Semiconductor Optoelectronics
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Lecture – 40
Responsivity & Impulse Response

In the last lecture, we discussed about general characteristics of photodetectors.

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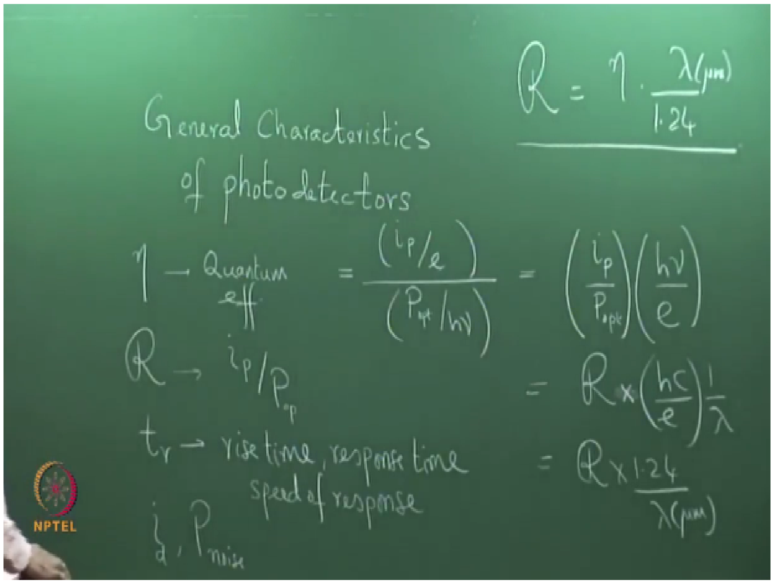

$$\mathcal{R} = \eta \cdot \frac{\lambda(\mu m)}{1.24}$$

General Characteristics of photodetectors

$\eta \rightarrow$ Quantum eff $= \frac{(i_p/e)}{(P_{opt}/h\nu)} = \left(\frac{i_p}{P_{opt}}\right)\left(\frac{h\nu}{e}\right)$

$\mathcal{R} \rightarrow i_p/P_{op}$ $\quad = \mathcal{R} \times \left(\frac{hc}{e}\right)\frac{1}{\lambda}$

$t_r \rightarrow$ rise time, response time, speed of response $\quad = \mathcal{R} \times \frac{1.24}{\lambda(\mu m)}$

i_d, P_{noise}

And we had listed first the quantum efficiency Q, just to recall the responsivity R which is equal to the photo current generated divided by incident optical power P optical here. The response time or the rise time tr or equivalently response time. Or equivalently one can have discussion on the speed of response and finally the dark current id or equivalently the noise power. So, these are the four general characteristic that we had listed in the last class.

And we have seen that the quantum efficiency is basically it is the carrier flux generated which means it is ip/e. Carrier flux generated due to an incident photon flux which is P optical/hv. So, the power incident divided by energy of one photon gives you the photon flux and this is the carrier flux. Current is ip and therefore divide by the charge gives you number of carriers or carrier flux.

So, this we have discussed and this we can write therefore as ip/p t optical into h nu goes to the numerator. So, we have h nu/e. So, which is also equal to, this is the responsivity so this is responsivity R this is = hc/e * lambda, 1/ lambda. And if we substitute lambda in microns then this turns out to be 1.24. So, this is = R responsivity*1.24/lambda micro meter just recalling and therefore we can write eta the responsivity=eta*lambda/1.24.

Where lambda is in micro meters. If we substitute lambda in micro meter then the responsivity of a photo detector can be written in the form r=eta*lambda/1.24 where eta is the quantum efficiency of the detector, quantum efficiency of the material of the detector. In the last lecture we have also discussed in detail how to maximize eta for a given structure and a given material. How one can maximize eta?

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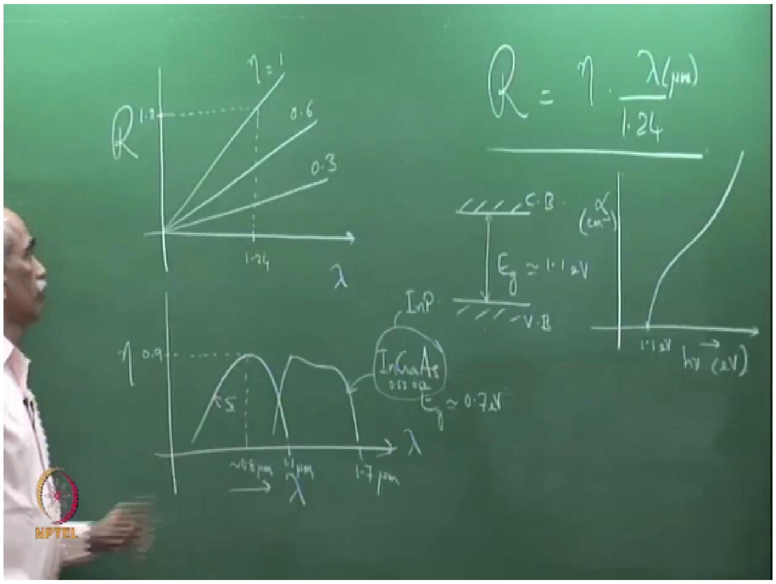

And if we plot the responsivity therefore so responsivity versus lambda if you plot R here then you would have straight lines or different values of eta. So, this is what we have plotted eta=1 may be 0.6, 0.3, and this is with wavelength. So, you can see the typical numbers when lambda=1.24. So, if take lambda here as 1.24 and eta=1 then responsivity here must be 1. So, lambda=1.24 then responsivity will be = 1.

So, this is the graph that we have for responsivity assuming that eta is a constant but in practice eta is not a constant because if you plot eta, so this is assuming that eta is constant. Eta is a quantum efficiency and if you plot eta for a typical detector eta versus lambda. The response would look like this. So, typically so this is for silicon and this is for indium gallium arsenide. Two very important detector materials silicon and indium gallium arsenide.

And the typical number the responsivity of eta the quantum efficiency of silicon is approximately the maximum value is about .9 and this is about .7, .8 and this occurs around lambda nearly = 0.8 micrometer. And this goes down to 0 around 1.1 micrometer here and this goes down to zero around 1.7 micrometer approximately. So what I have plotted is lambda versus eta for typical detector materials silicon and indium gallium arsenide.

Now why does the quantum efficiency go down at both the ends here. The longer wavelength end it is obvious because for a given material like silicon, silicon has a band gap Eg here. So Eg is 1.1 electron volt. This is the conduction band and the balance band. Inter band absorption the absorption coefficient goes to almost 0 for energy less than the band gap there cannot be electron whole pairs created.

And therefore the absorption coefficient goes down 0 if you remember the graph or absorption coefficient. So, if we have lambda like this or photon energy let me better plot in terms of photon energy. So this is h nu we recall. So, absorption coefficient alpha here starts at eg and then goes up so this is for silicon so this is eg=1.1 ev. So, h nu in ev and this is alpha centimeter inverse. Recall the absorption coefficient as a function of photon energy.

So, you can see that 1.1 ev is the band gap of silicon and below which there is no absorption and therefore there is no generation of photo carriers by inter band transitions. And there for the responsivity, the quantum efficiency of silicon goes down to 0 at longer wavelength. So, there is a longer wave length cut off. Exactly like that indium gallium arsenide has a cut off around 1.7 micrometer.

Because indium gallium arsenide here this is indium 0.53 gallium 0.47 arsenide. Why do we choose this combination? because this combination is lattice matched to indium phosphide. So that we can grow defect free heterostructures. So, it is lattice matched to the binary compound indium phosphide. So, this has a bandgap E 0 of approximately .7 iv. So, you find that the long wavelength cut off is here.

So, we know why eta goes down to small values or goes down to 0 at longer wavelengths because there is no absorption possible. Why does eta come down to 0 at shorter wavelengths? Energy is increasing shorter wavelengths, absorption coefficient increasing but why does it comes down. There are two mechanisms due to which this comes down. So, these two mechanisms very briefly and very quickly we will discuss one as energy increases.

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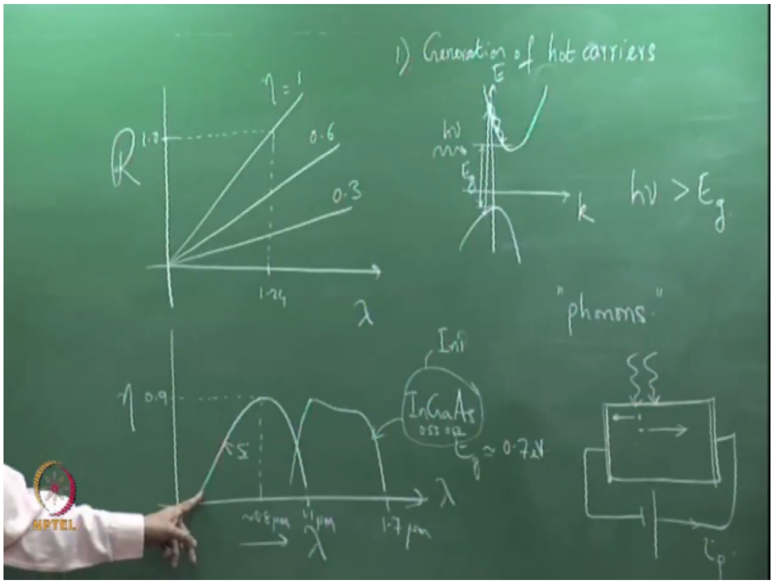

So, first because of generation of hot carriers if you take the band gap here so this is ek (()) (10:11) so k versus E. I have drawn an indirect band semiconductor to indicate that it is silicon for example. And when the energy is larger for example this is the Eg, for h nu incident photon energy much greater then Eg electron transition can take place an electron can make an upward transition to an allowed state here.

Electron from the balance band can make an upward transition due to the absorption of the photon of energy h nu greater then Eg it can make a transition because this is a vertical transition it is an allowed transition and therefore this carrier here is a hot carrier because it is a high energy carrier. So, this carrier generated starts coming down by thermalization, the process called thermalization.

We have discussed this earlier and it comes down to the bottom of the band. In the process of thermalization it gives down the difference in energy as phonons. So, energy is given in terms of phonons therefore generation of hot carriers lead to a large quantity of phonons in the lattice. And phonons present in the medium will faciliate none radiative recombination. In another words the generated carriers will recombine very quickly by none radiative recombination.

If the carriers are recombined very quickly, please recall we are discussing a photo reactor material in which photons are incident on which photons are incident and it is generating electrons whole pass. So, if you apply a bias then electrons will move in this directions holes will move in this direction and the carriers are collected and this is what is responsible for the reverse photo current Ip. There is a photo current in the circuit.

Now the generated carriers if they recombine very quickly then there is no more contribution to the current in the external circuit and therefore the response of the detector goes down or therefore the quantum efficiency of the detector goes down. Recall the definition of quantum efficiency as the carrier flux which contributes to the current in the external circuit which means the carriers must be moving in the medium.

If they recombine very quickly then there are no more contributions to the external current and therefore the quantum efficiency starts dropping. This is the first reason, generation of hot carriers. The second reason let me show here. The second reason is because of 2, absorption near the surface.

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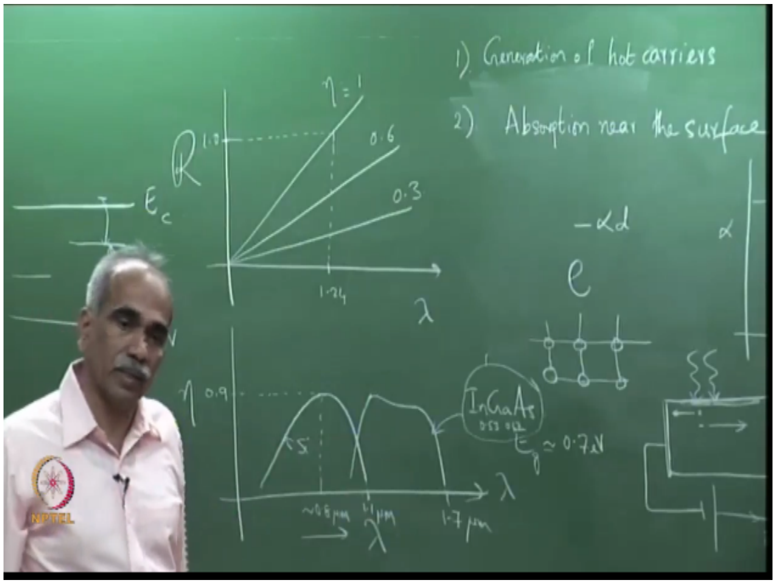

What do I mean by this? let me explain again I had the curve here that is h nu versus alpha. As you can see is the same curve which I had drawn earlier start from eg. We are looking at lower wave lengths response that is quantum efficiency at lower wave lengths and we are trying to explain why does it go down at higher energies or lower wavelengths. So, higher energy here corresponds to larger values of alpha.

Absorption coefficient is very large and therefore it means that the photons which are incident are absorbed completely close to the surface because absorption is given by e to the power of –alpha*d. d is the thickness over it where it is absorbed. Now if alpha is very large then d needs to be very small in another words almost all the incident photon energy is absorbed close to the surface and in any material surface is not a very good place to get absorbed.

Because there are surface states due to dangling bonds in the medium. Because near the surface if you enlarge we have discussed this earlier but just to recall if you enlarge the positions of atoms here and the bounds like this you can see that to one side the bounds are dangling they are free. They are not complete and therefore these dangling bonds if you take the band gap then they correspond to energy states somewhere in the gaps.

So, this is Ev. This is Ec and this is the eg corresponding to the surface states there are states which are in the forbidden gap and these act like trap states and they facilitate recombination of electrons and holes. So, again just like in the previous case the absorption near the surface where there are plenty of surface state which act like traps in the medium facilitate recombination of the carriers.

Quick facilitation of recombination of the carriers if carriers recombine means carriers are lost from the medium which means they no more contribute to the current. And that is why the quantum efficiency drops down like smaller wavelengths. And therefore the final picture now the responsivity therefore let us very quickly come to the responsivity. If eta were 1 the responsivity would have varied like this but eta varies like this.

It is not 1 it varies like this which means if you show you on the same plot.

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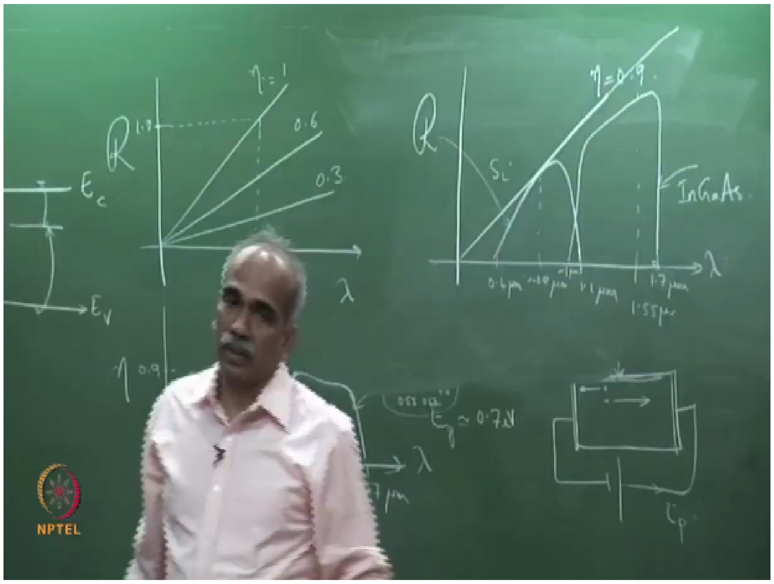

Or let me show it separately for a particular value of e, let us say eta=0.9. What I am plotting now is responsivity versus lambda for real detectors with a quantum efficiency that is realistically varying like this. So, if plot for silicon as you can see .9 is the peak and therefore it will touch this around .8 other places it will drop down. So, it will go like this and then drop. So, this where it touches is about .8 micrometer and this is 1.1 micrometer.

And this end is approximately .3 or .4 micrometer. So, what I have plotted is the real responsivity of silicon varies like this. If take a typical data sheet any silicon detector you can see the responsivity given like this. And if I want to plot indium gallium arsenide the maximum normally goes around .8 so it starts from about 1 micron here and this would go like this and come down somewhere here.

So, this is approximately around 1 micron and goes up to 1.7 micrometer. So, this is for indium gallium arsenide responsivity versus wave length. This is a very important curve because it tells you which detector to choose depending on the application. If you are interested in optical fiber communication naturally you are in the 1.55 micrometer window here and in gas is the best to detect.

And silicon will not work but if you are interested in around .8 then silicon is the best detector. So, responsivity this curve is very important in the choice of the detector. So, let us come to the third parameter which is the speed of response or the rise time of the detector. The rise time of the detector determines the speed of response. How fast the detector is? And a discussion will tell us how the design engineer can go about in increasing the speed of the detector.

What is the design? What is the structure and material one should choose so that the speed is very important. Let me redraw this diagram.

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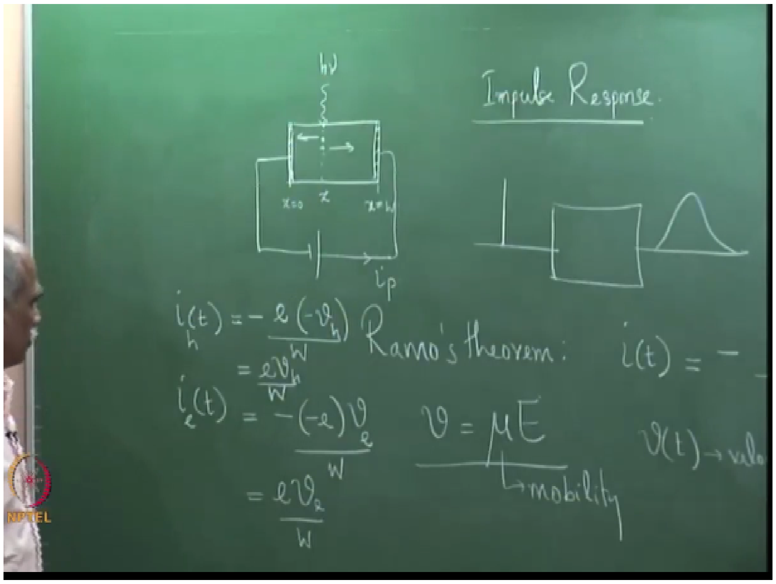

So here is the detector material few electrodes deposited these are semiconductor material on which let us say one photon is incident. Let us first start with discussion of one photon incident at so let this direction be x=0 and the width of the detector is x=w. So, this is incident at some value of x and we have a supply which is connected to sweep the generated detectors. So, the incident photon gives rise to a hole and an electron and the applied potential will drift it.

So electron will move in this direction and hole moves in this direction. And that leads to a current in the external circuit which is the ip photo connect. Now, we are knowing the speed of response or impulse response. Impulse response refers to response of the detector of response of a system to an input impulse, impulse is an instantaneous pulse. So you have the system here if you give an impulse a signal with a very small time duration impulse.

How would the output look like whether this signal will spread so that will determine the impulse response of the medium. So, we have an instant T, instantaneously 1 photon is incident at a particular incident we want to see how would the current look like. So, photon is incident at 1 incident how would the current in the external circuit look like? So, the current in the external circuit is given by Ramo's theorem.

We are not going to prove this. So, Ramo's theorem states that the current i of the external circuit is equal to minus if a charge q moves in a medium of length l or w then i of t = -q/w*v*t where v*t is the instantaneous velocity of the carrier. The charged carrier q. w is this width here and it is this velocity has come because you have applied a field there is a drift velocity as you know the drift velocity v=mu*E where E is the applied field mu is mobility of the carriers.

V is the drift velocity and E is the applied electric field. Therefore, we have a whole which is moving in this direction and an electron which is moving in this direction therefore we have a whole current i h *t and i e*t. This is the current induced in the external circuit. So, there is a whole current and an electron current. So, electron current i e*t = - charge is –e*velocity of electron Ve.

If I take a average velocity assuming that over the time duration the velocity is constant so I can write Ve/w. So, that is =e*ve/w the electron is moving in this direction so the velocity is here so ev e/w. The whole current ih*t = - charge of whole is +e but it is moving in the opposite direction. Therefore, it is moving with the velocity vh I am writing a separate velocity because as we will see mu the mobility is different for electrons and holes.

And therefore the velocity will be different although the applied electric field is the same and therefore the vh/w which is = evh/w. The total current therefore the total current in the external circuit i*t = i*t +Ih *t which is =e/w*ve+Vh. This is the current i*t in the circuit.

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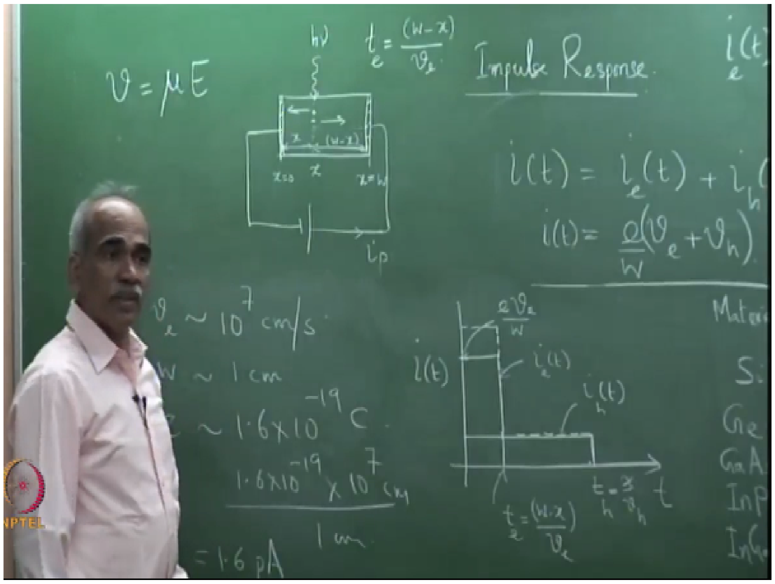

The photo current = e/w is the e little bit bigger I have written. Veh.is that alright? Now if we plot this external the current, current is the response of the detector due for the impulse. Impulse is the input photon or re-burst of photons which are incident and response is the current in the circuit. So, I plot i*t so with the time if I plot i*t then I will get impulse response. So impulse response is basically time spread over which the system is responding for an input impulse.

So, let us first plot ie*t now it would be worthwhile now to have some values of mobility so that we have an idea in plotting. So, if you take material let me give value for some materials so material mu e and mu h. So, if take silicon let me give you some numbers so this is 1500 what is the unite? mu e and mu h centimeter square/volte second. You can get from here so v=mu*E so mu = v/E, E is volte/centimeter.

And this is centimeter/sec so you will get centimeter square by volt second. So, this is 1500 and this is 450. If you take Germanium this is 3900 and this is 1900. If you take Gallium arsenide some of the most widely used materials Gallium arsenide you can see that this is 8500 whereas this is 400. The mobility of holes are much smaller if you take Indium phosphide because Gallium arsenide and Indium phosphide are the most widely used binary compounds.

And these are the most widely used detector materials 4600 and this is 150. And if we take Indium Gallium arsenide phosphide, Indium Gallium arsenide the most important detector material this is 14,000 and here 400. So, you can see the large difference between mobility of electrons and holes. This is now important because it will tell us what is the time taken by the detector.

So, first the current ie*t = so let me plot ie*t =e/w*ve and recall Ve is in general Ve=mu*e, electric field is the same but mu is large for electrons and this will be much larger compared to the whole current. Because vh is smaller compared to v. So, if I say ie*t =this value e*Ve/w is somewhere here then current will persist till the electron is collected by the electrode here. Electron moving in the semiconductor is responsible for the photo current.

When the electron is (()) (29:52) till this time current will persist in the external circuit. So, what is the time taken for electron to move from here to here? So, if this is w then separation is w-x. This is x and this is w-x so distance divided by so te=w-x/ve and there is the time taken. So up to that time te the current will persist and then it will drop down to 0. So, this value here is te =w-x/ve. Now, the whole current we know is smaller because vh is smaller.

So let me start at some value here. So, what is this value here. This is ev/w the value on the y axis here is eVe/w. The value here is w-x/Ve. We can put some numbers to get a better feel we can always put some numbers. So, what kind of numbers are we talking of I will discuss more about Ve a little latter but typically Ve is about 10 to the power of 6 or 10 to the power 7 centimeters/sec.

W let us say there is a 1 cm detector there can be smaller detectors but just let me put w approximately 1 cm to get a feel for the number and e as you know is 1.6*10 to the power of -19C and therefore the current i is e. Therefore 1.6 into 10 to the power -19*Ve 10 to the power of 7 so this is Coulomb's. This is centimeter/sec and in the denominator 1 cm. So, this is =1.6*10 power -12 that is pA. Why?

Because we have just put 1 photon the current is very, very small because 1 photon there is 1 electron moving and therefore the current is very, very small. We will see how? To just get a feel so that is the current which is persisting for a certain time and you can put say about 1 cm this 10 to the power 7 cm/sec therefore the time is 10 to the power -7 cm so approximately 0.1 microsecond, current persist for about 0.1 microsecond, alright.

So, if you reduce this naturally it will become a faster dictator. So, you want to take a small area dictator we will discuss this later. Now, let us plot the whole current so it starts at a lower value but it goes further why? Because th=x, the distance x/Vh. Vh is much smaller compared to Ve therefore this is th=x/h. This is plot of ie*t and this is plot of ih*t assuming that the carriers are moving with a constant average velocity still are collected at the ends.

So, the total current will be the sum of the two. So, if I want to plot in the same sum of two so here it will add up so let me draw with the dotted dash line. So, my total current will look like this. The box with the dash line shows the total current. So, what I have plotted, I have drawn impulse response at t=0 there was a photon incident on the detector in the circuit current persist for such a long time.

So the impulse response as I showed, ideally I should have got the response current also for a very small duration but instead the current is spreading over a long duration. And this is the impulse response due to one photon incidence. Now I extend a little bit further to n photons because we are interested in seeing n photons incident. So, the same detector now but photons are incident everywhere all over the detector not at one point.

If at one point there were n photons then the current would have been simply multiplied by n, same response will remain the same but it will be multiplied by n that is all. That is the only difference. So, this value here is i Ve*w if there were n photons incident at port I would have got n eV/w. So, typically if a very small amount of a burst of n photons let us say 1 billion photons are incident then the current will increase by 1 billion times. So this will become many ampere, alright. So, the numbers are quite practice numbers.

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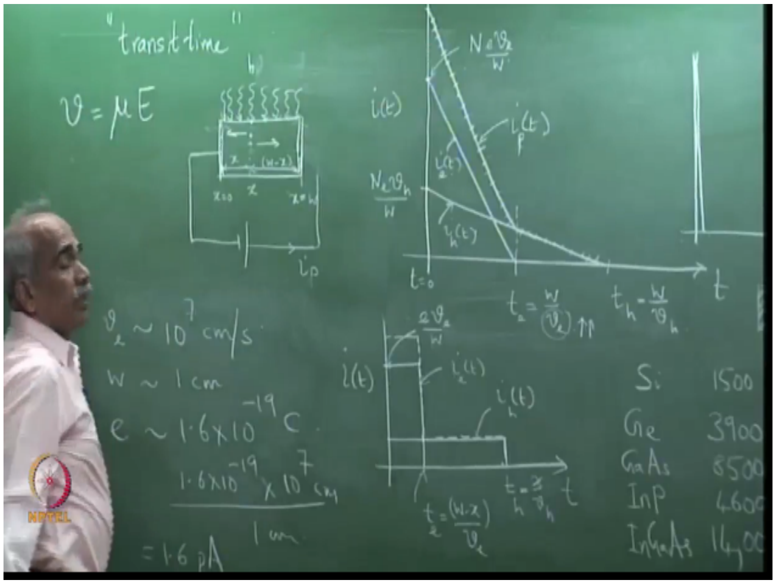

Now the photons are incident everywhere not at one point over the entire detector surface what will happen at every point electron whole pairs are generated. And electrons which is generated here is instantaneously collected. Where are electrons which is generated here will take a time t=w/v is the total time and so if I plot ie of t, please see this. So, this is time versus i*t. So, first let me plot ie*t. So, it will be largest at t=0 because all the electrons are moving.

But the electrons which are generated here are collected. Once it is collected no more contribution so the current will drop like this continuously till the time t =, what is t? Will be W/Ve, this is t. The currently is continuously, and what is the value here? N times e*Ve/tau.

Because there were n electrons whole pairs created. Similarly, the whole current holes which are generated here are immediately connected.

But the whole which is generated here has to travel all along and therefore it will vary from a smaller value here, I am taking a smaller value why? Because the whole current is NeVh divided by w, vh is smaller than Ve, therefore it starts somewhere here. And then it will continue for a duration which is up to this what is th =w/Vh. What is the net? The net current is sum of these two. So this plus this is here and up to this value it will have a sum.

So you can and then it will go just over this. So, just to distinguish that we draw these with, this is the total current. So what are the things I have plotted I have plotted ih*t, ie*t and this i total which is the photo current. ip*t which is equal to the sum of the two. So, where was the impulse, where was the impulse. Impulse is at a t=0, at a t=0 a burst of n photons where incident on the photo detector an instantaneous impulse.

The response is this but the output we see that the current which is the response of the photo detector is spread over a certain time. So, this is the impulse response. Now what is our objective if you want a high speed detector in an application this should be as small as possible. If it was so had an impulse here and then if you had got a response which is like this, then it would have been ideal very fast. The detector is very fast so how can we get high speed.

Obvious, you have to have as large, V should be as large as possible. First te should be =th otherwise this pedestal will always remain. So, if can make te=th. How can we make that? It is possible that if this is the detector material then you open a window somewhere here then you see the electron will take a slightly longer time whereas holes are very close to the, not that it is very good. But I want to avoid the pedestal.

This is the window where all the photons are incident then te will also be slightly larger to match th. So that this pedestal can be removed and we get the nice impulse response like this. First, thing we want te=th and as small as possible. How can we have as small as possible w should be as small which means you need a very small area detector, the detector should be very small not a large detector which we use with the normal power meters

You have a large area detector but all high speed detectors will have a very, very small area because this is one reason there is another reason because smaller the area, smaller will be the junction capacitance and the capacitance also determines the speed of response. But what we are looking right now is impulse response due to transit time considerations. We are looking at transit time considerations.

So, this is impulse response looking at transit time. Transit time consideration, the impulse response is determined by two factors. Let me make this clear. The impulse response is determined by two factors.

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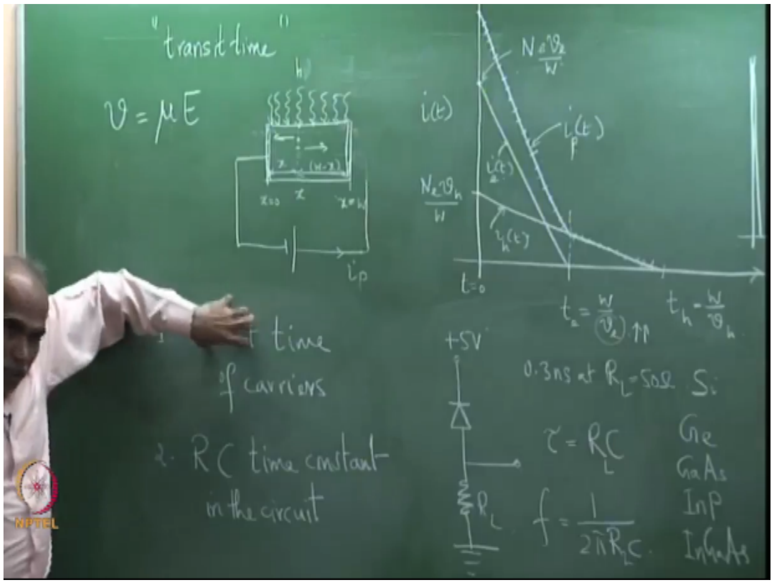

One the transit time of carriers. So, what we have been discussing is transit time spread. The second one it is determined by the RC time constant in the circuit. There will a detector circuit and there is a RC time constant in the circuit. This RC will include the RC of the detector itself. For example, if I take the standard detector circuit so here is let us take a diode PIN diode here. So, this is the output, this is the RL.

And here is +5 volt a reverse (()) (42:43) for getting a good drift current, drift velocity. Now, there is a load resistance and there is a junction, there is a reverse bios diode and there is a junction capacity. So, the speed of response tau or rise time is determined by the RC constant which is RL+ if you write the equivalent circuit of the diode there will be a series resistance and a junction capacitance.

So, this will contain the series resistance and the junction capacitance C. So, this will determine and the cut off frequency of this detector will be 1/ 2 pi Rl*C. So, the impulse response is determined by two factors. One is RC time constant therefore if you take any photo detector data sheet you will see they will specify the rise time for a particular load resistance. We will normally take 50 ohms as the standard load resistance.

So, they will specify that tau =.3 nano second at Rl =50 ohms that is the meaning because the rise time is determined by the circuit. The load resistance and junction capacitance rather than the transit time. The transit time can be minimized this factor can be minimized in semiconductor photo detectors by taking very small areas and very small length and very high velocity. So, this is the drift velocity how does this drift velocity vary with the applied electric field.

So, if you take Ve very large and very small w te can be very small and therefore this transit time consideration the impulse response is determined by two factors transit time and RC time constant in the circuit, actual system circuit. This can be minimized so that it is primarily determined by this. This also of course one tries to minimize but you cannot go beyond because RL you have to put some load resistance in a practical circuit.

You will see that if you reduce the load resistance detecting becomes extremely difficult. But you can reduce to some extent you cannot go beyond. But this can be really minimized.

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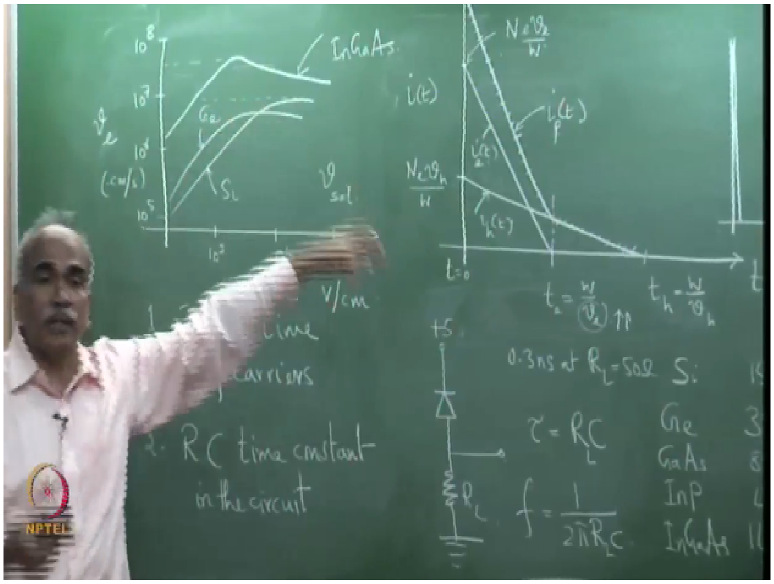

If you plot the drift velocity versus electric field, volt/centimeter versus the drift velocity Vd of carriers. So, if I plot for electrons so this is Ve typically the velocities are I will give some typical numbers 10 to the power 5, 10 to the power 6, 10 to the power 7, 10 to the power 8 this is centimeter per second. At the field typical numbers are 10 to the power 3, 10 to the power 4 and 10 to the power 5 volt per centimeter.

So, we can plot this and typically this would look like for indium gallium arsenide it looks something like this > 10.7 and drops. This is for indium gallium arsenide highest. If you take Germanium, it goes from here and then something here. If you take silicon, then so this is for silicon. This is for Germanium and this is for I have already written indium gallium arsenide.

These are quite typical the field is about 10 to the power of 3 or 10 to power 4 volt/ centimeter. It is volt/centimeter but typically we take thickness very small less than a millimeter and then if the volts are, it is only few volts. You do not have to apply very large volt it is volt/centimeter. Typically, we take .1 mm or .2mm as the dimension. So, this velocity here the highest value or the saturated value like you can see here it is saturated value is designated as Vset.

So, what is the point? Point is you must apply an electric field so that you are already at Vsat that is the maximum velocity possible. There is no point in applying very high field nor low fields. So, when I have shown this +5 volt I have written in some detectors you may need +15 volts. But

I did not write 1 volt because that may not be sufficient it may be here why they use +5 volt? Or +15 volt is to get a field which corresponds to Vsat that is the saturated velocity.

Now, where is the saturation coming? If you take the semiconductor, there are electrons and holes generated.

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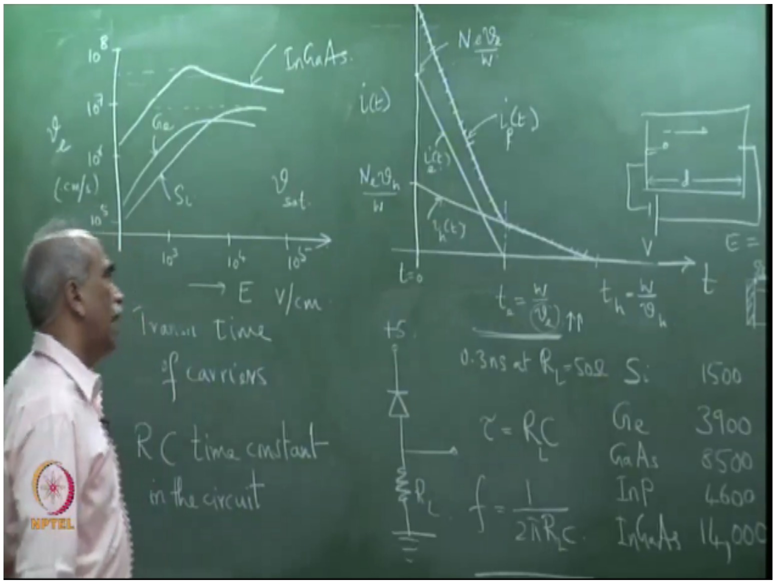

Electrons moves, holes move when you apply a field before you apply a field it just does not move there is nothing. So, that is why we have applied a field. So, you have applied a field here. So, if you applied a voltage V and this is d then you have E electric field, E=v/d. So, there is a electric field which is applied as you increase the voltage the electric field is increasing. The electron is getting drifted rapidly.

But after sometime when the electron is moving it is also colliding with the atoms and the electrons which are bound electrons in the lattice. So, it cannot go on increasing after sometime it has a saturated velocity and that is the Vsat that we have. So, to summarize this impulse response therefore with these discussions what we have seen is impulse response can be made very narrow or the speed of response can be very high, speed can be very high.

If you operate with a velocity corresponding to the drift, saturation velocity. If you apply an electric field corresponding to the saturation velocity and try to reduce the dimension of the detector, dimension of the active area these are two from this point and choose a material with a very large value of mobility. Because velocity=mu*e and therefore that is why we have been saying that this is the most important material.

And the most important material for optical communication because the responsivity is the highest for this detector in the 1.55 micrometer wind. So, this discussion tells us about the speed of response and the last parameter is the dark current or the noise power. This we will discuss if time permits in a separate lecture. Because noise power becomes very important when you have to detect very low power levels and one has to choose a material which has very low dark currents. So, we will stop at this point.