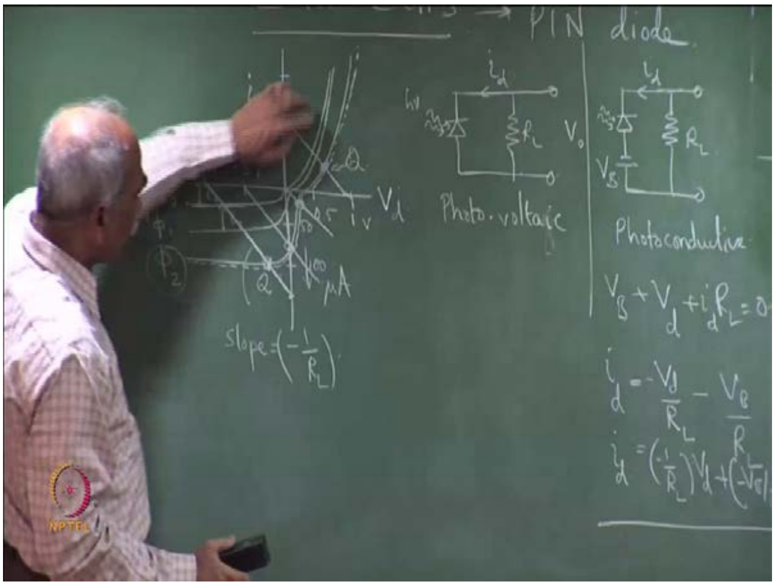

Solar cells. So, basically this is PIN diode and if we recall the IV characteristics, so this is the IV characteristics of the photo diode. Then we have when there is a photon flux which is incident, then we have scales on x and y axis are different. For example, here the numbers are 0.51 volt 1.0 and here we are taking of 5 volt minus 5 minus 10 and so on, so similarly the current here in micro amperes. So, typically 50, 100 micro amperes and here, the current is typically milli amperes. So, this is a forward bias region and this is the reverse bias region. So, this is highest, the saturation current when there is no incident photon flux. Phi is equal to 0 and this is for photon, for a incident photon flux phi 1 and because of that, there is a finite photo current IP.

Here, this is IP and this is the saturation current and there is the incident photon phi 2. We recall that there are two more modes of operation of a photo detector which we have already discussed, the photo voltaic mode and the photo conductive. So, the solar cells are operated in the photo voltaic mode without applying any bias, photo voltaic mode of operation. So, the incident photon flux here, incident on the photo diode and there is the load resistance here to be chosen appropriately and we have an output voltage v out. So, this is the photo voltaic mode generated voltage.

The photo conductive mode, on the other hand add a reverse bias which we applied here. This was VB, same photo diode, but now we have bias voltage which is a reverse bias and this is photo conductive operation. So, if this is RL and if the diode current through this is the reverse current here, id, the reverse current I am showing the reverse current id, then we write VB plus the voltage across the diode VD plus ID into RL is equal to 0 or ID, the equation of the load line ID is equal to vd minus by RL minus vb by RL. VD is this diode voltage. We plot VD plus id here. So, this is id and this is vd. So, this is the characteristic. We simply say that this is nothing but so the minus 1 over RL into vd minus plus minus vb by RL. So, it is like it is id and this we have already discussed the equation of the load line y is equal to m x plus c, the constant.

So, in this case, if I apply the reverse bias of 10 volt, then the load line will look at this, so this is the load line. So, the slope is negative is equal to minus 1 over RL and this value here is nothing but this vb by RL because when vd is equal to 0, id is equal to vb by RL here and this is vb. If vb turns out to be 0, if we let us say if we reduce to be vb 5 volt minus 5 volt, then this curve will shift here. The new load line will be this. If we turn vb to 0, the load line will be here and if we forward bias this, then the load line will be here. Please note that all of them are parallel. If we forward bias, then this will be the load line. The slope remains the same depending on, so this is reverse bias minus 10 volt vb. Then this is minus 5 volt, 0 volt and this is forward bias. Let us say, one volt forward bias. So, in this case, in the first case, the cube point. So, let me a consider only one of them, for example.

So, let me consider this, the case of phi 2 that is curve only. There is a incident photon flux phi 2 on this. So, the cube point. So, the intersection of the load point with the characteristic, IV characteristic is called the cube point or point which is an operation point. Cube point, it is here. The cube point is here. If I have 5 volt cube point, it is here and if I reduce it to 0, the cube point is here. Here is the cube point and if I forward bias, the cube point is here. So, this is the cube point, the operation point if the incident photon of flux is this.

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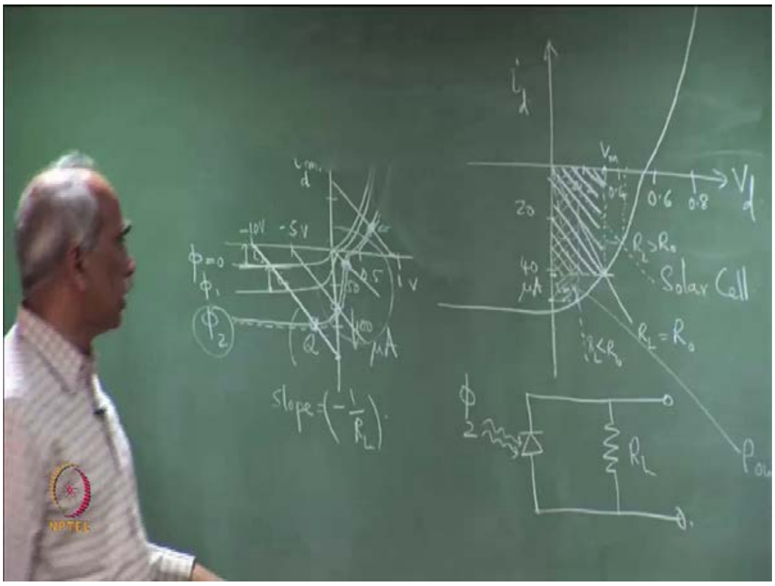

So, let me now draw only this one, only corresponding to this and erase all the rest. Here is the characteristics and let me zoom this part of the fourth quadrant because I am interested in solar cells which means we are not applying any voltage. Vb is 0. So, this will be the characteristics and therefore, I am interested in the fourth quadrant here. This is the fourth quadrant and let me draw that. It is a zoomed quadrant. So, here is the same id and this is vd. So, the numbers just it is just zoomed. So, see that the numbers are small. So, this is 0, 0.2, 0.4, 0.6, 0.8 holes here and this is the current. So, let me write this as 20, 40. This is a micro ampere, this is micro ampere and here is the load line. There is the load line which I have drawn and this is the operating point. So, what does this mean? So, we are looking at this part that is we are looking at a photo detector, a photo diode here, and a load resistance across it, here and incident photon flux phi 2. This is the same curve I have expanded this part of the curve. So, we are in the fourth quadrant.

So, this is the region of operation of a solar cell. There is no bias applied. Depending on the load resistance RL here, if an incident photon flux phi 2 is incident on the photo detector, then it will generate a current corresponds to this and a voltage across the resistance here. This is the current and this is the voltage, so VM and IM, the photo current voltage. So, obviously, this slope is 1 by RL depending on the chosen RL. So, if I use a smaller RL, we will have a load line which is like this. So, this is for an RL. Now, this will be RL is equal to let us say RL is equal to R 0 some number, then it will be RL less than R 0, and if I use a larger load line, that is if I use a larger resistance, then this will be the load line corresponding to RL greater than R 0. If I use a smaller resistance, please see that current is here.

The photo current generated is this much and a voltage across the load is this much here. If I use this is the RL, then the photo current generated is this much and the voltage generated is this much. So, the area under this rectangle for example, let me show. Shade one of the rectangle. The area of the rectangle that is the current I into the voltage gives us the power, the power generated. So, the power is the electrical power generated because of the incident photon flux is given by the area of that is I into v. If I choose this as the RL, then the area would be this. So, let me do a reverse shading to show that the area is here. So, the power generated will this current multiplied by this. So, this will be and if I use the other load resistance, I will have a area which is different. The point is by an appropriate choice of RL, we can maximize the power generated and this is an important consideration in the designs of solar cells and circuits to collect the photo voltage.

So, solar cell is basically a photo diode which is operated in the fourth quadrant and without any bias. So, an important issues is a load resistance, the choice of load resistance form a circuit design point of view. The material issues are there. Material issues are completely different. So, this is certainly from the circuit designer's point of view to get maximum power output of this. So, the power generated. So, let me move to the next detector. Very briefly we are just discussing these various detectors. One can go a for further details to various references, but these are very closed to the discussion that which we already had and that is why I am just bringing them one by one. So, let me go into the remaining 10 minutes also.

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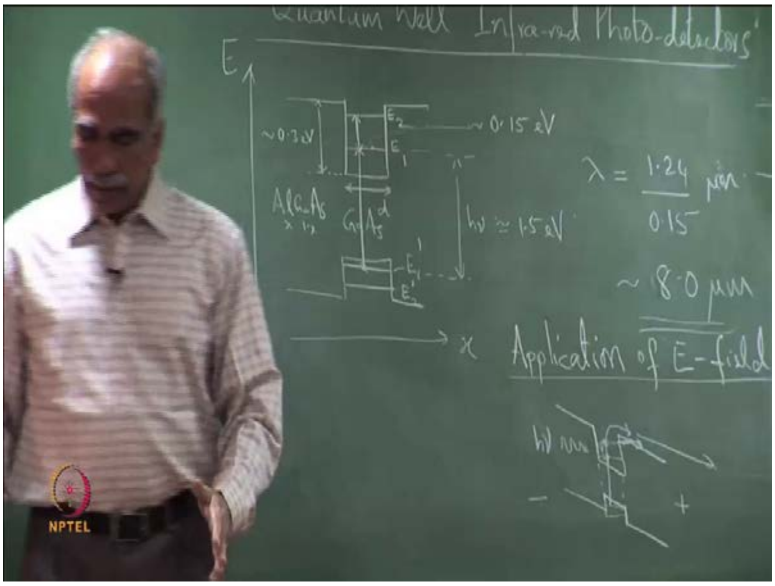

Let me go to the next detector which is quantum well infrared photo detector. So, we have come here. These are photo detectors used in the IR as the name indicates use for infra red. They make use of inter sub band transition in quantum well device. If you recall, we have studied the quantum well structures are here in detail. If we recall a quantum well, let us say for example, gallium assonate and aluminum gallium assonate als 1 minus x assonate in need, A QWIP consisting of aluminum gallium assonate and gallium assonate. Quantum wells are widely used. So, if we have a large band gap and a small band gap material sandwiched between two large band gap material, we can obtain a quantum well depending on the dimension of these layers. Here, when d is smaller than or comparable to debacles wavelength, the energy levels are quantized and we have a loud energy levels here which corresponds to energy sub bands. So, E 1 and E 2 and we also have similarly energy sub bands are discrete levels in two dimensions.

This is x and this is E and we have E 1 dash and E 2 dash allowed energy levels for holes in the valance band E 2 dash, and the inter band that is inter band transmission takes place from here to here, that is the energy level lowest energy level allowed energy level here. So, an electron from here can make a transition to the conduction band here to event and create the hole and electron in the process and electron which is sitting here. So, these too require an energy difference which corresponds to this. So, this is the h new should correspond to this. So, if it a gallium assonate as you know that this is about 1.42 eg and therefore, these will be an larger than that. So, h new is say 1.5 EV approximately on the order of 1.5 EV.

The energy difference here this is of course, not to scale because the height of the barrier here this is typically about 0.3 EV 0.3 EV or 300 m EV and therefore, the energy difference between the energy sub bands here is quite small. So, this difference would be 0.2 ev or 0.1 5 ev of the order of 0.15 ev 150 m ev, which means the photons which can result in an electron going from E 1 to E 2 by absorption from one energy sub band to the other sub band correspond to the wave length lambda which is equal to 1.24 divided by 0.15 ev. So, this is in micrometer. So, that is something like this will be around 8 micrometer. So, we can see that we are in the infra red. So, when infra red ration is incident on a quantum well structure like this, then the energy there can be inter sub band transitions within the conduction band and photon can get absorbed by this inter sub band transitions. So, the inter sub band transitions, of course unless we take away the electron from here, then only the process can continue. The process detection can continue and one of the ways to do this is by applying an electric field, so application of electric field. We already have discussed this in the context of electro absorption modulators.

So, application of E field, application of an electric field. So, this leads to the energy band diagram tilting again not to scale. So, here is the first level and here is the second level with the application of the electric field. So, the electron in the incident photon here, so h new incident photon leads to an inter sub band transition and electron moves towards this level here. The electron which is here can either because the potential barrier is much smaller, the electron can spill over, that is thermayalic emission mounting over the barrier and then it will be swept to this end. The electron will be swept, because this is an application of electric field. This side we have applied a positive and this side we have applied negative. So, the electron will be swept away the electrode, where we applied an electric field. It can also tunnel through the electron because now the barrier thickness here is the very small. So, the electron could also tunnel through here and come out, but the important point is that this application of the electric field provides a means for a thermayalic emission or electron tunneling through the barrier and escape from the well and therefore, there can be furtherer photons which can be observed by the same process.

So, the basic mechanism is this. The incident photons creates and there inter sub band transition, an electron which are move toward the exited level is ejected or moves over the barrier and is collected which contributes the photo current the external circuit. So, the quantum well infra red photo detectors are based on this principle. Normally, one does in it use a single quantum well. Multiple quantum wells are used to enhance the effect, always identical multiple quantum wells are used. We have already discussed this in the context of lasers, quantum well lasers and multi quantum well lasers that one uses multiple quantum wells to enhance the effect, several quantum wells similarly on this side.

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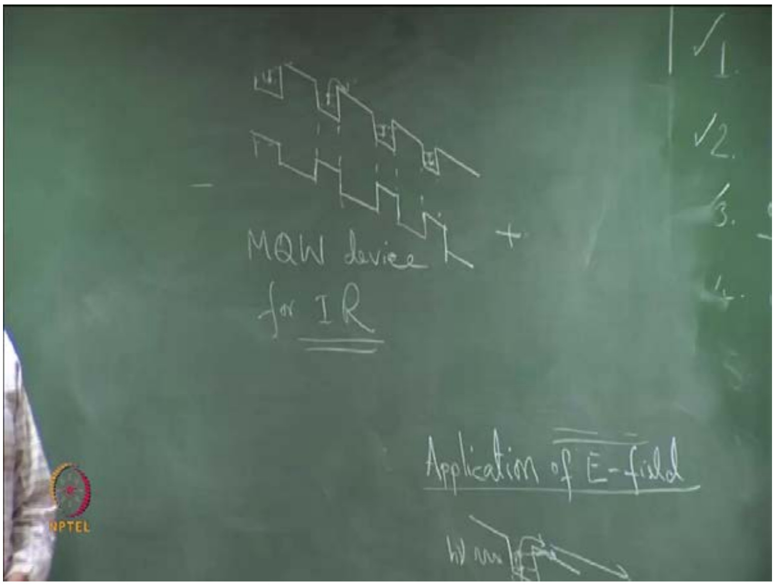

So, here are the levels. In each of the wells, we have the same energy difference, provided they are identical. If the well width is the same everywhere, they are identical in the energy separations here between the two sub band levels is the same everywhere and therefore, the photon of the same energy can be absorbed. So, the electron makes an upward transitions and then transients outward. So, there is a applied potential here, plus and minus. So, this is a multiple quantum well device. So, multiple MQW device which uses inter sub bands transition detect for IR radiation, for detection of IR. So, QWIP we have discussed here, and you could go through details for further details on these devices.

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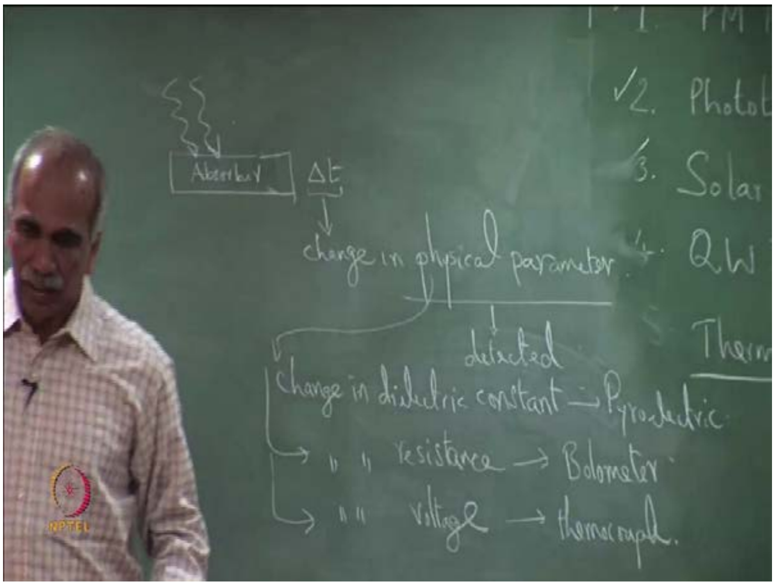

One sentence on, we are just running out of time, so one sentence on thermal detector; thermal detectors are a class of detectors. The basic idea is simple that there is an absorber, appropriate absorber. The incident radiation leads to a change in temperature delta t. This is the observer. The incident radiation leads to a change in temperature delta t. So, delta t leads to change to a physical parameter, change in physical parameter absorbent here, and this change in physical parameter is detected.

So, what is the change in physical parameter? What are parameters could be changed? For example, this physical parameter could be a change in dielectric constant. This could be a change in resistance as is in the case of, so this is in the case of bolometer. This is change in dielectric. Piezoelectric are based on this principle of piezoelectric detectors. This is bolometer. It could be a change in pressure or any one of the physical parameters could change. For example, temperature, this could change in voltage as in the case of a thermo couple, but the basic idea is this that chose an app, it could be a mechanical change as well. For example, bimetallic absorbers could change and correspondingly, there could be a physical deformation depending on the change in delta t. So, this is sensed the change in the physical parameter is sensed by different techniques, but the basic principle is just that incident photon flux leads to a change in temperature which subsequently changes physical parameter that is measure.

Hence, all of these fall under the class of thermal detectors. So, we stop here. It is a time and in the next class will be the last class of this course. So, we will discuss, we will just review and discuss photonic integrated circuits.

Thank you.