Semiconductor Optoelectronics
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Lecture - 44
Other Photodetectors

Welcome to this lecture. This is lecture number 45. We are nearing the end of this course. Today in the last 2 classes, we have seen primarily the photodetectors, photodiodes and pin photodiodes and APD, 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 photodetectors referred to miscellaneous photodetectors.

Some of them very important, although not from the point of view of optical communication. So the first of these, let me list some of the important photodetectors here.

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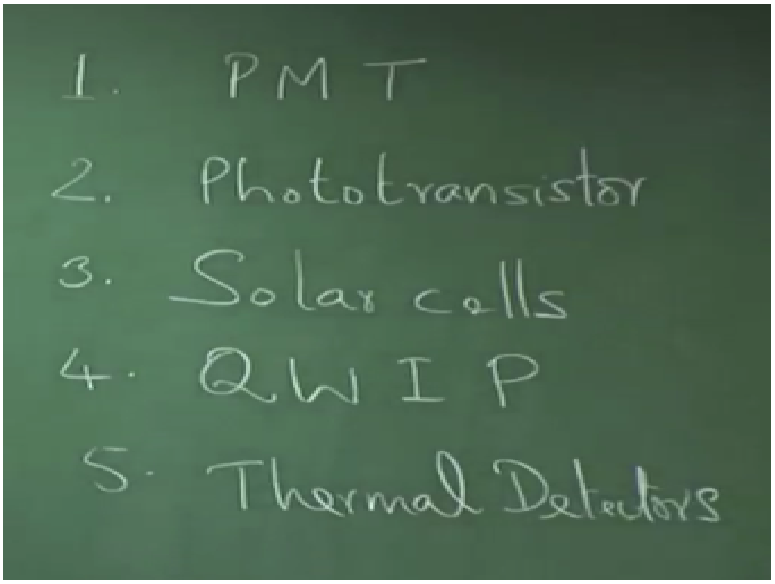

1. PMT
2. Phototransistor
3. Solar cells
4. QWIP
5. Thermal Detectors

The photomultiplier tube, PMT, we also have photo transistors. Then we will briefly discuss solar cells. We discuss solar cells because it is basically a photo detector, which is operated in the photovoltaic mode of operation, as we will. Then we will briefly touch up on quantum well infrared photodetectors, QWIP, and if time permits we will also discuss little bit about thermal detectors. These are basically a class of thermal detectors. So let me start with PMT, because widely used photodetector.

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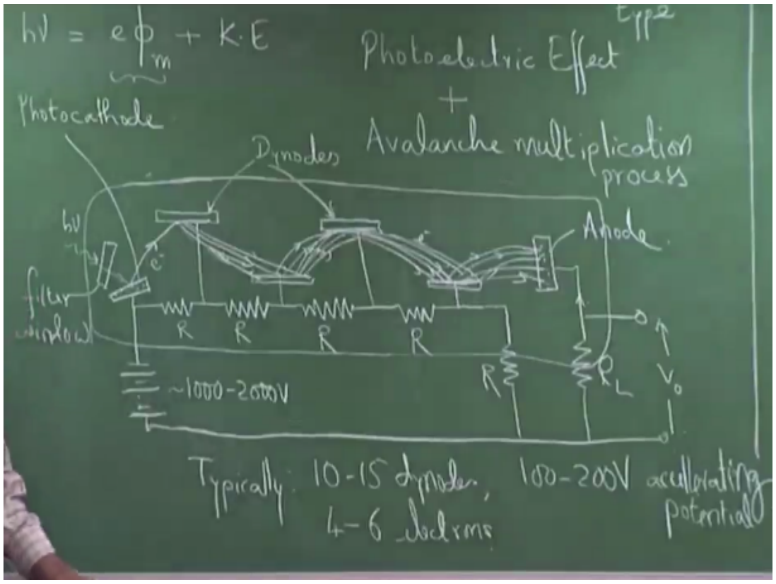

Photomultiplier, the basic principle of operation is first photoelectric effect, photo-emissive type of detector. Photoelectric effect which is followed by Avalanche multiplication process. The photoelectric effect + Avalanche multiplication process, so let me illustrate the simple basic schematic of a PMT and then we will discuss in detail. This is a photo cathode. Photon is incident through a filter or a window.

I will explain, it will become clear once I explain these. This is the photo cathode. The light to be detected is incident on the photo cathode here. The photo cathode releases an electron, a photo electron. As you can see these are the dinodes. This is an anode. These are resistances, all equal resistances, R, R, R. So these are the dinodes. This is a schematic representing the operation of a PMT. The incident photon releases a photoelectron provided the photo cathode.

The work function of the photo cathode is smaller than the photon energy or this is basic equation of photoelectric effect, is here. H nu=e*phi n or w. So this is the work function + kinetic energy. So kinetic energy of the electron. If H nu is the energy of photons, which are incident on the photo cathode. If H nu is > the work function, then an electron with this much of kinetic energy is released. Now as we see here, this is at a high negative potential.

Typically, 1000 to 2000 volt here of power supply and the subsequent dinodes are at lower potential or positive potential with respect to this and therefore they immediately get attracted towards the dinodes. The dinode, 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 the next dinode, move towards the next dinode because there is a potential difference between this. There is a resistance here.

Therefore, they hit this dinode with certain kinetic energy and they lead to further Avalanche multiplication. 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 dinodes, we have an avalanche, which takes place, so let me illustrate further that the avalanche is taking place.

These are all electrons released, which are finally collected. As you can see, this is at a certain potential and this is connected to ground or the common line here and therefore this is again at the same potential difference as this one and therefore these are collected at the anode. So the electrodes from the last dinode are collected at the anode. This leads to a photo current and voltage. This is the load resistance RL and this leads to an output voltage Vo here.

So a single photon incident leads to creation of an avalanche of electrons. Typically, the entire thing, of course the entire thing is housed in a tube like this. Let me show you in another diagram, but the principle is illustrated here and typically a PMT, the tube contains 10-15 dinodes and accelerating potential difference of 100-200 volts between adjacent dinodes, so typically 100-200 volt accelerating potential.

Typically, 4-6 secondary electrons per primary electron, which releases 4-6 electron, which further multiplies 4-6 times, further multiplies 4-6 times and therefore current gain due to one photon incident here. The current gain, let us say, what will be the current gain. How do we calculate the current gain? So we have typically 4-6, let us call this as delta, this is n the number of dinodes, then the gain.

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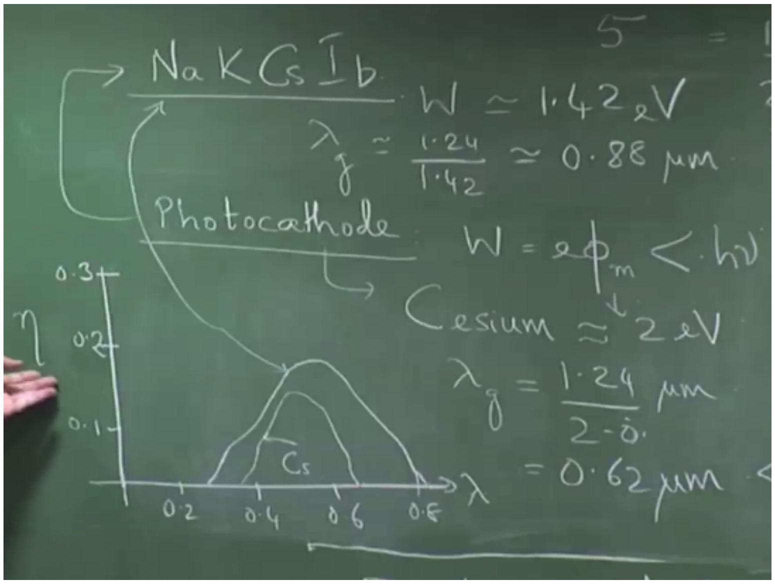

The gain, the carrier gain will be = delta to the power n. So if delta for example, delta=5, so typically 4-6 per primary electron is released, and if it is 10-15 dinodes, so let me assume n=10. So this is 5 to the power of 10 is the gain because one releases 5 and each 5 releases 5, so it is 5 to the power of n, n number of dinodes. So this is nothing by 10 to the power of 10/2 to the power of 10. So that is approximately 10 to the power of 7. 2 to the power of 10 is 32*32 approximately, so this is approximately 10 to the power of 3 and therefore this is 10 power 7.

So the current gain G is approximately 10 to the power of 7, which means we have a large current gain. So how does this number manifest in terms of the detection power. We can take an example and let me erase the diagram here and let me take an example. So example, let us say 1 picowatt, the incident power is 1 picowatt. Incident P optical is 1 picowatt, so how to calculate what is the output across the load resistance.

So the typical responsivity of the photo cathode, photo cathode material, so let me, before I continue with the example, let me talk about the photo cathode materials. The photo cathode must have work function W or e*phi n, which would be < h nu. So if generally one uses cesium, which has a work function of approximately 2eV that means up to 2eV photons or above, photons with energy 2eV or more than 2eV are able to create electrons, lead to photo electric effect.

So cesium is about 2eV, that means the wavelength corresponding to this is 1.24/2eV micrometer. So which means this is 0.62 micrometer. This means that light with wavelength 0.62 micrometer that is 620 nanometer or less wavelength, 620 nanometer can be detected using this. So indeed the responsivity, if we see the typical quantum efficiency eta versus wavelength, we typically have 0.2, 0.4, 0.6, 0.8. So lambda versus eta typical numbers are and the numbers here are about 0.1, 0.2, 0.3 eta.

The quantum efficiency of the detector, quantum efficiency is of this order here. So this is for cesium, if I take cesium there are other materials, for example one of the materials, which is an alloy, a compound of sodium, potassium, cesium antimonide. This has a work function e phi m. So W is nearly = 1.42 eV almost the same as the band gap of gallium phosphide, but this is the work function. So a photo cathode material this has about 1.42 eV.

This means the lambda G is nearly= 1.24/1.42 that is nearly= 0.88 micrometer, which means it can go to about 0.8 or beyond, a little bit beyond 0.8. So this is for this material and this is for cesium and the curve which I have shown here is for this material, photo cathode materials. The important point to recognize is that the quantum efficiency is finite and usable quantum efficiencies are in the range of visible range, primarily in the visible range.

It is very difficult to find materials which have non-0 quantum efficiency beyond 1 micron. So this is in fact one of the primary limitations of photo multiplier tubes is the range of detection wavelengths are limited to visible or near ultraviolet or very close to infrared. So let me come back to this. Because I wanted to show you in practice what kind of numbers that we have for the quantum efficiency.

Once we know the quantum efficiency, we can come back to this example. Now I come back to the example. The example of what kind of voltage is generated at the output if one picowatt of optical power is incident.

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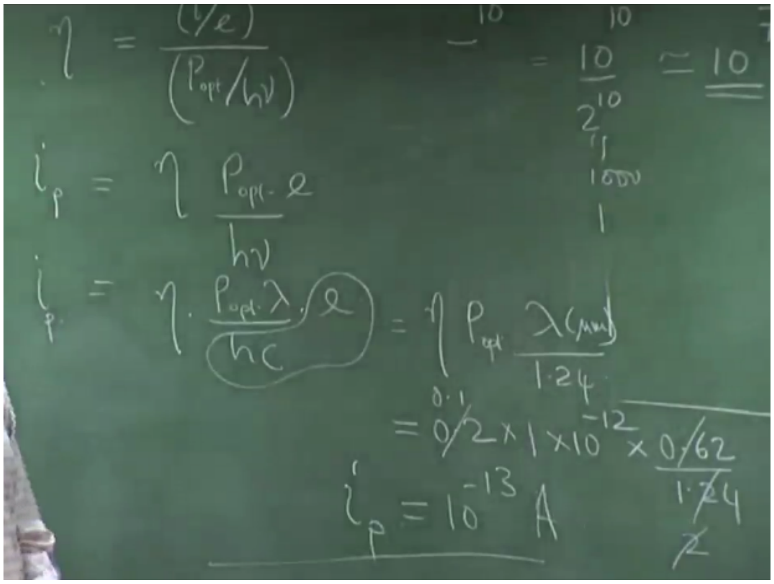

So I go by the definition of quantum efficiency=electron flux, so i/e/incident photon flux P optical/h nu, incident photon flux and therefore this is the primary photo current generated with this eta here. Therefore, we have i, the primary photo current=we have eta*P op/h nu*e, so that is = eta*P op/h*C/lambda*e and we know this quantity here hC/e is 1.24 if lambda is in micrometer. So this is = eta*P op*lambda in micrometers now/1.24.

For an incident optical power P op, you can find out what is the primary current generated by the photo cathode. So if I look at the previous curve, these are 0.1 to 0.2. So let me assume 0.2, eta=0.2, incident optical power is 1 picowatt, so 1*10 power -12 and the wavelength. Let me assume the wavelength as 0.6 or 0.62/1.24. So this is the primary photo current generated. So this is nothing but 2 and 2 goes here to 0.1 that means this is.

So approximately 10 to the power of -13. So ip=10 to the power of -13 ampere, the primary photo current generated. However, the current which comes out at the output. So we have a gain 10 to the power of 7.

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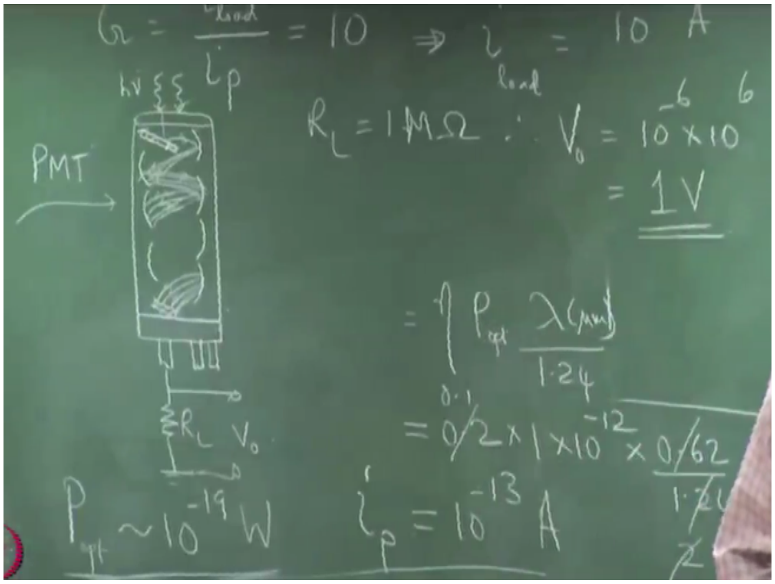

So gain which is = i at the load resistance, output current/i primary. This is = 10 to the power of, the number which we have calculated here, and therefore the current generated this implies i load=iP is 10 to the power of -13, so this is simply 10 power -6 amperes, i load=10 power -6 amperes. So recall that we have a tube. The PMT normally looks like this. There is a tube and a window at the top for photons to incident. So this is incident photons. It is the tube.

It is the PMT schematic of a PMT now. So incident as soon as it is incident there is the photocathode here. I am not showing the electrical connections, and then there is a dinode here, a dinode here, a set of dinodes and then the final anode, so just recall that the incident photon generates an electron, which then multiplies and gets attracted to this dinode. From here, it gets further multiplied to this dinode, from there it is further multiplied to this dinode.

So we have an avalanche of electrons, which are coming and finally the last avalanche of electrons reaches the anode and this is the anode, which is connected. So there are normally terminals to connect the power supply and the cathode current. So this is passing through the load resistance Rl and here we have the output. One can even measure the photo current, which is coming out or the voltage generated here.

For example, if I take Rl=1 mega, so therefore the voltage V out=10 power -6*10 power 6 is 1 volt. 1 volt is a very large output to measure. So 1 picowatt can be easily detected by measuring the output voltage here. So 1 picowatt incident here by considering typical numbers, we have calculated that 1 picowatt incident here generates a photo current, primary photo current of 0.1 picoampere and then the current because of the current gain, we have the current at the load of about 1 microampere and across the load resistance we have about 1 volt.

In deed one can easily detect power. I mentioned this that output power of the order of 10 power -19 watts. We have already this calculation for 1 picowatt, 10 power -12 watt and one can detect powers as low as 10 -19 watts using a PMT. It is a very sensitive detector, but as I mentioned the primary limitation of the photo multiplier tube is the material for photo cathode to find materials for photo cathode, which can respond to infrared radiation.

Work function of materials sufficiently low work function of materials. It 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. So let me quickly go to the next one, photo transistor.

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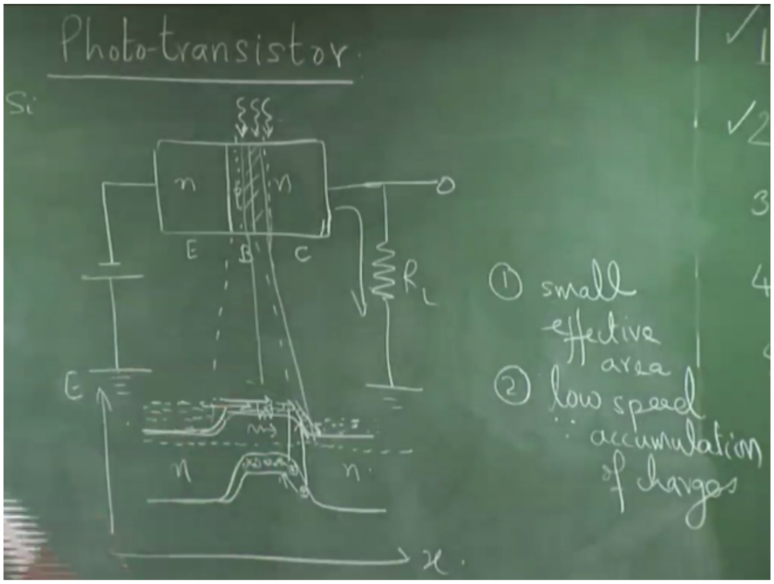

Photo transistor basically is a transistor. We consider an NPN transistor here. That is a silicon NPN transistor. The incident light is incident at this junction. The light incident at other junctions do not really contribute to the current and therefore the active junction is this one. So this is an NPN transistor. This is the emitter, this is the base and collector. So usually this end is forward biased and in 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. What the base current does to achieve 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 look at the energy band diagram of this NPN junction. So let me plot the energy band diagram here. So this is NPN junction, so PN in reverse.

So this is the P region and the N region and we also have this. This is the energy band diagram E versus X, where X is this dimension here. So the Fermi function this is the N side. So Fermi level is here. So before you applied any bias the Fermi level is constant all around and there is a steady state, the net carrier which is traveling in this direction is=the carrier flux traveling in the opposite direction. So there is no net current.

But when you bias here, this is forward biasing this end. So this moves up here, this end goes up, or this end comes down. So there is relative bias, so you have plenty of electrons here. There are holes here and again there are plenty of electrons, because this is N side, so this is N, this is P and this is N. A photon flux, which is incident on this junction here that is let us look at this junction. This is the active area. That is the base collector junction, PN junction.

A photon which is incident here creates an electron hole path, so an electron makes an upward transition here. So the incident photon, let me show the photon incident h nu. So in this region, creates an electron hole path. The electron which is here comes down the slope, so the electron flows down the slope here of the potential slope. The hole, which is generated here, the positive hole, this moves up, so we have all holes here. So there are more holes coming here.

There are more holes and an electron 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 lowered, schematically let me show the barrier lowering. So the barrier getting lowered. This comes down here, similarly the barrier is getting lowered.

When the barrier is getting lowered, there are 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 the holes accumulating in the P region. The electron is flowing towards 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 base current.

When you forward bias the emitter based junction, the barrier is lowered and consequently large current flows from N side, that is from the emitter to the collector, that is carriers move 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 accumulating 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 depends on the incident photon flux, but the current is not just the primary current because of the 2 electrons which are generated or 2 holes which are moving. If 2 photons were incident generating a pair of hole and electron, then the primary current would be very low.

But because of the lowering of the potential barrier, large electrons, large number of carriers move from the emitter to the collector leading to a current gain and this is the primary working of a photo transistor. So in the last class we discussed about avalanche photo diode, which has a current gain because of the avalanche process, exactly like that we see that the first 2 detectors, which I have listed here, other detectors, the photo multiplier tube has a large gain again due to avalanche process.

It is not a semiconductor PN junction diode, 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 its gain also provides an overall gain to the photo current. Typical current gains hfe is of the order of 200-500. The current gain is of the order of 200-500 in photo transistors.

Photo transistors are used in certain simple applications where you have a sufficient amount of light incident, because one of the primary difficulties or demerits of photo transistor is that the junction, the catchment area here is very small, because it is at the base collector junction, which is the active region. So the area here is very small. It is a small area photo detector, so it is normally required to focus the incident light on to the junction.

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 2 merits, 2 demerits, one is small active area, small effective area, and 2 lower speed device because of accumulation of charges in the bases. This is a device, which is used for many simpler applications primarily due to the photo current gain, which is available with photo transistors.

So let me go to the next detector here, solar cell. Solar cell is not used as a detector normally. It is used for power generation as all of us are aware, but its proximity to the photo detector operation that we have discussed, proximity 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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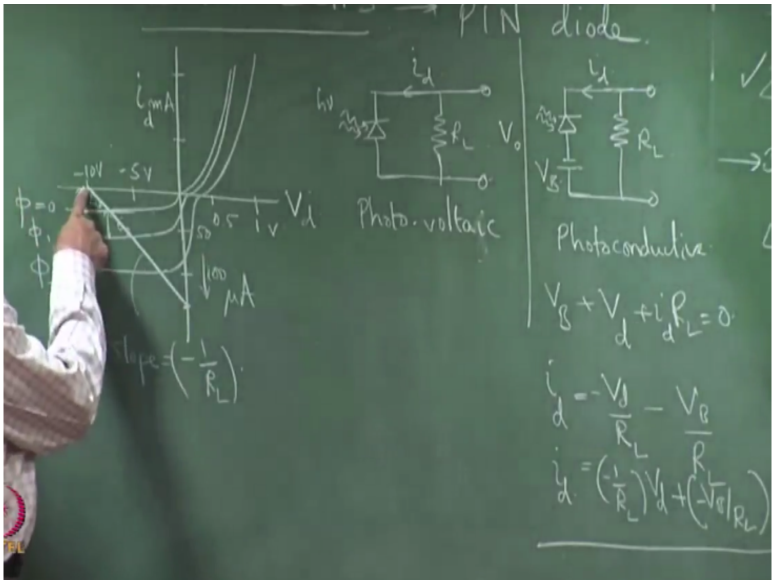

Basically, this is PN diode or PIN diode and if we recall, the IV characteristics of the photo diode, then we have, when there is a photon flux, which is incident, then we have the scales on the x and y axis are different. For example, here the numbers are 0.5, 1.0 volt and here we are talking of -5, -10 and so on. Similarly, the current here is in microamperes. So typically 50, 100 microamperes and here the current is typically milliamperes.

Because this is the forward bias region and this is the reverse bias region. So this is saturation current when there is no incident photon flux, phi=0 and this is for an incident photon flux phi1 and because of that there is a finite photo current IP here. This is IP, this is IS, the saturation current and another incident photon flux phi2. We recall that there are 2 more soft operation of a photo detector which we have already discussed.

The photo voltaic mode and the photo conductive. 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 a load resistance here to be chosen appropriately and we have an output voltage. So this is the photo voltaic mode, photo generated voltage. The photo conductive on the other hand had a reverse bias, which we had apply.

So here, this was Vb, same photo diode, but now we have a bias voltage, which is a reverse bias and this is photo conductive mode of operation. If this is Rl and if the diode current through this the reverse current here Id, then we write Vb+ the voltage across the diode Vd+Id*Rl=0or Id, equation of the load light, Id=Vd-Vd/Rl-Vb/Rl. So Vd is this, the diode voltage. We plot Vd versus Id here, so this is Id and this is Vd.

This is the characteristic which simply says that this is nothing but -1/Rl*Vd-Vb/Rl. So this is Id, this we have already discussed. This is the equation of the load line Y=Mx+C the constant. In this case, if I apply a reverse bias of 10 volt, then the load line would look like this. So this is the load line, the slope of this is negative =-1/Rl. This value here is nothing but this Vb/Rl because when Vd=0, Id=Vb/Rl and this is Vb.

If Vb turns out to be 0, if we reduce Vb to -5 volt, then this curve will shift here. The new load line will be this. If we turn of 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, this will be load line. The slope remains the same depending, so this is reverse bias-10 volt Vb, this is -5 volt, 0 volt and this is forward bias, let us say 1 volt.

So in this first case, let me consider only one of them for example. So let me consider this, the case of phi2, that this curve only. There is an incident photon flux phi2. So I am just showing a dotted line to distinguish that, incident photon flux phi2 on this, so the cue point, the intersection of the load line with the Iv characteristic is called the cue point or point which is operation point, the cue point is here.

If I have 5 volts, the cue point is here and if I reduce it to 0, the cue point is here. If I forward bias the cue point is here. So this is the cue point, the operation point. The point of operation if the incident photon flux is this. So let me now draw only this, only corresponding to this and erase all the rest. Here is the characteristic. Let me zoom this part of the 4-th quadrant because I am interested in solar cells, which means we are not applying any voltage, Vb is 0.

So this will be the characteristic and therefore I am interested in the 4-th quadrant here. So this is the 4-th quadrant and let me draw that.

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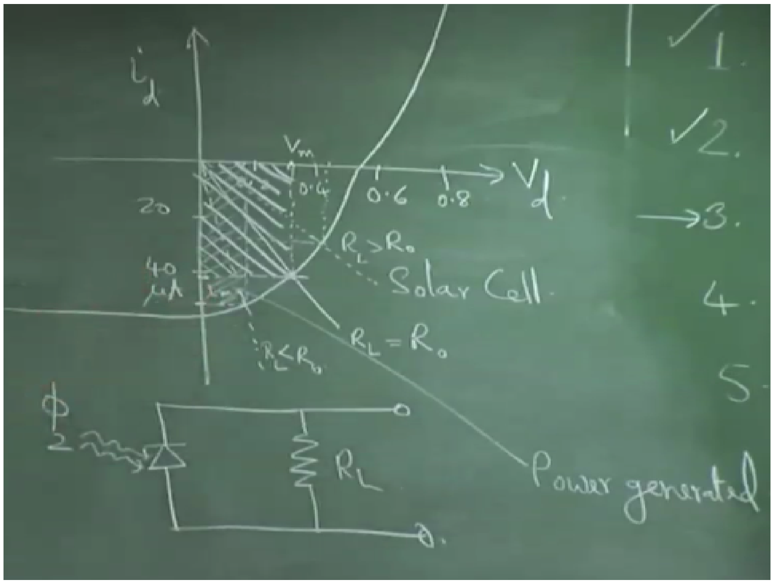

It is a zoomed quadrant. So here is the same Id, this is Vd. It is just zoomed. See that the numbers are small. So this is 0.2, 0.4, 0.6, 0.8 volts here and this is the current, so let me write this as 20, 40, micro amperes and here is the load line, which I had drawn and this is the operating point. What does this mean. So we are looking at this part that we are looking at a photo detector, a photo diode and a load resistance across it here and incident photon flux phi2.

This is the same curve; I have expanded this part of the curve. We are in the 4-th 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 phi2 is incident on the photo detector, then it will generate a current which corresponds to this and a voltage across the resistance here. So this is the current, this is the voltage. Let us say Vm and Im, the photo current and the voltage.

So obviously the slope is 1/Rl depending on the choice of Rl. If I use a smaller Rl, we will have a load line, which is like this. This is for an Rl, now this will be Rl=R0, then this will be Rl<R0 and if I use a larger load line, if I use a larger resistance, then this will be the load line corresponding to Rl>R0. If I use a smaller resistance, please see that the current is here. The photo current generated is this much and the voltage across the load is this much here.

If I use this as the Rl, then the photo current generated is this much and the voltage generated is this much. So the area under this, this rectangle for example, let me show shade 1 of the rectangles, the area rectangle, that is the current I into the voltage gives us the power, the electrical power generated. The electrical power generated because of the incident photon flux is given by the area of this, that is I*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 different here. So the power generated will be this current multiplied by this, and if I use the other load resistance, I will have an 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 design of solar cells and circuits to collect the photo voltage that one gets.

Solar cell is basically a photo diode, which is operated in the 4-th quadrant and without any bias. An important issue is the load resistance, the choice of the load resistance, from a circuit designer’s point of view. The materials issues are there; materials issue are completely different.

This is from a circuit designer's point of view to get maximum power out of this, the power generated. Let me move over to the next detector.

Very briefly, we are discussing these various detectors, one can go for further details to various references, but these are very close to the discussion that which we already had, that is why I am just bringing them one by one. So let me go to in the remaining 10 minutes or so, let me go to the next detector, which is quantum well infrared photo detector.

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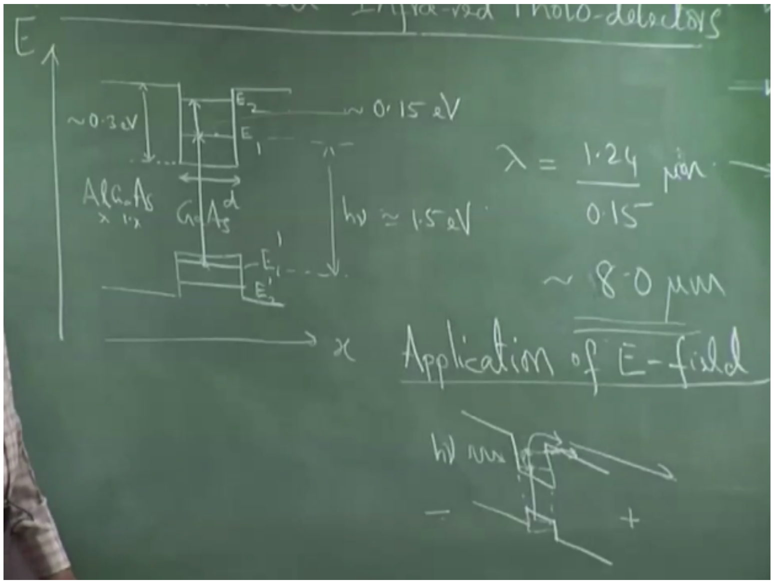

So we come here, Quantum Well Infrared Photo Detectors. These are photo detectors used in the IR, as the name indicates for infrared. They make use of inter-sub band transitions in a quantum well device. If you recall, we have studied the Quantum Well structures earlier in detail. If you recall a quantum well, let us say for example, gallium arsenide and aluminium gallium arsenide, Al gallium1-Arsenide, indeed QWIP consisting of aluminium gallium arsenide and gallium arsenide quantum wells are widely used.

So if we have a small band gap material sandwiched between 2 large band gap material, we can obtain a quantum well depending on the dimensions of this layer here, D. when D is smaller than or comparable to the De Broglie wavelength, then the energy levels are quantized and we have loud energy levels here, which corresponds to energy sub-bands, E1 and E2 and we also have similarly energy sub-bands or discrete levels in 2 dimensions. This is X and this E.

We have E1 dash and E2 dash, allowed energy levels for holes in the band E2. The inter-band that is inter-band transitions take place from here to here that is lowest energy level allowed energy level here, so an electron from here can make a transition to the conduction band here to even and create a hole and electron in the process. An electron, which is sitting here, this would require an energy difference which corresponds to this.

This is the h nu, should correspond to this. If you take gallium arsenide as you know that this is about 1.42 eG and therefore this will be even larger than that, so h nu is say 1.5 eG approximately of 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 or 300 meV and therefore the energy difference between the energy sub-bands here is quite small.

So this difference could be 0.2 eV or 0.15 eV of the order of 0.15 eV, 150 meV, which means the photons which can result in an electron going from E1 to E2 by absorption from one energy sub-band to the other sub-band, correspond to a wavelength lambda, which is = 1.24/0.15 eV, so this is in micrometers. This will be around 8 microns. So we can see that we are in the infrared. When infrared radiation 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 of detection can continue, and one of the ways to do this is by applying an electric field. So application of an electric field. We have already discussed this in the context of electro-absorption modulators, application of e field, this leads the energy band diagram tilting again not to scale.

Here is the first level and here is the second level, with the application of the electric field. So incident photon here, so h nu incident photon leads to an inter-sub-band transition, an electron moves over to this level here, the electron which is here can either because the potential barrier is now much smaller, the electron can spill over, that is thermionic emission mounting over the barrier and then it will be swept to this end.

The electron will be swept because there is an application of electric field, this side we have applied positive and this side we have applied negative, so the electron will be swept to the electrode where we have applied an electric field. It can also tunnel through because now the barrier thickness here is very, so the electron can tunnel through here and come out, but the important point is application of the electric field provides a means for thermionic emission or electron tunneling through the barrier and escape from the well.

Therefore, there can be further photons which can be absorbed by the same process. So the basic mechanism is this. An incident photon creates an inter-sub-band transition. The electron which has moved to the excited level is ejected or moves over the barrier and is collected, which contributes to the photo current in the external circuit. So the quantum well infrared photo detectors are based on this principle.

Normally, one does not 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 multiple quantum well lasers that one uses multiple quantum wells to enhance the effect.

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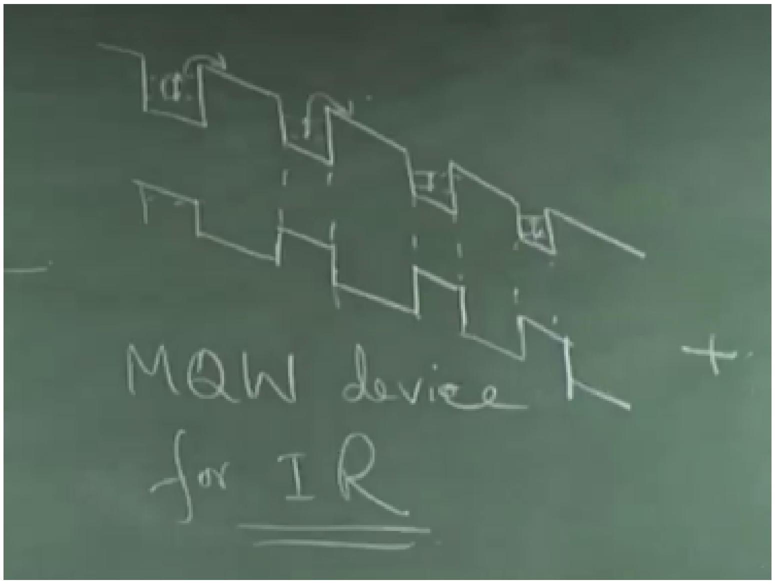

Similarly, on this side, so here are the wells. In each of the wells, we have the same energy difference provided they are identical. If the well width is the same everywhere, if they are identical, then the energy separation here between the 2 sub-band levels is the same everywhere and therefore the photon of same energy can be absorbed. So the electron makes an upward transition and then a transition outward.

There is an applied potential here, plus and minus. This is a multiple quantum well device, so multiple MQW device which uses inter-sub-band transition to detect for IR radiation. We have discussed QWIP here and you could go through further details on these devices and one sentence on, just we are running out of time, so one sentence on thermal detectors. Thermal detectors are a class of detectors.

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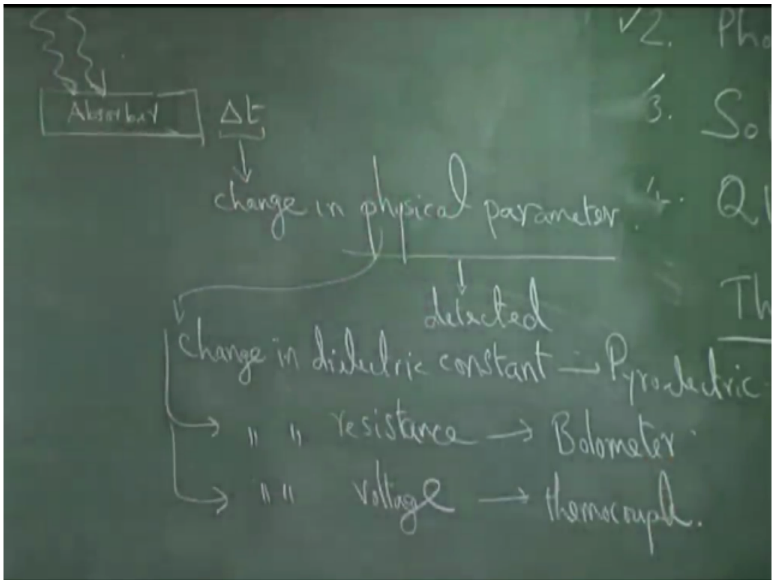

The basic idea is simple that there is an absorber, appropriate absorber. The incident radiation leads to a change in temperature delta T. This is the absorber. So delta T leads to a change in physical parameter of this material absorber here and this change in physical parameter is detected. So what is the change in physical parameter, what all parameters could be changing. For example, this physical parameter could be a change in dielectric constant.

This could be a change in resistance, as in the case of bolometer. Pyroelectric detectors are based on this principle. 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 thermocouple, but the basic idea is this. It could be a mechanical change as well. For example, bimetallic absorbers could change and corresponding there could be a physical deformation depending on the change in delta T.

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 a physical parameter that is measured and hence all of these fall under the class of thermal detectors. So we stop here. It is time and in the next class will be the last class of this course. We will just review and discuss photonic integrated circuits. Thank you.