Semiconductor Optoelectronics
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Lecture - 41
Responsivity and Impulse Response

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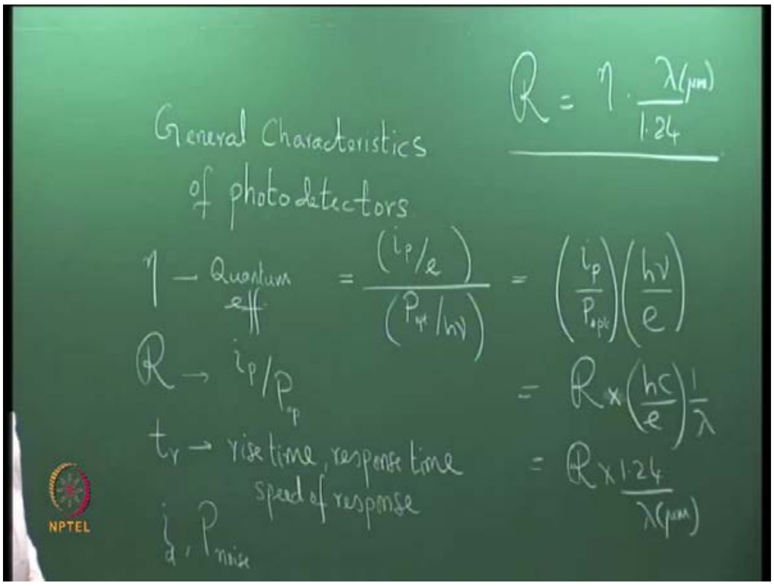

General Characteristics of photodetectors

η — Quantum eff $= \dfrac{(i_p/e)}{(P_{op}/h\nu)} = \left(\dfrac{i_p}{P_{opt}}\right)\left(\dfrac{h\nu}{e}\right)$

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

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

i_d, P_{noise}

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

In, the last lecture we discussed about general characteristics general characteristics characteristics of photo detectors. And we had listed first the inter, the quantum efficiency Q quantum efficiency 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 t r, so rise time or equivalently response time, or equivalently one can have discussion on the speed of response speed of response speed of response and finally, the dark current i d dark current or equivalently the noise power. So, this are the four general characteristics 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 i p divided by e carrier flux generated, due to an incident photon flux which is P optical divided by h nu.

So, the power incident divided by energy of one photon gives you the photon flux, and this is the carrier flux current is i p and therefore, divided by the charge gives you number of carriers or carrier flux.

So, this we have discussed and this we can write therefore, has i p by P P optical here, into h nu goes to the numerator, so we have h nu by e here. So, which is also equal to this is the responsivity so this is responsivity R, this is equal to h c by into lambda 1 over lambda. And if we substitute if we substitute this into if we substitute lambda in microns then, we this turns out to be 1.24, so this is equal to R responsivity into 1.24 divided by lambda micro meter just recalling. And therefore, we can write eta the responsivity here equal to eta into lambda divided by 1.24, where lambda is in micro meters. If we substitute lambda in micro meter in the responsivity of a photo detector can be written in the form R is equal to eta into lambda divided by 1.24.

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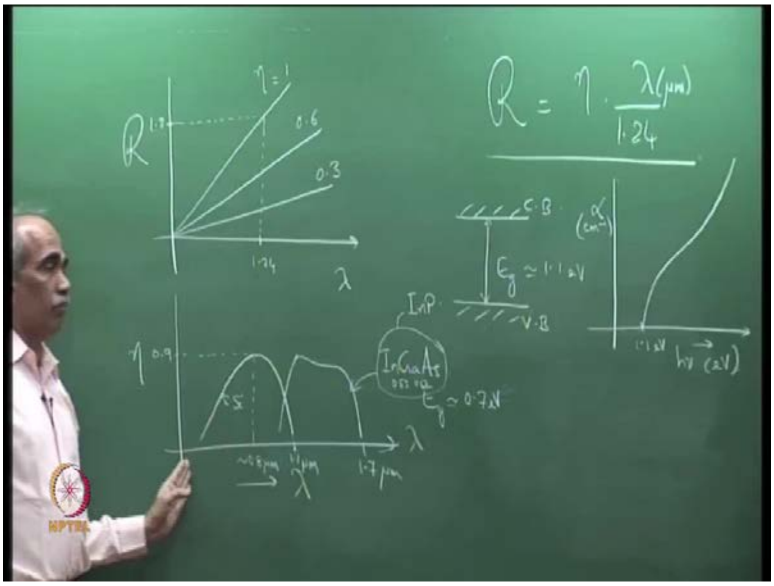

Where eta is the quantum efficiency of the detector, quantum efficiency of the material of the detector. In the last lecture we have also discussed in detail how to maximize eta for a given structure and a given material, how one can maximize eta, and if we plot the responsivity therefore, so responsivity versus lambda if you plot R here. Then you would have straight lines for different values of eta, so this is what we have plotted eta is equal to 1 may be 0.6, 0.3. And this is with wavelength, so you can see the typical numbers when lambda is equal to 1.24. So, if you take lambda here as 1.24, and eta is equal to 1 then responsivity here must be 1.0, so lambda is equal to 1.24, then responsivity will be equal to 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 eta, 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 eta, the the internal the quantum efficiency of silicon is approximately the maximum value is about 0.9, and this is about 0.7, 0.8. And this occurs around lambda nearly equal to 0.8 micro meter. And this goes down to 0 around 1.1 micro meter here, and this goes down to 0 around 1.7 micro meter 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 goes down on in both at both the ends here, the longer wavelength end in is obvious. Because, for a given material like silicon silicon has a band gap e g here, so e g is 1.1 electron volt, so this is the conduction band, and valance band. Inter band absorption the absorption coefficient goes to almost 0 for energy less than for energy less than the band gap, there cannot be electron hole pairs created and therefore, the absorption coefficient goes down to 0 if you remember the graph for absorption coefficient, so if we have lambda like this are photon energy let me better plot in terms of photon energy.

So, this is h nu we recall that we have, so the absorption coefficient alpha here, starts at e g and then goes up. So, this is for silicon so this is e g equal to 1.1 e v, so h nu in e v, and this is alpha centimeter inverse, recall the absorption coefficient has a function of photon energy. So, you can see that 1.1 e v 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 therefore, the responsivity the quantum efficiency of silicon goes down to 0 at longer wavelengths, so there is a longer wavelength cut off. Exactly like that indium gallium arsenide has a cut off around 1.7 micro meter, 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 phosphate. So, that we can grow diffract free hetero structures, so it is lattice matched to the binary compound indium phosphate, so this has a band gap e g of approximately 0.7 e v.

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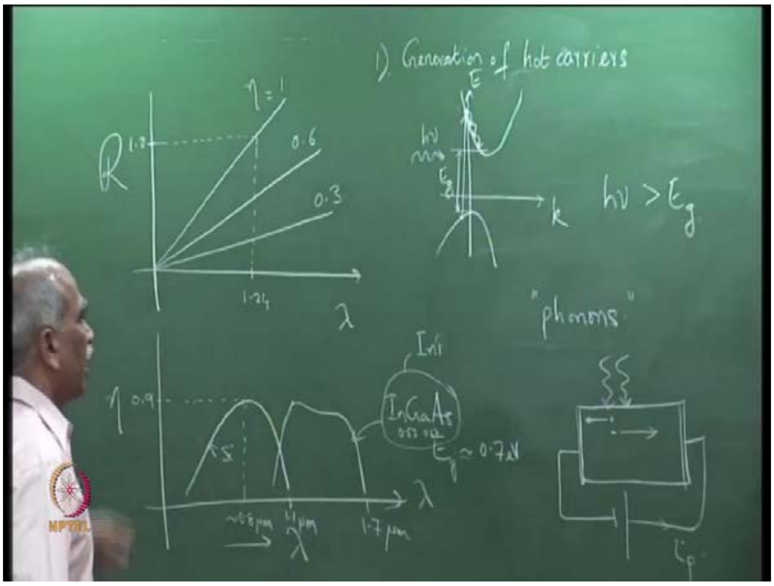

So, you find out the wavelength cut off is here, so we know why eta goes down to small values or goes down to 0 at longer wavelengths, because there is no absorption possible. Why does eta come down to 0 at shorter wavelengths? Energy is increasing shorter wavelengths, absorption coefficient increasing but, why does it come down? There is two mechanisms due to which this comes down. So, let us discuss these two mechanisms, very briefly and very quickly we will discussed. 1 has energy increases, so first because of generation of hot carriers generation of hot carriers hot carriers. If you take the band gap here, so this is e k diagram, so k versus e, I would drawn a indirect band gap semiconductor, to indicate that the silicon for example. And when the energy is larger for example, this is the e g so this is e g, for h nu for h nu incident photon energy much greater than e g. Electron transition can take place transition can take place and electron can make an upward transition to an allowed state here. Electron from the valance band can make an upward transition due to absorption of the photon of energy h nu greater than e g, it can make the transition to, because this is a vertical transition which is an allowed transition and therefore, this carrier here is a hot carrier because it is a high energy carrier.

So, this carrier generated start coming down by thermalization the process called thermalization, we have discuss 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 facilitate non radiative recombination's very quick non-radiative recombination. In other words, the generated carriers will recombine very quickly by non-radiative recombination's.

If the carriers are recombine very quickly, please recall we are discussing a photo detector here material, in which photons are incident on which photons are incident and it is generating electron hole pairs, so if you apply a bias then electrons will move in this direction, holes will move in this direction, and the carriers are collected. And this is what is the responsible for the reverse photo current i p, there is a photo current in the circuit.

Now, the generated carriers if the 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 the recombine very quickly then there are no more contributes to the external current and therefore, the quantum efficiency starts dropping. This is the 1st reason generation of hot carriers.

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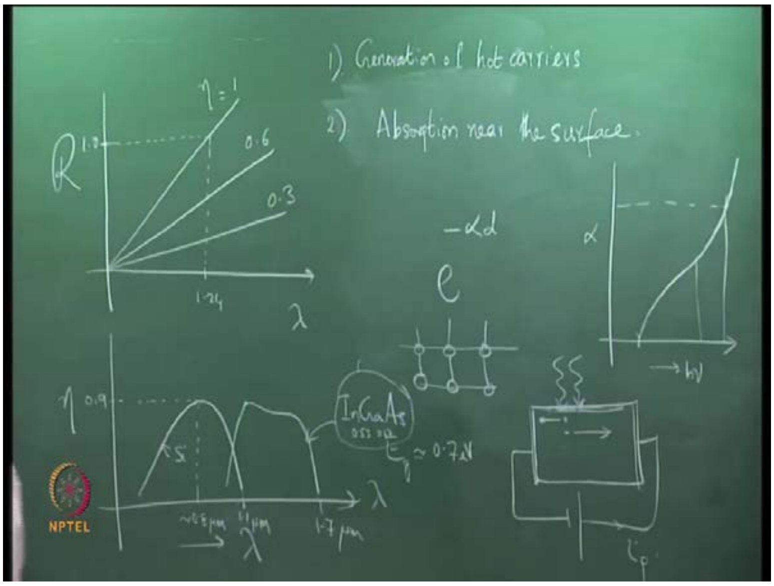

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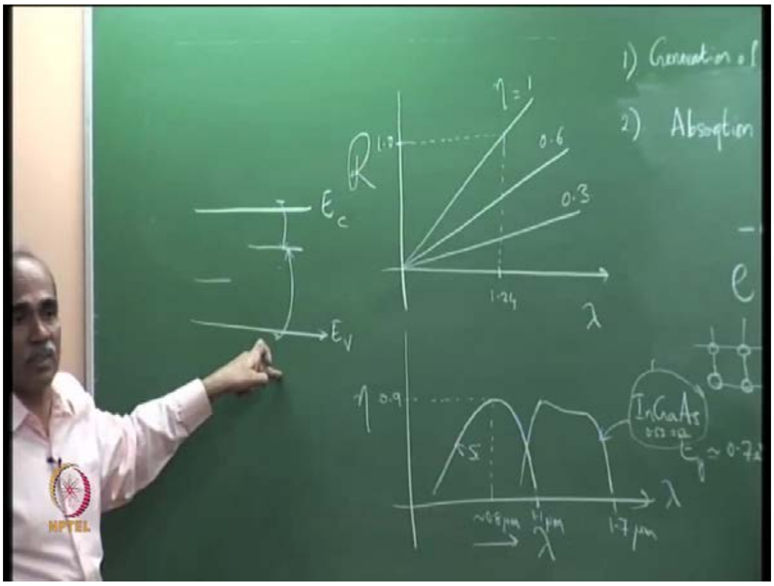

The second reason, so let me show here. The second reason is because of 2 absorption near the surface. absorption near the surface what do I mean by this? let me explain again I had the curve here, that is h nu versus alpha as you can see in the same curve which I had drawn earlier. It starts from e g we are looking at lower wavelengths response that is quantum efficiency at lower wavelengths. And we are trying to explain why does it go down at higher energy is for lower wavelengths. So, higher energy here corresponds to larger values of alpha larger values of alpha. Absorption coefficient is very large and therefore, it means that the photons which are incident or absorbed completely closed to the surface. Because absorption is given by e to the power of minus alpha into d. d is the thickness or it where it is absorbed.

Now, if alpha is very large then d needs to be very small. In other words almost all the incident photon energy is absorbed closed to the surface. And in any materials surface is not a very good placed get absorbed, because surface there are surface states due to dangling bonds in the medium. because near the surface if you an large. We have discuss this earlier but, just to recall if you an large the positions of atoms here and the bonds like this, you can see that to 1 side the bonds are dandling, 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 gap. So this is e v, this is e c and this is the e g, corresponding to the surface states there are states which are in the forbidden gap, and this act a 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 states. Which acts like traps in the medium facilitate recombination of the carriers, quick facilitation of the recombination of the carriers. If carriers recombine mean carriers are lost from the medium, which means they no more contribute to the current. And that is why the quantum efficiency drops down at smaller wavelengths and therefore, the final picture now the responsivity therefore, less very quickly come to the responsivity.

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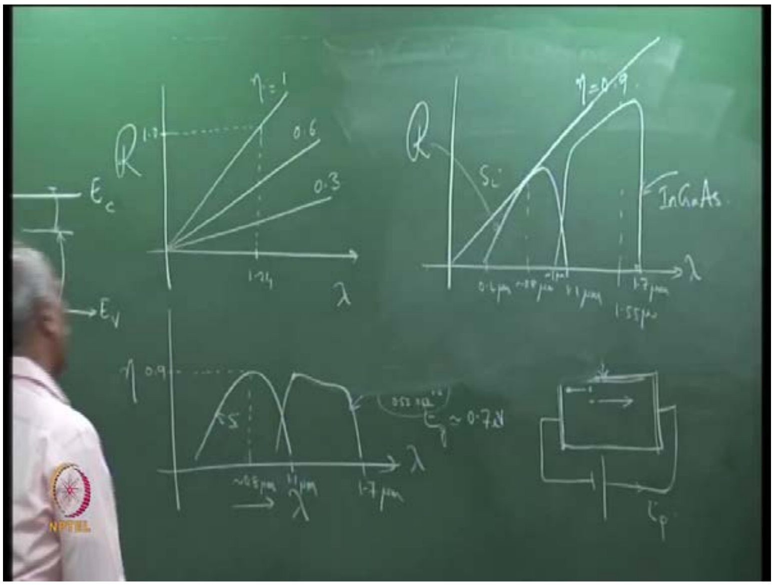

If eta where 1 the responsivity would have varied like this but, eta varies like this it is not one it varies like this which means if i show you on the same plot or let me show it separately, for a particular value of eta. Let us say eta equal to 0.9 what I am plotting now is responsivity versus lambda for real detectors, with a quantum efficiency that is realistically varying like this. So if i plot for silicon as you can see 0.9 is the peak and therefore, it will touch this around 0.8, other places it will drop down. so it will go like this and then drop down.

So, this where it touches is about 0.8 micro meter 0.8 micro meter, and this is 1.1 micro meter and this end is approximately 0.3 or 0.4 micro meter. So, what i have plotted is the real responsivity of silicon varies like this. If you take a typical data sheet of a silicon detector you will see the responsivity given like this. And if i want to plot for indium gallium arsenide the maximum normally goes around 0.8, so it starts from about one micron here and this would go like this and come down somewhere. So this is approximately around 1 micron, and goes up to 1.7 micro meter. so one point seven micro meter. So this is for indium gallium arsenide responsivity versus wavelength, these 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 micro meter window here, and InGaAs is the best detector, and silicon will not work but, if you are interested in around 0.8 then silicon is the best detector.

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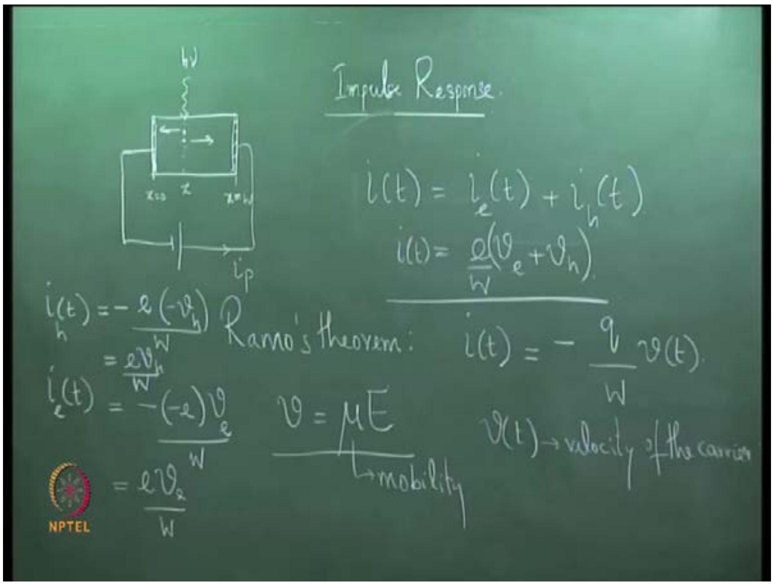

So, responsivity this curve is very important in the choice of the detector.

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 a 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.

So, we consider let me draw this diagram redraw this diagram. So here is the detector material two electrodes deposited, this are semiconductor material on which let say, a photon 1 photon is incident. Let us first start we discussion of 1 photon, incident at so this is let this direction be x equal to zero and the width of the detector is x is equal to w. So this is incident at some value of x so this is some value of x. And we have a supply which is connected to sweep the generate detectors. So the incident photon gives rise to a hole and electron, and the applied potential will drift it, so electron will move in this direction, and hole will moves in this direction. And that leads to a current in the external circuit which is the i p photo current.

Now, we are interested in knowing the speed of response or impulse response impulse response. Impulse response refers to response of the detector or response of a system to an input impulse. Impulse is an instantaneous pulse impulse. So instant you have the system here if you give an impulse here, a signal with 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 at an instant t instantaneously 1 photon is incident at a particular instant, we want to see how would the current look like? so photon is incident at 1 instant 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 in the external circuit is equal to minus. If a charge q moves in a medium of length l or w then, i of t is equal to minus q divided by w into V of t. Where V of t is the velocity is the velocity instantaneous velocity, velocity of the carrier of the carrier, the charge carrier q. w is this width here. And this velocity as come because you have applied a field there is a drift velocity, as you know the velocity drift velocity V is equal to mu into e, where e is the applied field, mu is mobility of the carriers. mobility mu is the mobility of the carriers V is the drift velocity and e is the applied electric field.

Therefore, we have a hole which is moving in this direction, and an electron which is moving in this direction therefore, we have a hole current i h of t and i e of t, this is the current induced in the external circuit. So, there is a hole current and an electron current. So electron current i e of t is equal to minus, charge is minus e, minus e into velocity of electron V e. If i take a average velocity assuming that over the time duration the velocity is constant so i can write v e divided by w, so that is equal to e into V e by w the electron is moving in this direction, so the velocity is here, so e V e by w. The hole current i h of t is equal to minus, charge of hole is plus e but, it is moving in this opposite direction therefore, it is moving with a velocity V h. 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 the different although the applied electric field is the same and therefore, V h divided by w which is equal to e V h by w.

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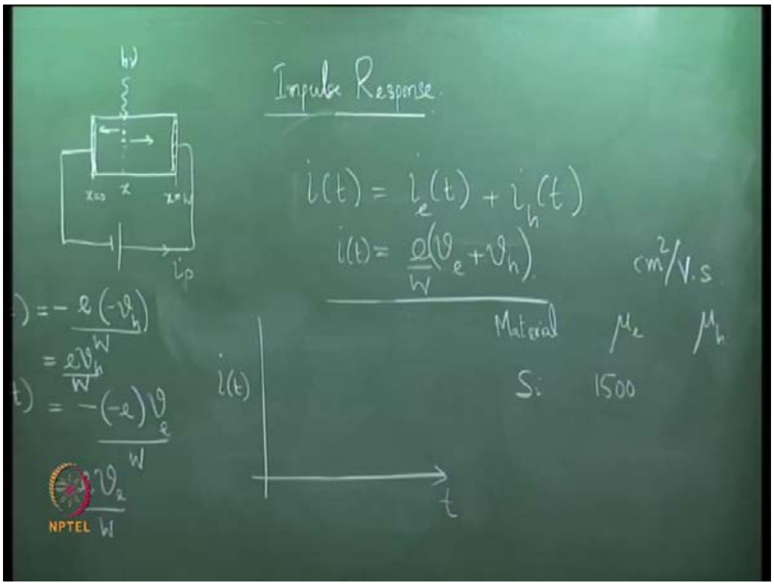

The total current therefore, the total current in the external circuit i of t is equal to i e of t plus i h of t, which is equal to e V e so or e by w into V e plus V h, this is current i of t in the circuit. The photo current is equal to e divided by w, this e the little bit bigger i have written V e h 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 a burst of photons, which are incident. And response is the current in the circuit. So if i plot i of t, so with the time, so this is with a time if I plot i of 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 i e of t. Now, it would be work while 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, mu e and mu h. So if we take silicon silicon or let me give you some numbers, so this is 1500. what is the unit? mu e and mu h centimeter square per volt second. centimeter square per volt second You can get from here.

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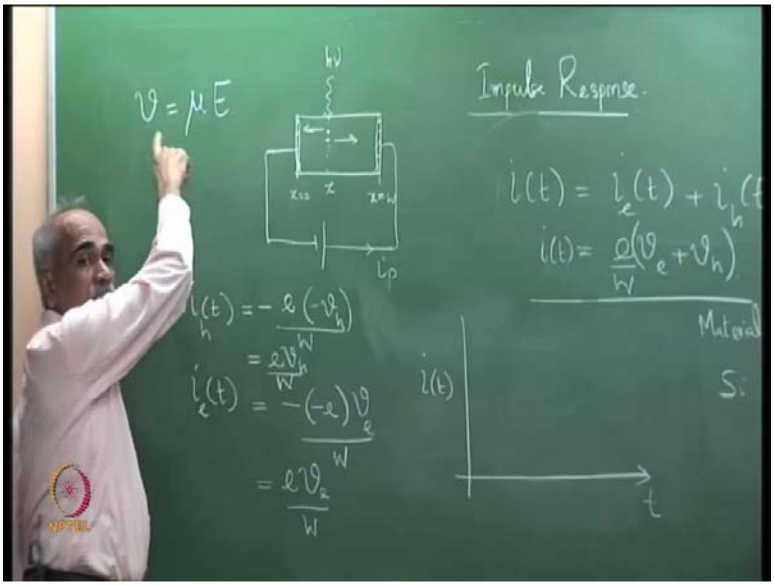

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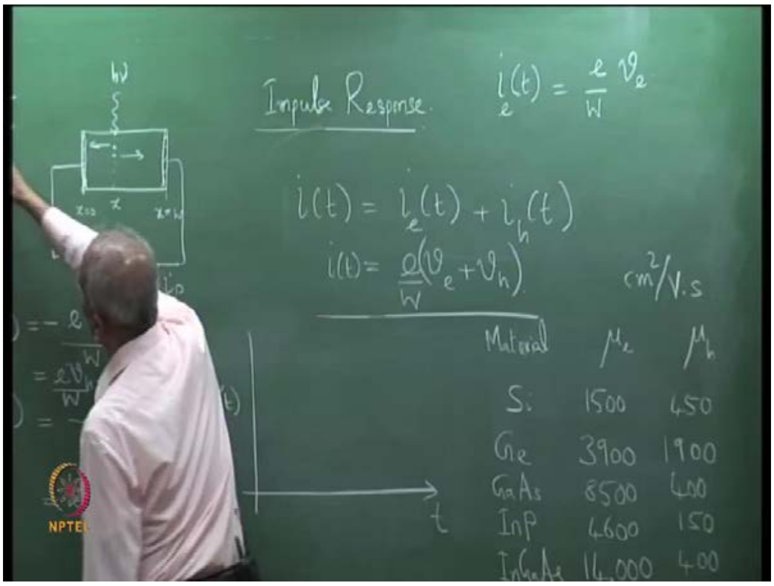

So, V is equal to mu into e, so mu is equal to V by e, e is volt per centimeter and this is centimeter per second so you will get centimeter square by volt second. So this is 1500 and this is 450. If you take germanium this is 3900 and this is 1900. If you take gallium arsenide, some of the most widely 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 phosphate, indium gallium arsenide the most important detector material. This is 14000 and here 400. So you can see the large difference between mobility of electrons and holes.

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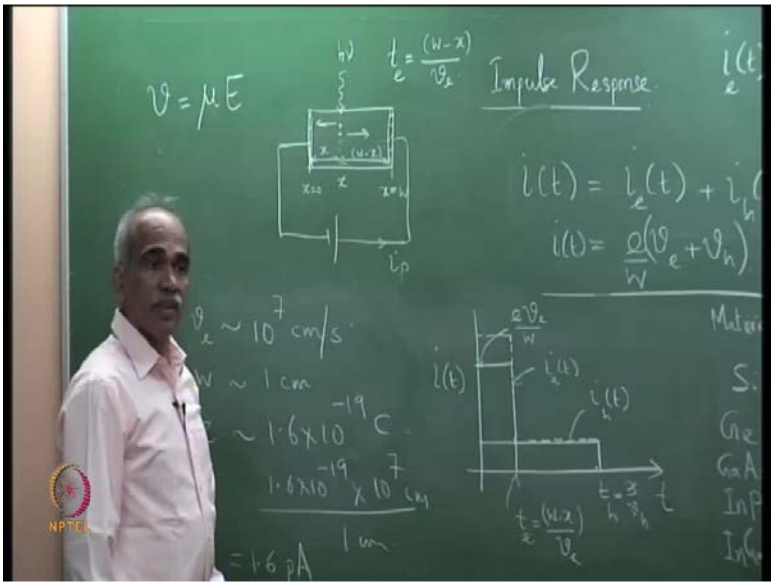

This is now important because it will tell us what is the time taken by the detector. So the 1st the current i e of t is equal to, so let me plot i e of t is equal to e by w into V e. And recall that V e is in general V e is equal to mu into e electric field is the same but, mu e is large for electrons and this will be much larger compare to the hole current because V h is smaller compare to V e. So if I say that i e of t is equal to this value e into v e by w is somewhere here then, current will persist till the electron is collected by the electrode here. Electron moving in the semiconductor is a responsible for a photo current, when the electron is correct 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 this separation is w minus x this is x so this is x and this is w minus x so distance divided by so t e is equal to w minus x divided by V e. And there is a time taken, so up to that time t e the current will persist and then it will drop down to 0. So this value here is t e is equal to w minus x divided by V. Now the hole current. Hole current we know is smaller because V h is smaller. So let me start at some value here, so this is what is this value here? this is e V e by w, the value on the y axis here is e V e by w, the value here is w minus x by V e. We can put some numbers to get a better field we can always put some numbers. So what kind of numbers are we talking of I will discuss more about V e a little latter but, typically V e is about 10 to the power of 6 or 10 to the power of 7 centimeters per second. w let us say this the 1 centimeter detector there can be smaller detectors but, just let me put w approximately 1 centimeter, to get a field for the number and e as you know is 1.6 into 10 to the power of minus 19 Columbus. And therefore, the current i is e therefore, 1.6 into 10 power minus 19 multiplied by V e, 10 to the power of 7, so this is Columbus, this is centimeter per second and in the denominator 1 centimeter. So this is equal to 1.6 into 10 power minus 12 that is pico Ampere. Why? because we have put just one photon.

The current is very very smaller, because 1 photon there is 1 electron moving and therefore, the current is very very small. We will see how? so just to get a field, so that is the current. Which is persisting for a certain time, again you can put this is about 1 centimeter, this 10 power 7 centimeter per second therefore, the time is 10 power minus 7 second, so approximately 0.1 micro second, current persist for about 0.1 micro second. So if you reduce this naturally, it will become a faster detector. So if you want to take a small area detector, we will discuss this later.

Now, let us plot the hole current, so it is start at a lower value but, it goes further. Why? because t h t h t h where is t h? t h is equal to x the distance x divided by V h. V h is much smaller compare to V e therefore, so this is t h equal to x divided by V h. This is plot of i e of t, and this is plot of i h of t, assuming that the carriers are moving with a constant average velocity, till they are collected at the ends. So, the total current will be the sum of 2. So if i want to plot in the same sum of the 2, so here it will be, it will add up let we draw with a dotted dash line. So my total current will look like this, the box with a dash line shows the total current. So what I have plotted I have drawn impulse response at t is equal to 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 1 photon incident.

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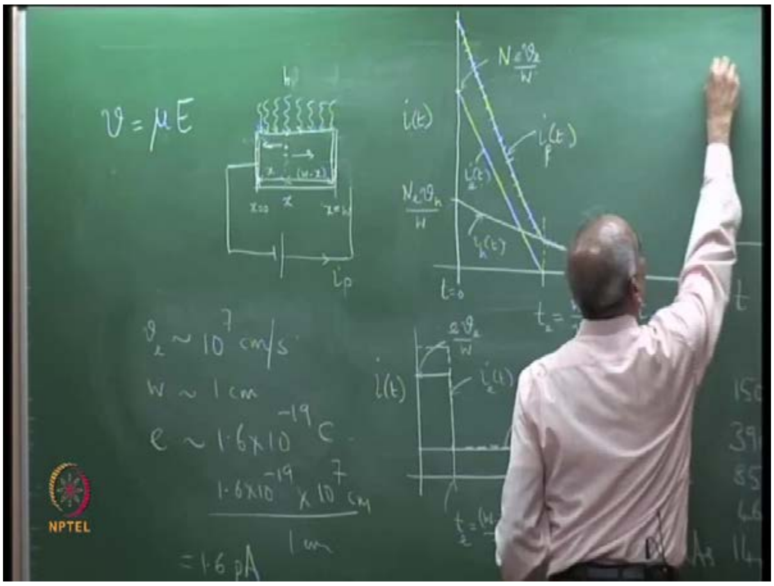

Now, I will extend a little bit further to n photons, because we are interested in seeing n photons incident. So the same detector now but, photons are incident everywhere all over the detector, not at 1 point. If at 1 point there where n photons then, the current would have been simply multiplied b n, same response will remain the same but, it will be multiplied by n that is all that is the only different. So this value here is i V e into w. If there where n photon incident at this part, I would have got n e v by w.

So typically if a very small amount of a burst of n photons let say 1 billion photons are incident, then the current will increase by 1 billion time so this will be the mille Ampere. So the numbers are quite practical numbers. Now, the photons are incident everywhere not at 1 point over the entire detector surface, what will happen? at every point electron hole pairs are generated, and electron which is generated here is instantaneously collected whereas, electron which is generated here will take a time t is equal to w divided by V e is the total time. And so if I plot i e of t please see this. So this is time versus i i of t, so first let me plot i e of t so it will be largest at t is equal to 0 because all the electrons are moving but, the electrons which are generated here or collected, once it is collected no more contribution so the current will drop like this, continuously till a time t. t is equal to what is t? will be equal to w divided by V e, so this is t e the current is continuously, and what is the value here? n times n times e into V e divided by w.

Because there where n electron hole pairs created similarly, the hole current holes which are generated here are a immediately collected but, the hole which is generated here has to travel are along and therefore, it will vary from a smaller value here I am taking a smaller value why? because the hole current is n e V h divided by w, V h is smaller than V e therefore, it starts somewhere here. And then it will continue for a duration which is up to this. So what is t h? is equal to w divided by V h. 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 let me draw this with, this is the total current. So what are the things are plotted I have plotted? I have plotted i h of t, i e of t i e of t and this is i total i total which is the photo current, i p of t which is equal to the sum of the two.

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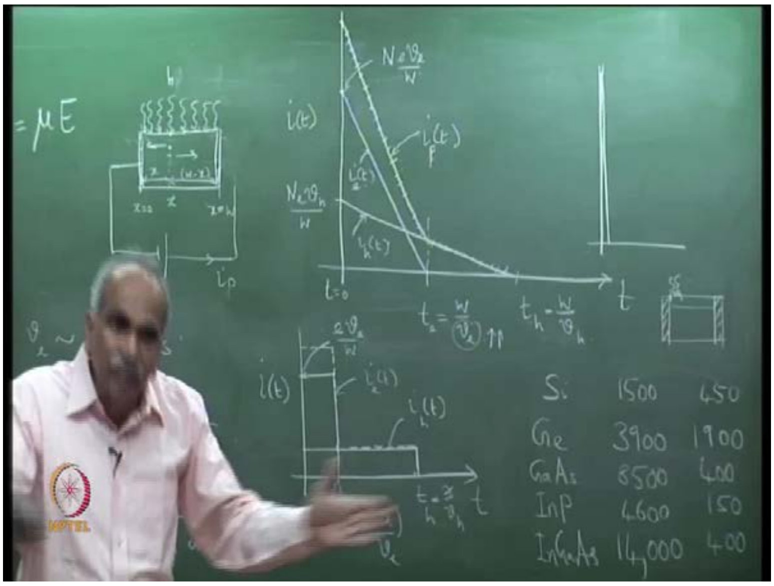

So, the impulse where was the impulse? Impulse is at t is equal to 0. At t equal to 0, we have a burst of n photons where incident on the photo detector, and instantaneous impulse the response is this. At the output we see that the current, which is the response of the photo detector is spread over the certain time, so this is the impulse response. Now, what is an our objective if you want a high speed detector in an application? this should be as small as possible. If it was so you had an impulse here and then if you had a response which is like this it would have been the idea very fast the detector is very fast. So how can we get high speed, obviously you have to have as large we should be as large as possible, 1st t e should be equal to t h otherwise this pedestal will always remain. So if you can make t e equal to t h. 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 that is very good but, i want to avoid the pedestal.

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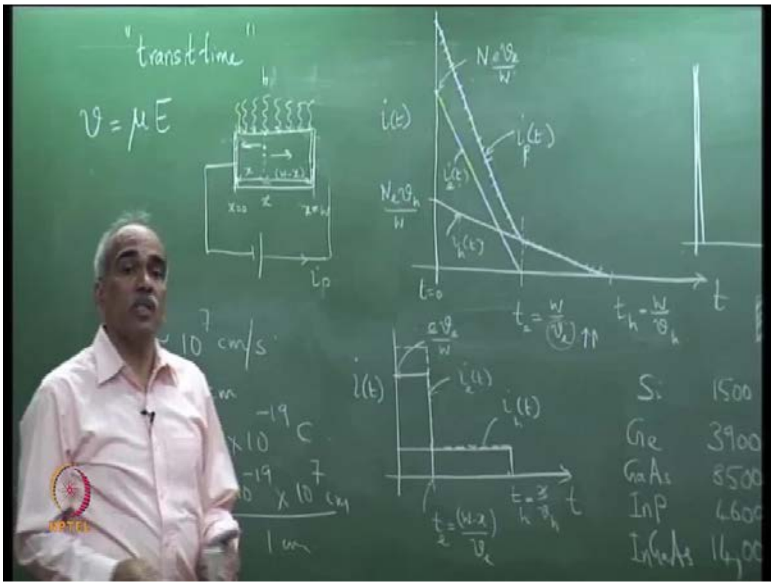

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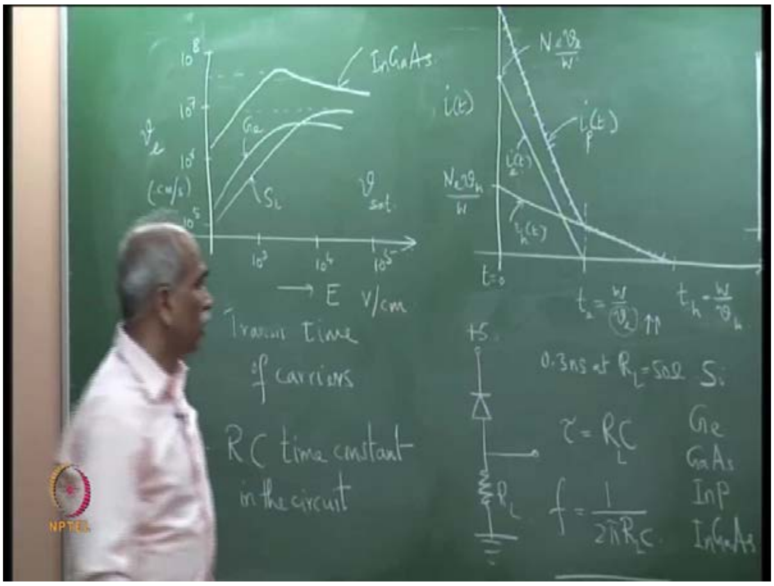

This is the window where all the photons are incident then t e will also be slightly larger to match t h, so that this pedestal can removed and get the nice impulse response like this. 1^{st} thing we want t e equal to t h and as small as possible. How can we have as small as possible? w should be as small, which means you need a very small area detector. The detector should be very small not a large detector which we use a normal power meters, you have a large area detectors 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 determine the speed 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. So transit time considerations, the impulse response is determined by 2 factors. Let me make this clear the impulse response is determined by 2 factors. So 1 the transit time of the carriers. so transit time of carriers So what we have been discussing is the transit time spread. The second one it is determined by the R C time constant time constant in the circuit. There will be a detector circuit as there is an R time constant in. This R C will include the R C of the detector itself. if I for example, if i make the standard detector circuit. So here is let us take a diode PIN diode here, so this is the output this the R L and here is plus 5 volt, we reverse bias is for getting a good drift current drift velocity.

Now, there is a load resistance and there is a junction case is a reverse bias diode. So this is a junction capacitance. So the speed of response tau or rise time is determined by the R C time constant, which is R L. Plus if you write the equivalent circuit of the diode there will be a series resistance and a junction capacitance. So this will contains the series resistance and the junction capacitance C. So this will determined the frequency cut off frequency of this detector will be 1 over 2 pi R L into C. So the impulse response is determined by the 2 factors. 1 is R C time constant therefore, if you take any photo detector data sheet, you will see they will specify the rise time they will specify the rise time, for a particular load resistance, you will normally they take 50 ohm as the standard load resistance. So they will specify the tau is equal to 0.3 nano second at R L is equal to 50 ohm.

That is the meaning because the rise time is determined by the circuit, the load resistance and the 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 is very interesting? how does this drift velocity vary with the applied electric field? So if you take V e very large and very small w, t e can be very small. And therefore, this transit time consideration, the impulse response is determined by two factors transit time, and R C time constant in the circuit, actual system circuit. This can be minimized so that it is primarily determined by this, this also of course ones try to minimize but, you cannot beyond one because R L 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 reduced some extant you cannot go beyond but, this can be really minimized. If you plot the drift velocity versus electric field. Electric field volt per centimeter versus the drift velocity V d of carriers.

So, if I plot for electrons so this is V e typically the velocities are, I will give some typical numbers 10 power 5, 10 power 6, 10 power 7, 10 power 8 this centimeter per second. And the field typical numbers are 10 power 3, 10 power 4 and 10 power 5 volt per centimeter. So we can plot this a typically this would look like for indium gallium arsenide it looks something like this, greater than 10 point 7 and then drops something like this, this is for indium gallium arsenide highest. If you take germanium goes from here and then something like this. 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. This are quite typical the field is about 10 to the power of 3 or 10 power 4 volt per centimeter, is volt per centimeter but, the typically we had take thickness a very small, less than a millimeter and then V to the volts are it is only few volts, we do not have to apply very large volt which is volt per centimeter, typically we take 0.1 mm or 0.2 mm as the dimension. So, this velocity here the highest value or the saturated value, like I you can see here it is saturated value is designated as V sat. So what is the point? Point is you must apply an electric field.

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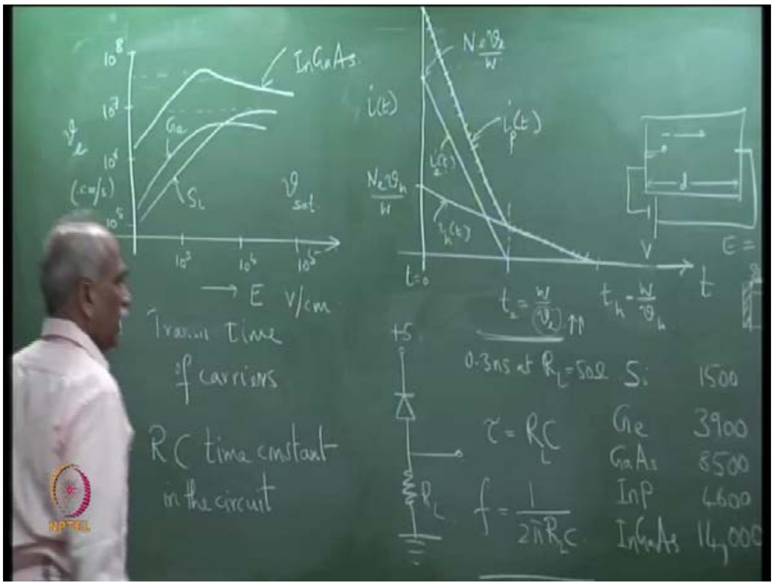

So that you are already at V sat, that is a maximum velocity possible, there is no point in applying very high fields nor low fields. So when i have shown this plus 5 volt I have written, in some detectors you may need plus 15 volt but, I did not write 1 volt because that may not be sufficient it may be here, why they use plus 5 volt or plus 15 volt is to get a field which corresponds to V sat that is the saturated velocity. Now where is the saturation coming? If you take a semiconductor there are electrons and holes generated, electron moves, hole moves. When you apply a field before if you a field does nothing it just does not move there is nothing, so let us why we had applied a field. So you have applied a field here, so if you had applied a voltage V and this is d then you have e electric field e is equal to V by d.

So there is a electric field which is applied, as you increase the voltage 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 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 v sat that we have. So to summaries this impulse response therefore, with these discussion what we have seen is impulse response can be made very narrow or the speed of response can be very high, this speed can be very high. If you operate with a velocity corresponding to the drift saturation velocity, if I applied an electric field corresponding to the saturation velocity and try to reduce the dimension of the detector, dimension of the active area, this are two from these point and choose a material with a very large value of mobility. Because velocity is equal to mu into e and therefore, that is why we have been saying 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 micro meter window.

So, this discussion tells 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 detect very low power levels, and one has to choose material which has choose very low dark currents. So we will stop at this point is there any specific question .

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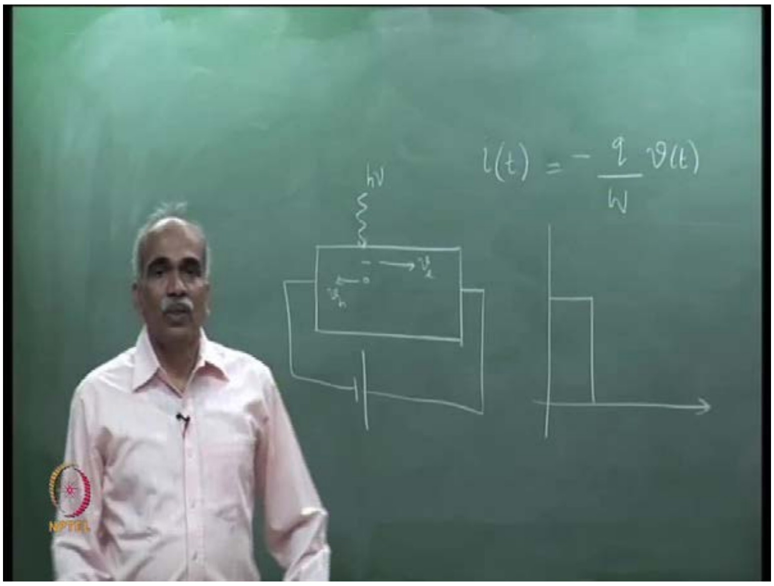

Sir when you say only one (( )), so there will be only 1 electron and 1 hole till it generated. So how can we continuous (( )), it will be a it should be a very, it should be (( )) only (( ))

Ok the question is this is the detector. So the question is one photon is incident h nu which creates one electron and a hole in the medium. Now because of the applied field they start moving drifting to two sides, otherwise they would recombine again because if there is no field, so this starts otherwise they would recombine again because if there is no field. So this starts V h here, as soon as the carrier start moving in the medium there is current in the circuit, it is not when it is collected you get current, once you it is collected then it is it as gone into the conductor no more current. So when it is moving inside the detector then you have current and because it takes certain duration therefore, if you plot the current the current persist, I have taken one photon just to say that it will remain constant till it is collect and drop down. So Ramo's theorem shows which can proved actually by simple heuristic explained i of t is equal to minus q by w V into V of t. So the current persist over a certain time, so long as the charge is moving inside the semiconductor and that is why the reason the continuous current. It is not like a counter when it has reach there, there is a count, there is a spike, is not that it is because of the motion of carrier there is a current, because current is basically flow of carriers. Is that ok so we will stop at this point.