Semiconductor Optoelectronics
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Lecture - 42
Photoconductors

These two topics I had skipped because of shortage of time. In the last two lectures we discussed about the general characteristics of photo detectors.

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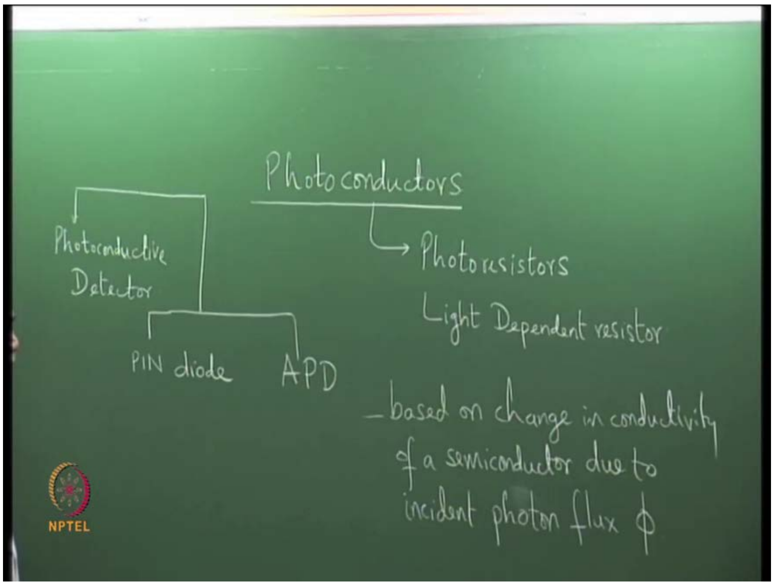

And today we will consider photo conductors, photo conductors. So there are as I indicated, there are three different important semiconductor detectors. One is the photo conductors or photo conductive, sometimes it is called photo conductive photo conductive detector, detector. And photo diodes in which we have two important categories, that is pin photo diode. So pin diode and avalanche photo diode APD.

So today we will discuss about photo conductive detector or simply photo conductors. Sometimes people also call this as photo resistors synonyms photo resistors. And when used in visible light applications; many times we also call this as light dependent resistor LDR. Light dependent resistor basically variations of the photo conductive detector. The basic principle of operation is as the name indicates it is based on it is based on change in conductivity. Detection of the change in conductivity conductivity of a semiconductor of a semiconductor due to due to incident photon flux phi incident photon flux phi incident photon flux.

So, based on the change in conductivity and hence the name photo conductive detector or photo conductors. It is one of the simplest detector which is basically simply a piece of semiconductor of appropriate material.

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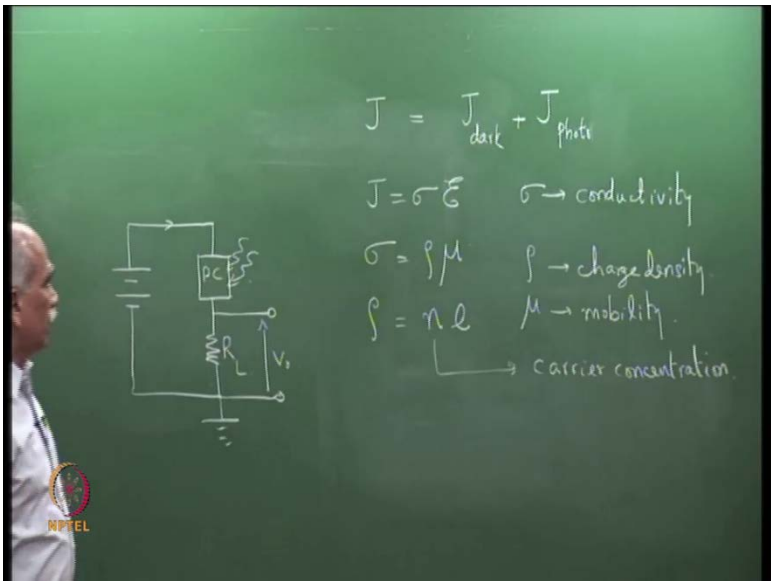

And generally used in this configuration. So, you have a supply here and here is the photo conductor. The different designs. So this is the photo conductor and here is the load resistance. So, the whole things grounded and here is the output, so Vo.

The output taken across a load resistance and this is the photo conductor. So incident light is incident on the photo conductor. Light is incident on the photo conductor which changes the conductivity of this element and therefore, hence the current through the device. So, the current through the device changes and the current across the load resistance changes and therefore, you get an output.

So this is the basic configuration of use of a photo conductor or a photo conductive detector is one of the simplest detector and it is a detector which has a gain as we will see. So, let us see the responsivity of this detector responsivity of the photo conductor. So how do we go about this? So there is a change in conductivity. Therefore, if j is the current density j is the current density through of through the current through the photo conductor; then j comprises of two components.

One is j dark plus j photon j dark is the current density through the photo conductor when there is no incident photon flux and J photon or J photo. not not Write photon J. Photon is the current density when there is a photon flux incident. We know that J is equal to sigma into e where let me write the flowerily because sigma e where sigma e is the conductivity. Conductivity and sigma is equal to rho into that is charge rho charge density rho into sigma is conductivity.

So, this is rho into the mobility sigma is equal to rho into mu and rho is equal to rho itself is equal to. If n is the number of carriers per unit volume then n into e is the charge density rho is the charge density charge density. And mu is the mobility mu is the mobility and n is the carrier concentration carrier concentration which means number of carriers per unit volume n is the carrier concentration.

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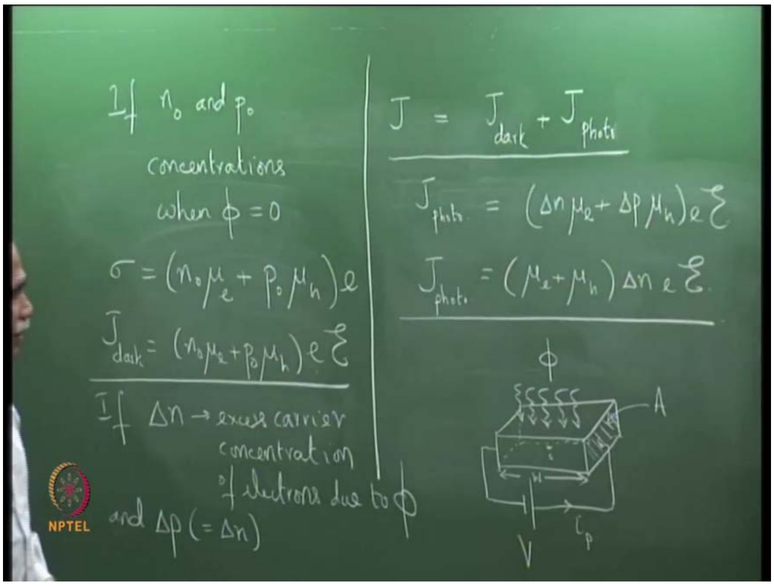

If n_0 and p_0 concentrations when $\phi = 0$

$$\sigma = (n_0 \mu_e + p_0 \mu_h) e$$

$$J_{dark} = (n_0 \mu_e + p_0 \mu_h) e \mathcal{E}$$

If $\Delta n \rightarrow$ excess carrier concentration of electrons due to ϕ and $\Delta p \; (= \Delta n)$

$$J = J_{dark} + J_{photo}$$

$$J_{photo} = (\Delta n \mu_e + \Delta p \mu_h) e \mathcal{E}$$

$$J_{photo} = (\mu_e + \mu_h) \Delta n \, e \mathcal{E}$$

So, if if n 0 and p 0; n zero and p zero are the carrier concentration of electrons and holes dark carrier concentrations electrons. And holes which means n zero and p zero are the concentrations concentrations when when pi is equal to zero. If n zero and p zero are the concentrations when pi is equal to when pi is equal to zero. That is dark carrier concentrations. Then we have sigma is equal to rho which is mu zero n zero n zero into this is for electrons. Therefore, mu e plus p zero plus mu h into e.

So this is sigma sigma is equal to n zero; mu zero into this or j dark j dark is equal to n zero, mu e plus p zero mu h for the holes into e ee is the electric field applied electric field. So, this is the dark current density. We want to find out the total current density because from the current density. Then we can determine the current. So this is the dark current density.

Similarly, delta n is the excess carrier concentration is the excess carrier concentration carrier concentration of electrons of electrons. Due to pi incident pi due to pi when a photon flux pi is incident on the photo conductor it gives rise to. So here is the photo conductor. So, let me show the three d picture and we have applied a field here a potential here. There is a photo current ip our interest is to determine ip due to an incident photon flux pi. And then estimate, then calculate what is the responsivity. So the photon flux is incident here.

So this is pi the photon flux my objective is to estimate the responsivity photon flux pi incident. Let consider a dimension w here length of the photo conductor and this area of cross section here, area of cross section is a.

If delta n is the excess carrier concentration of electrons due to pi and delta p is that of holes excess carrier concentration of holes which is equal to delta n. Please see there because it is the incident photon which is creating electron hole pairs. Therefore, the excess carrier concentration delta n is equal to delta p delta n is equal to delta p then j photo. I want to find out j photo. Just like that we have determine. So j photo is equal to delta n into mu e plus delta p into mu h into e into e but, delta n is equal to delta p and therefore, this is equal to mu e plus mu h mu e plus mu h into delta n e into e. And therefore, the photo current my final interest is to determine the photo current. Let me come back to it in a in a minute. So, this is so this is dark j dark current density when the then there is no photon flux.

When there is an incident photon flux, this is the current density delta n is the excess carrier concentration e is the charge mu e and mu h are the mobility’s. And e is the electric field electric field is. If you apply a volt v here and w is the width then v by w is the electric field.

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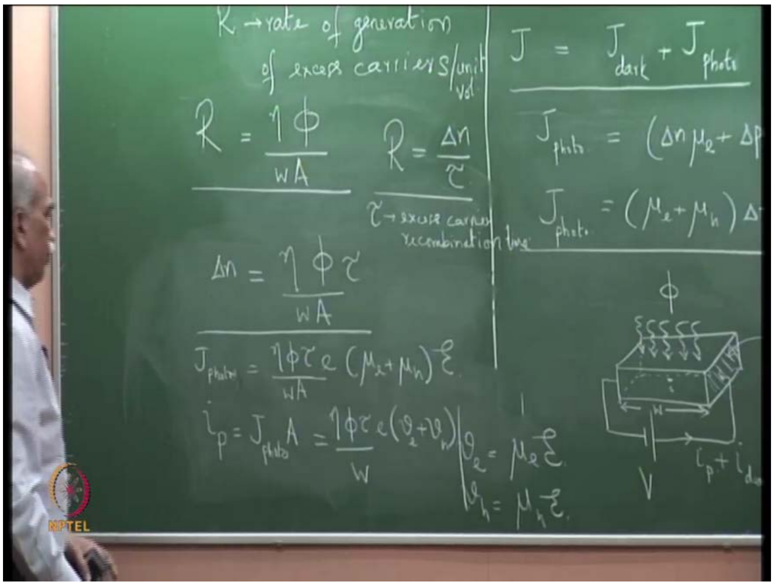

R → rate of generation of excess carriers/unit vol

$$R = \frac{\eta \phi}{wA}$$

$$R = \frac{\Delta n}{\tau}$$

τ → excess carrier recombination time

$$\Delta n = \frac{\eta \phi \tau}{wA}$$

$$J_{photo} = \frac{\eta \phi \tau e}{wA}(\mu_e + \mu_h)\mathcal{E}$$

$$i_p = J_{photo} A = \frac{\eta \phi \tau e (\vartheta_e + \vartheta_h)}{w}$$

$$\vartheta_e = \mu_e \mathcal{E}$$

$$\vartheta_h = \mu_h \mathcal{E}$$

$$J = J_{dark} + J_{photo}$$

$$J_{photo} = (\Delta n \mu_e + \Delta p$$

$$J_{photo} = (\mu_e + \mu_h)\Delta$$

So, let us recall let me write p zero mu h e into e. If r represents if r is the rate of generation of carriers rate of generation that is excess carriers generation of excess carriers excess carriers then r per unit volume per unit volume per unit volume. Then r is equal to eta quantum efficiency into photon flux. Recall that if pi is the photon flux eta is the fraction which will tell you the number of electron the carrier flux which is generated.

So, eta divided by w into a w into a has come because per unit volume. So, r is the rate of carrier generation per unit volume. Then r is equal to eta pi divided by w into a where this is for volume. But, at steady state the rate of carrier generation will be equal to the rate of recombination. And we have already seen in an earlier lecture that r the rate of recombination is given by delta n divided by tow where tow is the excess carrier recombination time excess carrier recombination time.

Just before electroluminescents we had discussed before we discussed electroluminescents. We had shown that r rate of recombination of carriers is equal to delta n by tow where tow is the excess carrier recombination, time excess carrier recombination time at steady state.

The rate of recombination is equal to rate of generation. And therefore, let me remove this dark for a minute j dark so that from these two. We can write delta n is equal to r into tow which is eta into pi divided by w a into tow delta n is equal to this. Now, we are prime although the total current density comprises of j dark plus j photo. We are primarily interested in the photo generated current. That is current generated due to the incident photon flux. Ideally, we would like j dark current to be zero. If there is a finite dark current it will contribute to the noise power and hence in lowering the signal to noise ratio. But, ideally we would like this to be zero.

But, our primary interest is what is j photo? And hence what is the photo current generated? I have written here ip photo current but, actually this comprises of also of i dark ip plus i dark the total current. I will actually in this case comprise of i dark both ip plus i dark however our interest is to find out what is ip. So to get ip so delta n is equal to eta pi tow into this. And if I substitute this j photo, so j photo that is photo generated current density is equal to eta pi tow by w a. That is delta n into e into mu e plus mu h into e mu e into mu h plus e into e mu e plus mu h into e. I have substituted from this expression here for delta n.

Here, I have substituted from here that solve rest is the same. Now, a into j is the photo current ip. Therefore, ip is equal to j photo j photo into a which is equal to. So a has gone here eta pi tow now mu e into e what is mu e into e. If you recall the velocity of carriers ve is equal to mu e into e and vh is equal to mu h into e. If e is the electric field and mu is the velocity hmm mobility then velocity of carriers is given by this. So, mu e into e is simply ve so this is equal to eta into pi i do not want to jump any steps divided by w into e.

Let me keep e into ve plus vh ve plus vh. So, this is ip. I do not want to jump any step so that we do not miss anything. Otherwise you can simplify this very rapidly very quickly so ip is equal to. Now, please see that ve by w w is the width ve is the velocity with which the electrons travel and therefore, that represents time. So, w by ve w by ve is the transit time of electrons.

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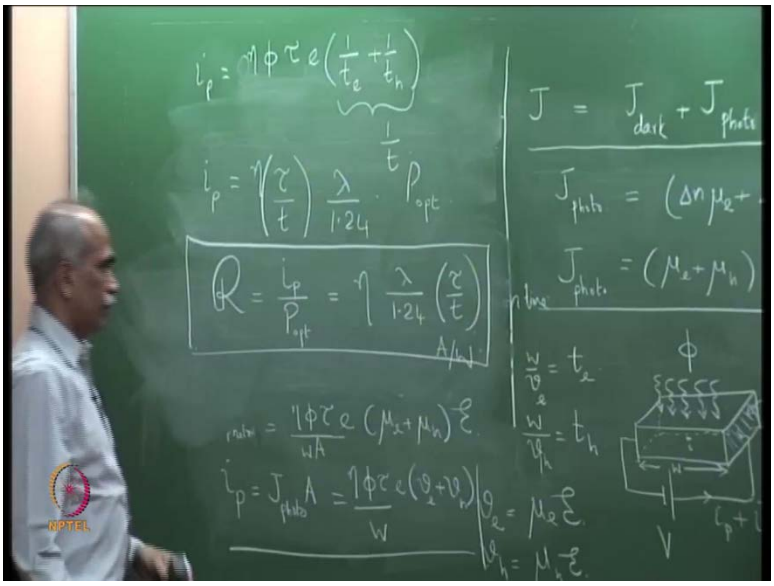

So transit w by ve shall I write? let me write w by ve is equal to transit time of electrons. And similarly, w by vh is transit time of holes w by vh is equal to transit time of holes. So, this is essentially nothing but, one by te plus one by th. So, let me again not jump any steps and write repeat again pi tow divided by w oh w is gone into e into one over te plus one over th pi is incident photon flux. So, if p zero is the optical power which is incident then p zero pi h mu is the photon flux.

This is power that is energy incident per unit time and divided by energy of one photon gives a number photons incident per unit time. That is the photon flux pi. So, this is equal to p of t divided by h c by lamda here hc by lamda or I can take this lamda r and I write this as in lamda. Now pi into e pi e here pi e is equal to p opt divided by hc by e into lamda. If you substitute c in micro meters lamda should be substituted in micrometers. Then this number is 1.24. We have done many times. This one.

So this is equal to p opt divided by 1.24. You can substitute constant 6.6 into ten power minus 34. This is in microns. Therefore, it is three into ten power 14. Now that three into ten power 8 meters or three into ten power 14 and this is 1.6 into ten power minus 19 will give you simply 1.24. 1.24 into lambda lambda to be remembered that this is to be substituted in microns. So phi into e phi into e is this. So I want to substitute for phi into e. This one. So here so this is let me remove these now. We do not need this.

So phi into e is this one. This term I want to call one over t which is one over te plus one over th and therefore, we can write ip is equal to eta into tau eta into tau divided by t here. This one by t tau by t into lambda divided by 1.24 into p opt lambda divided by 1.24 into p opt. You know why I have written like this is my final interest there. It is my expression for responsivity is equal to ip divided by p optical power incident which is equal to eta into lambda divided by 1.24 into tau divided by t responsivity ip by p opt. So the units are amperes per watt.

So I have from basic relations basic concepts. We have derived a simple expression for the responsivity of a photo conductor. Responsivity of a photo conductor it is not a difficult derivation at all. It's very simple one without jumping any steps.

I have shown you that we get an expression for the responsivity of the photo conductor responsivity of the photo conductor r is equal to when we discuss the general characteristics. A couple of lectures before when we discussed the general characteristics of a detectors.

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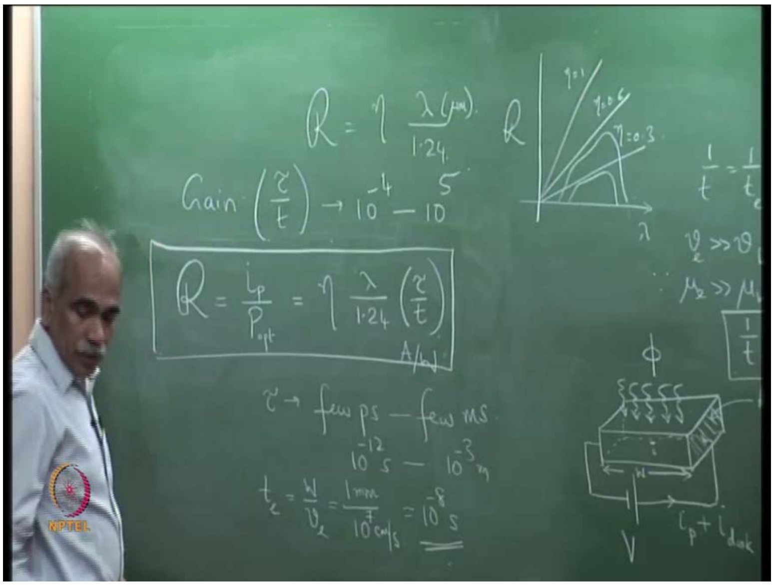

We had an expression for responsivity r which was equal to eta into lambda divided by 1.24. Hope you recall the graphs that we had plotted if eta was not changing. Eta was constant then we do this.

So responsivity r versus lambda for different values of eta eta equal to 1 eta equal to 0.6 eta equal to 0.3 and then we in the following lecture we discussed the dependence of eta on wavelength. And then we got responses like this because eta there was a long wavelength cut off and also it was decreasing down to zero in a short wavelength.

Now, we see that there is an additional term tau by t. In all these considerations we did not take transit time of carriers into account. Now we in this analysis we have taken the transit time w divided by ve. So because of the transit time now we have a factor tau is by t tow is the carrier recombination time. Tau is carrier recombination time.

Typically this could be from few pico second to few milli second depending on the material. And the structure design it could be few pico second to few milli second which means of the order of ten power minus 12 seconds to ten power minus three seconds. Tow carrier recombination time the transit time t.

Let us look at one over t here one over t is equal to one over te plus one over th. In general ve is much greater than vh because mobility mu e because mobility mu e is much greater than mu h in a detectors like gallium arsenide or indium arsenide. If you take indium arsenide; it is mu e is about 33000. Whereas, a mu h is few hundred so, you can see that mu e is much greater than mu h in general.

But, there are many materials where even mu e could be less than mu h. But, most of the detector materials which we used they have mu e much greater than mu h or at least greater than. Therefore, ve is greater than vh and therefore, te is much smaller compared to th. Therefore, one by te is much greater compared to one by th. In other words we can write that one over t is approximately equal to one over te because th is much larger compared to te transit time of holes that this one over th is becomes much smaller compared to one over te.

And therefore, one over t is approximately equal to one over te we could detain one over t itself. There is no problem but, if we take this than we need to discuss about the transit time of electrons only otherwise it does not matter. There is no so te transit time of electrons is equal to w divided by ve and w. If I take typically w is equal to let us say one milli meter; the width here is about one milli meter or few milli meters.

The semiconductor material the dimension of the semiconductor if and ve. If I apply an electric field so there ve is approaching saturation velocity. We discuss about saturation velocity which is of the order of ten to the power of seven centimeters per second. Then this will be nearly equal to ten power minus eight seconds the transit time of electrons is approximately ten power minus eight per second. We are putting some numbers to get a feel for what kind of what kind of factor.

If this factor is greater than one it means responsivity as a gain that is a gain factor and indeed photo conductors provide gain. Because of this now if I use ten power minus eight; then we can have gain means tow divided by t. So, if you go to this end it is ten power minus twelve divided by ten power minus eight which is ten power minus four. So tow this is ranging from ten power minus four. If you come to this end; it is ten power five. This factor is as high as ten power five.

So, you see that in photo conductors there is a gain possible the responsivity can be very high. I will show you a typical plot and the number for responsivity if use ten power two ten power three ten power four; very high responsivity. That is because of this of course, it has high responsivity or high gain comes at a cost. You will see that the speed is going to be much less compared to pin diodes. But, there is a gain which is available in this. How does this gain come?

We know about gain coming from avalanche multiplication like in apd’s. There is carrier multiplication taking place. That is an accelerated electron knocking out more electrons and hence there is avalanche multiplication there is no avalanche multiplication.

In this case in the case of photo conductor but, there is gain and the gain could be very significant. So, you could have this factor tow by tow. In this range so if you make the transit time te. If the carrier recombination time is very small then it could be here. Otherwise you can have a large gain possible. Now, how does this gain come? Let us briefly discuss the physical origin of this. Where is the gain coming?

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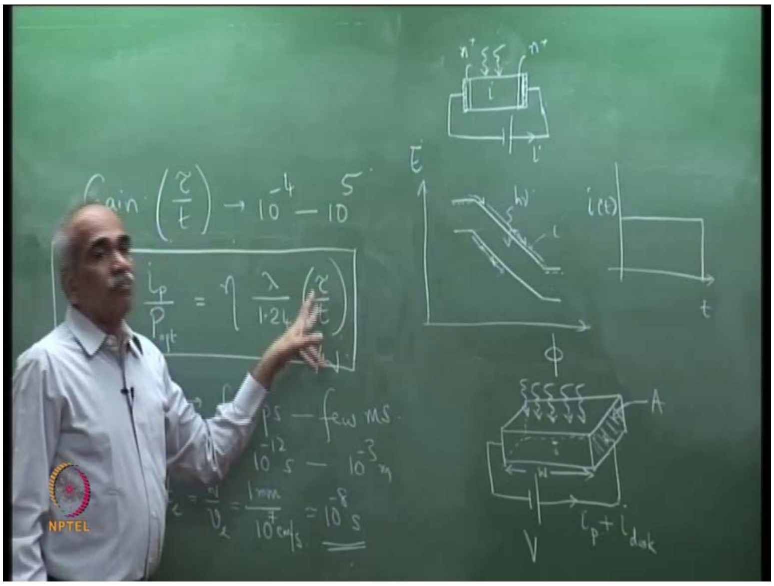

Typically it is a the photoconductor is typically like this. The normally use a metal contact here let us say metal and therefore, for ohmic contact we normally use n plus here and then an intrinsic medium and n plus is only for contacts take this is metal. So, this is n plus and intrinsic. So, the carriers are the photon flux is incident here. They have better designs. But, I am just explaining that that is so. If you draw the band diagram of this; so you have n plus which means the electron fermi level is here and then it is the intrinsic region and then we have a inverse.

What I have drawn is the familiar energy band diagram of this. So, this is the high region intrinsic. So I have applied positive to this end. Therefore, the potential here is decrease. So, what is plotted is e versus the distance? So e versus the distance incident photon. Let us say one photon is incident here to this region hv.

So, it creates a hole and an electron electron in the conduction band and the hole in the valance band the hole starts moving up its like air bubble. So, starts moving up the slope and this is like water droplet. So it starts going down this are the two ends where it is collected now because the velocity of electrons is very high compare to this electrons goes rapidly and reaches this end.

When electron reaches this end so when electron is moving this side and hole is moving this side. There is a current in the external circuit. That is a current I here in the external circuit because of charge carriers moving. We have discuss this in the last class before impulse response by ramoestheorm. It tells you that thus a current which is in the external circuit when the electron is collected here then to maintain charge neutrality. The second electron is released from here. From this contact because thus only one hole which is moving hole is still before the hole has come here.

The electron has been collected so a second electron is released because this is once it is collected it is gone into the conductor. So, this electron again starts going down hole is further proceeding and it is collected here next electron is released. This is further proceeding so till either the electron hole recombine in the medium or both electrons and hole are collected by the contact electrode at the ends. This process takes place. Please see the there was only one photon which was incident.

There is a carrier pair which was generated but, there were so many electrons are transiting through this by that by that time one hole was travelling up and this why there is a persistent current in the external circuit for a long time. Although you have just put one photon which has made one carrier. So the current flows for a longer period in the external circuit and that is response we have discussed with one photon. If you have large number of photon you can imagine that there is a big current in the external circuit although there was just a burst.

So this is responsible for this and that comes because of a large carrier recombination time which means these electron and hole are not recombining inside the semiconductor for a long time. The momentary recombine if this was very small. For example, this is smaller than this then even before it reaches here. It to get recombine which means the current will persist only for a small duration and therefore, it is the carrier recombination time which will.

But, we know that because it takes a long time to go here the impulse response will be spread even now. The impulse response would look like so it is continuously coming for a long time. So this is time t and this is current I of t for a long time because the carrier recombination time is very large. So, what have we compromise the speed to get gain?

What you have compromised is speed because the impulse response is now spread. The transit time spread is much larger. So photo conductors can provide gain. But, at the cost of speed you can indeed show that the gain band width product remains a constant now let us come to materials which are used.

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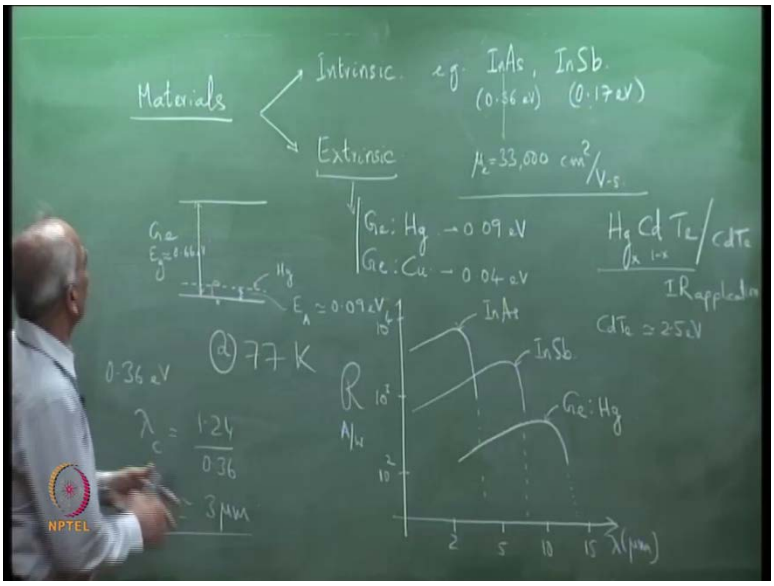

So long I did not discuss about materials. So materials generally photo conductors are used to generally this are used to detect long wavelength materials and therefore, there are two types of two kinds of material which are used they are intrinsic and extrinsic. Intrinsic and extrinsic as you intrinsic normally refers to refer to pure semiconductor and extrinsic refers to doped semiconductor.

And the same thing is to here that we have intrinsic semiconductors such as widely used semiconductors. For example, are indium arsenide and indium antimonide. This has a band gap eg of point three six ev and this is 0.17 indium antimonide. This two materials are widely used because as I how so mention they have very large mobility electron mobility in indium arsenide is about 33000 centimeter square for volt second mu e.

Similarly, in indium antimonide it is about 8000 or 8500 centimeter square per volt second very large mobility. And therefore, very small Te and therefore, you can get relatively large gain and extrinsic extrinsic semiconductors. The widely used semiconductor is germanium doped mercury doped germanium or copper doped germanium. Typically the activation energy here we are referring to this.

So let me draw this what we are showing is this is germanium band gap of germanium ge eg is approximately 0.66 ev. And because of mercury doping there is a activation energy here that is an excepted level. So, this is the mercury level hg dope end and this activation energy energy gap here is approximately ea is approximately 0.09 and for copper it is even smaller. I think about 0.04. So, for this it is approximately 0.04 ev and here it is 0.09 ev. So, obviously if you want to use these detectors they have to be cooled otherwise thermal emitation at room temperature the acceptor atoms will all accept electrons there and there will be plenty of holes here. And therefore, the dark current will be very large. So usually you should cool these detectors at 77k.

Normally this are cooled at liquid nitrogen temperature while using. So the incident photon energy if it corresponds to this activation energy then it will respond in the sense if the electron will go here to the acceptor level living behind a hole. And the hole will cause conduct. So the conductivity is due to holes created here and just like in a p type material. You have a acceptor levels which accept.

So the widely used extrinsic materials are germanium doped mercury and people also use for infra red application a material which is also widely used is mercury cadmium telluride hg cadmium telluride. So it is hgx one minus x telluride cadmium telluride. So this is mainly for ir applications although cadmium telluride because this is mercury cadmium telluride is lattice mash to cadmium telluride. So you can grow different combinations of hg cadmium telluride on cadmium telluride and cadmium telluride has a band gap of about 2.5 ev which is very much in the visible.

But, mercury telluride has a band gap which is very close to zero so you can by varying by varying x. You can cover the entire ir range from visible to ir it is possible because this is an important material which is used for ir applications. A ternary compound mercury cadmium telluride and cadmium telluride. So, if I plot typical typical responsivity curves for these. It looks like this. So, let me plot the responsivity.

So, responsivity amperes per watt typically ten to the power of two; ten power three ten power four and wavelengths are of course, large. You can calculate for example, for this 0.36 ev. What is the so 0.36 ev? So which means 1.24 example. So lambda cut off. So lambda c is equal to 1.24 divided by 0.36. How much is that approximately? Three. Approximately three micro meter.

So lambda cut off in so approximately three micrometers and similarly, if you go for this (( )) about. So let me plot so 2, 5, 10, 15; so 2, 5. This is lamda in micro meters. So the responsivity typically looks like this. So this is for indium arsenide indium arsenide. This is for indium antimonide. And this one I have plotted for hg germanium. Germanium doped hg other way to get it germanium. So typical responsivity you can see initially the linear behavior because it is proportional to lambda.

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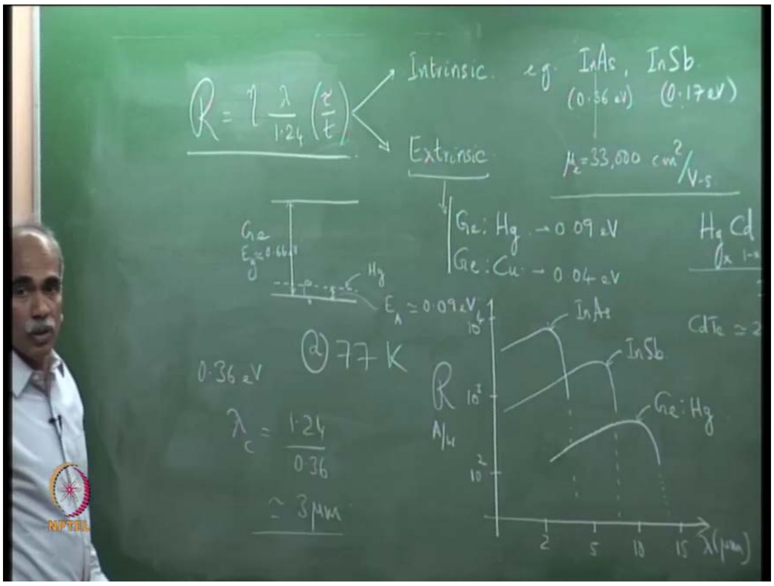

If you recall the responsivity for r is equal to eta into lambda divided by 1.24 into tow divided by t why indium arsenide has a very high responsivity. You can see its mobility is very high. Therefore, this t is very small. So that is why the responsivity is very high. When we see for normal p i n photo diodes you will see that the responsivity is 0.51. 1.2 that is the kind of numbers but, here you have very large numbers.

So indium arsenide because it has a very large mobility has a very high responsivity. The only thing is this are much slower detectors one and I will come to the second disadvantage. Also, initial portion you can see this linear variation is primarily because of this linear dependence on wavelength. And then this drop we know because of long wavelength cut off because the band gap of the material so further long wavelength the band gap of the material is larger than the photon energy.

And therefore, that is no absorption no carrier generation is this alright. So, we come to finally, one high speed high speed design which is widely used with photo conductors. One of the as we discussed one of the major problem is carrier transit time and recombination time. So recombination time can be minimized can be reduced by using pure materials with minimum defects and transit time can be minimized by using inter digitated transducers.

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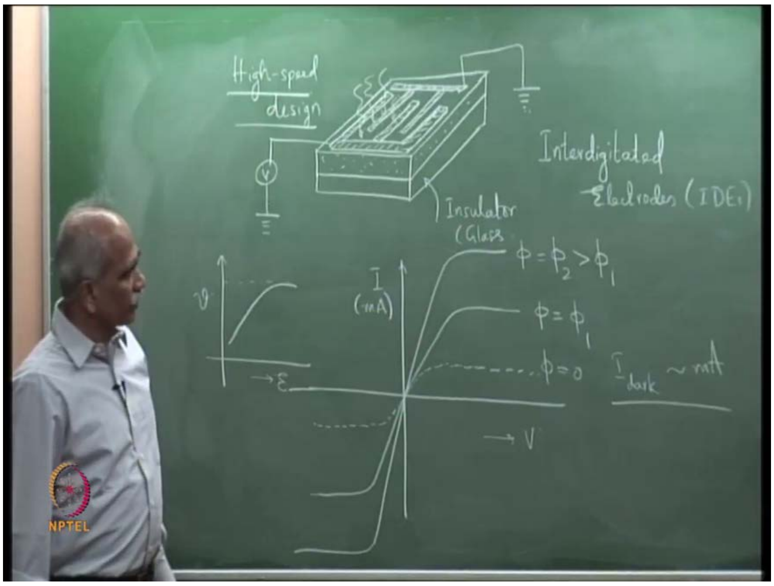

So the normal design we are were these photo conductors are used they use ide's inter digitated electrodes. So let me show you so this is the photo conductor and this is grown a film of a photo conductor grown on an insulator typically insulator usually glass transparent glass. And this is the photo conductor this layer is the semiconductor and on this they make ide's. That is inter digitated electrodes.

So, let me show you so let me draw it it will become clear. As soon I said finish the drawing these are monolithic electrodes. What I have drawn here is metal electrode which are deposited on top by lithography. So this electrode here for example, is collected to a a supply and this is other electrode which is grounded. So there is an electric field between these this finger like structure. So it is inter digitated they are call inter digitated electrodes ide's inter digitated digitated electrodes inter digitated electrodes. The advantage is that this reduces the transit time.

So photons are incident here that is light is incident. The advantage is the generated carrier will find a electrode very close it does not have to travel as I had shown the diagram earlier. That photon incident the electrons and holes have to travel a long distance. So this increases the transit time. So minimize that to minimize the transit time and hence to increase the speed one use as ide's. The second advantage is if you apply an electric field at the end to get an e please remember to have a high saturation velocity ve.

We need fields electric fields of the order of ten to the power of four to ten to the power of five volt per centimeter. We want to have high speed. So ve should be saturation velocity as discussed in the last lecture. You need very high electric field. If you if the this separation is large.

Let us say several milli meters then the field required will also with the voltage required the v upto be applied is also very large. But, here they are close by the separation is very small so even by applying very small voltages like the TTL logic plus five volt.

You can get very large electric field between them because the separation is small. That is the advantage of using ide’s in all high speed devices. These are also widely used in saw devices surface aquastic wave devices where ide’s are used to increase the speed. So high speed design. One last point before we come the iv characteristics of the photo detector. So in all for the design engineer the iv characteristic is very important.

One is the responsivity whenever you want use a photo detector are a source you have to know the responsivity. And the second is the iv characteristics. So how do you think the iv characteristic look like would look like iv characteristic. It is a simple piece of semiconductor and you have applied a current. So the iv characteristic of a photo conductor looks like this. So this is what I have shown by dash line is when. Let me draw it completely. So what I am plotting is the i the photo current ip versus the applied voltage v.

So you have so this is with pi equal to 0. So pi is equal to pi one and pi is equal to pi two which is greater than pi one the incident photon flux. But, what you see is it is symmetric because it is simply a piece of semiconductor. It does not matter whether you apply from this side or that side is not a diode. And therefore, there are there are no rectifying the behavior. So it is simply the same.

The current here is in milli ampere including the dark current. Please see the dark current i dark is also of the order of milliamperes. Whereas, in the case of a photo diode; there is a reverse biased photo diode the dark current is of the order of micro amperes. So the major disadvantage of photo conductors is the dark current large dark current. This is the major disadvantage of photo conductors in any high speed application or where you need very good signal to noise ratio.

But the real advantage of photo conductors is if you want to detect long wavelengths i r wavelengths. For example, then photo conductors are the detectors which are used. So this is the iv characteristic with one disadvantage is i dark. So what we have shown is for different photon fluxes. You can see initially it varies linearly because you are applying velocity. So voltage and therefore, the electric field is increasing.

But, once the saturation velocity as reached there is no more change in current because current is proportional to the mobility into the total number of carriers that you have. And therefore, as electric field increases the velocity increases. Therefore, initially it is bearing linearly. But after words as you know that one reaches saturation velocity. So this is electric field e versus velocity v.

So this is the saturation velocity and therefore, there are no more carriers which are remaining to be swept. So there is a average velocity where it has saturated and therefore, the current saturates to that value. So I think there we have covered almost all aspects which are relevant to photo conductors. One type of detector which is used for common application but, normally not used for a high speed applications.

All high speed applications we use either pin diodes or apd’s the highest speed. The various designs of pin diodes and the highest speed that we have we now have there are detectors which can detects hundreds of Gigahertz band width. And they are based on pin detectors pin diodes or they are variants. So we will stop here is there any specific question any specific question. So we will stop here.