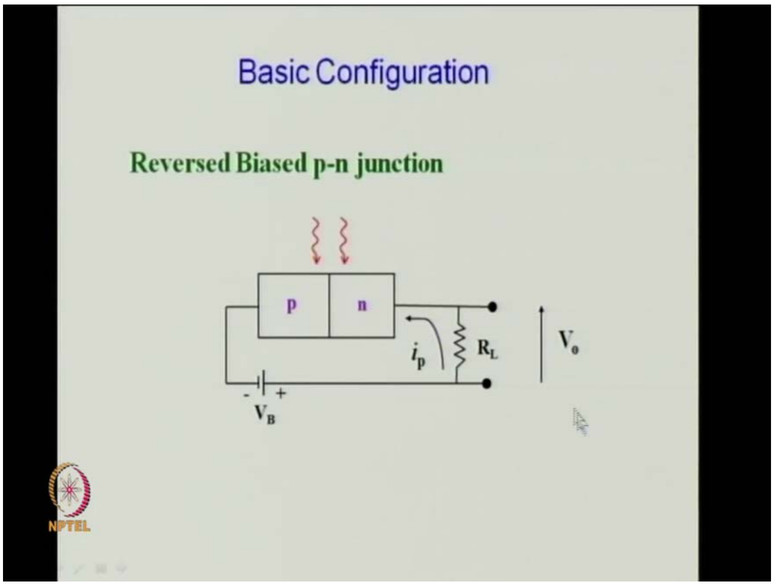
Semiconductor Optoelectronics
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

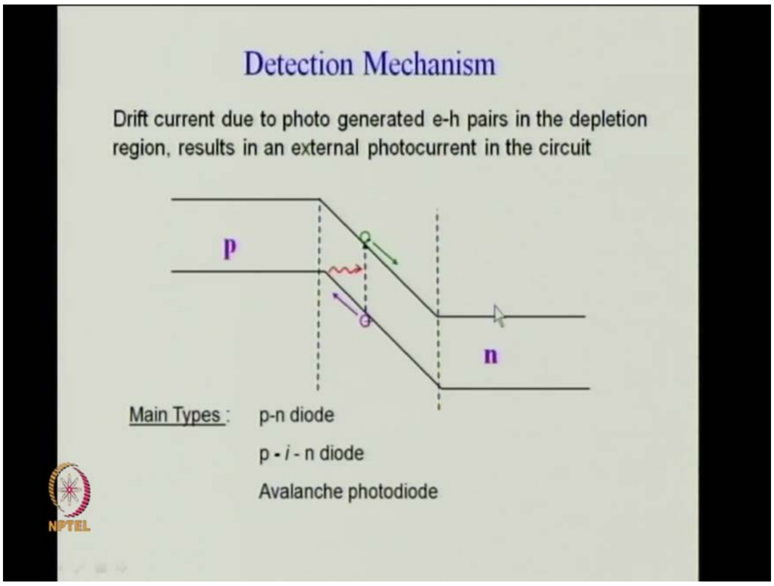
Lecture - 43
Semiconductor Photo-Diodes

(Refer Slide Time: 00:36)



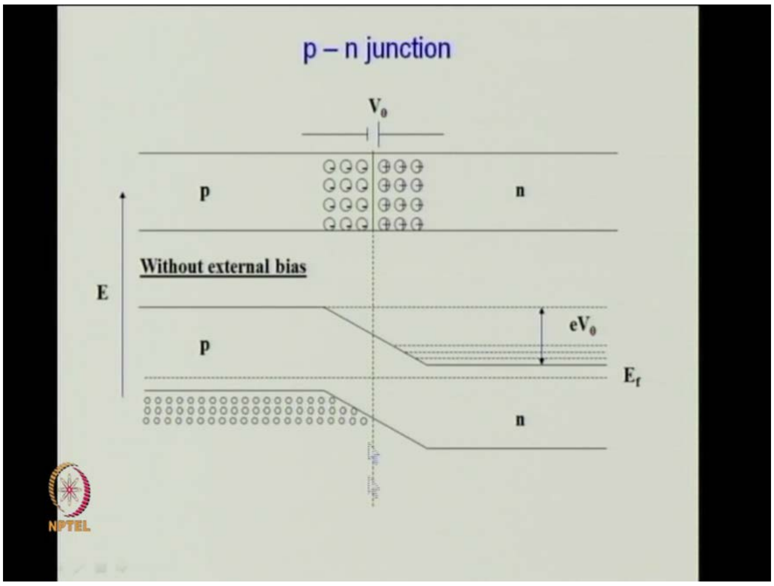
Today, we will discuss semiconductor photo-diodes and in particular we will discuss about pin-diodes. So, semiconductor photo-diodes the basic configuration is a reverse biased p-n junction, we will see why it is reversed biased, is a reverse biased p-n junction. So, as you can see there is a p-n junction here and a load resistance and this is the biased supply here and output is measured here.

(Refer Slide Time: 01:01)

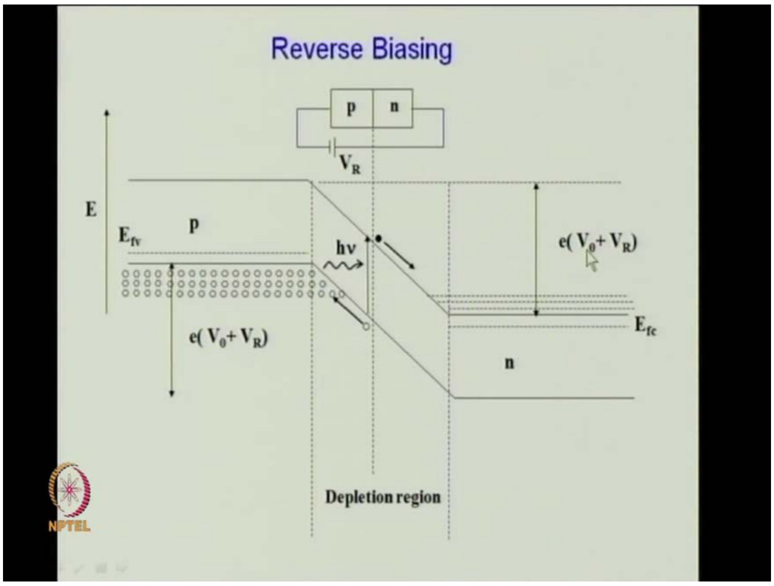


The detection mechanism is illustrated here an incident photon in the active region, we will discuss what happens in the photons incident in other regions. But an incident photon in the active region generates an electron hole pair e-h pair here. And in this biased region there is a potential here build in potential due to which the hole travels upwards here towards the p side and electron travels always downwards here and towards the n side. And then it is reverse biased and therefore, the carriers are swept apart the carriers are swept apart immediately and that gives the reversed photo current. This is unlike the forward photo current, forward current of a diode where electrons are injected to the p side this in this case as you can see electrons go towards the n side and the reverse biased sweeps away the carriers resulting in a reverse photo current, i p is a reverse current.

(Refer Slide Time: 02:08)

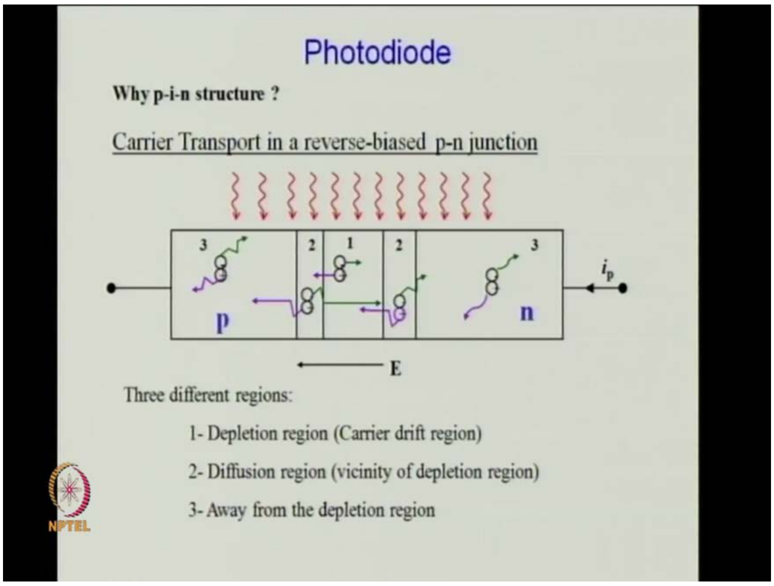


(Refer Slide Time: 02:35)



The p-n junction here just to recall very quickly we have seen this in detail without any external bias a p-n junction is shown here. Plenty of electrons on the n side and plenty of holes on the p side and in any common region there is a no region where you have simultaneously plenty of electrons and holes. If you reverse bias the potential barrier increases the height of the barrier increases you can see here, earlier it was e times V 0 where V 0 was the built in potential. Now, it is e times V 0 plus V R, e times because as you can see this is the energy axis and therefore, it is the build in potential is e times V 0 plus V R. The slope is steeper now and therefore, an electron as we discussed in the early part of the course can be imagined as a water droplet it rushes down here down the slope and reaches this side that is the n side.

(Refer Slide Time: 03:16)

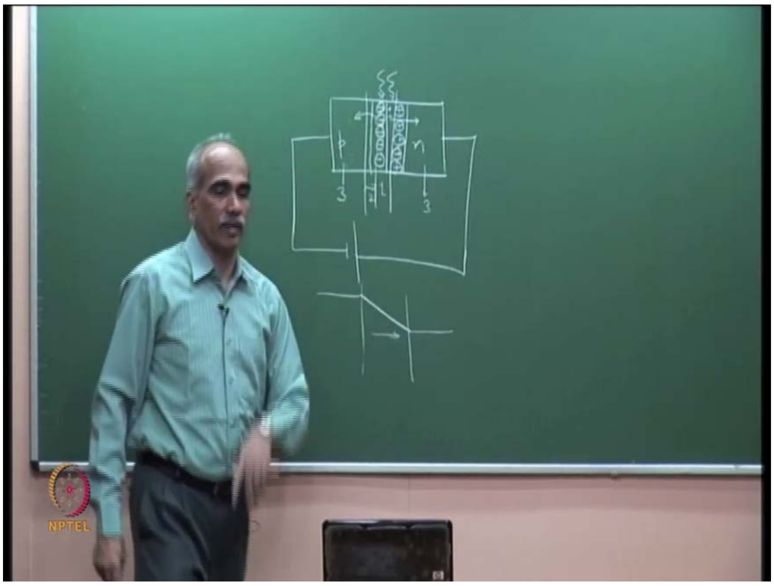


Then why do we use pin structures almost all detectors which are used in high speed applications are pin photo diodes and why we go for a pin structure, there are several reasons. So, let us just look at the carrier transport in a reversed-biased p-n junction. So, this is a p-n junction p side n side, assume that light is incident allover the p-n junction, this is p-n junction allover the p-n junction. And this is the junction region here this is write now this is not PIN this is p-n junction, carrier transport in a reverse-biased p-n junction. So, this is the junction region what happens to the photons incident at different parts of this p-n structure. Let us see this end here photons incident here create an electron hole pair, but there is no potential there it is flat there is no potential difference and therefore, the electrons feely wonder around and they may recombine as well.

But they electrons which are incident in the active region or the depletion region, they because of a built in potential there because of a potential there, they the electrons move towards the n side and holes move towards the p side. So, there is carrier drift. So, this region, so distinctly as you can see in the diagram there are three regions. The first region is the depletion region where there is a potential, potential difference between p side and n side. Two diffusion region that is region which is in the vicinity of this side is p, there are plenty of holes this side is n, plenty of electrons. Therefore, electron holes which are generated in the depletion region, because of carrier concentration difference here there are there are plenty of holes. And therefore, electrons tend to diffuse this side because of the concentration difference.

One is because of drift, drift means applied potential, applied voltage driving a carrier is called drift whereas, due to concentration difference here you have large concentration of holes, but no electrons. And therefore, the electrons would like to move there because of concentration difference and that is called diffusion. And therefore, the region which is in the vicinity of drift and no field region, there is no electric field in this region for away from the junction, there is no electric field and this is called diffusion region. Region number two is the diffusion region if you find it difficult we can draw it on the board and see this.

(Refer Slide Time: 06:17)

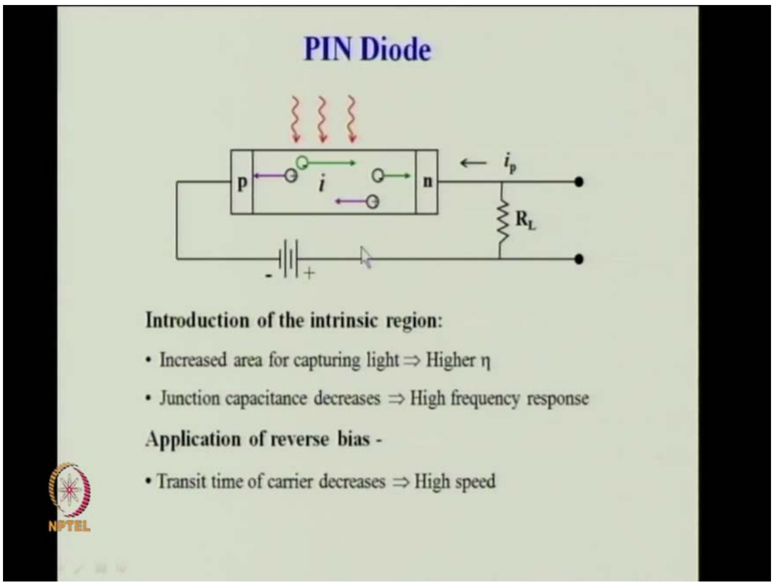


Recall that this is the junction region p n, this is the depletion region here. So, we have plenty of this is the p side plenty of immobile ions negative ions here and plenty of positive immobile ions here and this is the region now I am discussing. So, we have applied a reverse bias like this. So, this region which is righted the junction is denoted as the region number one, for away from the junction these regions are called three for away from the junction. And those which are in the vicinity of this depletion between depletion region and this one and three this is denoted as two.

I hope it is clear now the electron hole pairs which are generated here, because of a potential difference which is built like this the potential difference. The electrons tend to move to this side, why because of the potential difference. Therefore, this region is called drift region because, there is a potential difference here and therefore, this is drifting drifting under the influence of a field, diffusion is because of concentration difference of the carriers. And that is why this region is called diffusion region because, here you have large number of holes, but very little concentration of electron. Therefore, the electrons which are generated here would tend like to migrate here by diffusion.

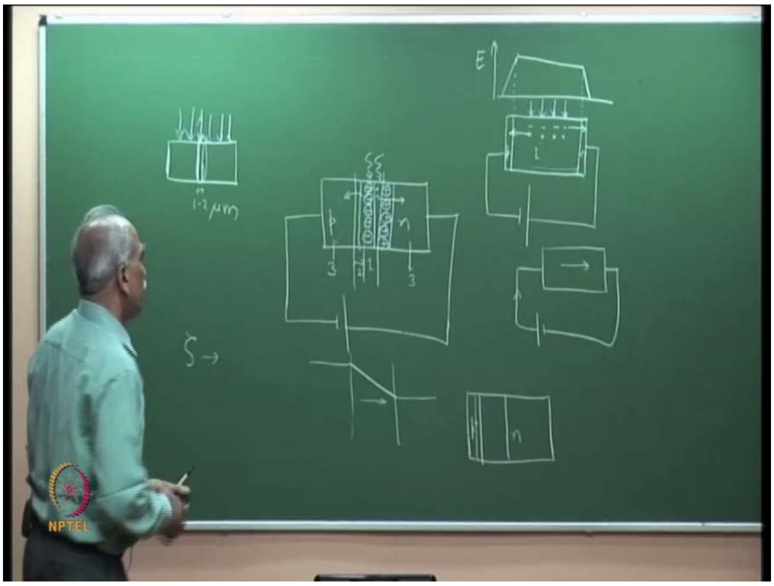
So, diffusion region and drift region and for away from the region a away from the depletion region where there is no field there is a potential, but there is no field. That is d v by d x is the field there is no change in the potential there, it is flat as you can see the potential energy is flat. And therefore, there is no field, field is only at the junction region therefore, this is the drift region. And so, what you see is those carriers which are generated for away from the junction region or not swept away by any applied field. Those who are generated in the diffusion region or swept away, because of the field presence of the field and in addition the second mechanism which is there is diffusion here. In the second region electrons moving to this side, because of concentration difference electrons moving to this side, because of the drift. I hope the this clear.

(Refer Slide Time: 09:06)



So, let us see more carefully the next slide. If we see the next slide then now, we have shown a pin diode. Why do we go for pin diode? I come back to this in a minute, let me show the diagram again. Carriers moving in side this region, inside the semiconductor carriers moving, that is electron moving in this direction, hole moving in this direction, constitutes a current in the external circuit in the external circuit.

(Refer Slide Time: 09:47)



When as I discussed in an earlier class, the when carriers move inside a semiconductor that results in a current in the external circuit. In the external circuit there is a current because, carriers are moving inside the semiconductor. So, carriers moving in this region here constitutes a current in the external circuit, carriers are not moving drifting in this region, they are wander in randomly because, there is no electric field. And therefore, these do not contribute to the current in the external circuit. Please remember in the definition of eta we had a we had a parameters zeta, which I said that it has two components. One is not all photons absorbed will generate carriers, the second component was not all generated carriers will contribute to the current in the external circuit, they may recombine again.

So, this regions do not contribute to the current in the external circuit. Therefore, the photons absorbed in the active region here leading to the generation of carriers, which are swept to opposite side here constitute a current in the external circuit. Which means it is the region one that is important, it is the region one which is primarily contributing to the current in the external circuit. If that is so, we would like to increase the width of that region because, light has to be captured. If you take a p-n junction like this, if you take at actual dimension you know that the depletion region here is very small it is just to 1 to 2 micron. So, this is 1 to 2 micro meter, which means out of all the places where light is incident, only this is the region which is primarily contributing to the current. Therefore can we increase that region, so that there is more capture area can we have a larger capture area and that is the region why we went to PIN structures.

So, we come to PIN. So, instead of a simple p-n junction now we have a p, p doped region an intrinsic region are very lightly doped region and n PIN. You can see in this schematic diagram that the width of the p region is very small, width of the n region is very small, it is the high region which has a large width. So, because light captured in this region what happens if you make a PIN structure, you make a thin p here is the i and this is n. And now, we applied a reverse bias a strong reverse bias, the entire i region entire i region in acts like a depletion region. Because, in this case you have depletion region only here, but in this case this entire i acts like a depletion region. Why because if you plot the field electric field here, the electric field will be will go up like this then it will remain almost constant up to this, you can find this because of a lack of time let me not going to this.

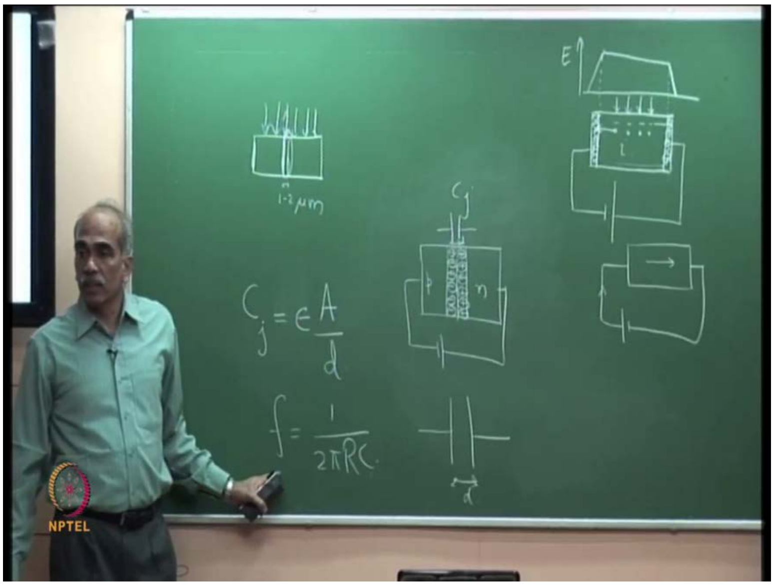
So, if you plot the electric field E, it would look like this. The entire i region as electric field because that is now depleted, the region is extended, you can those of you are not able to get a good picture see this if I take a p plus region here and in a n region. p plus region means highly doped p region and lightly doped n region, what is the width of the deletion region, here it will be very small here it will be very large. Because the width of the deletion region depends on the doping concentration, if the doping concentration is high width of the deletion region is small. So, the deletion region is extended up to this.

So, imagine instead of n doped if I put intrinsic the width of the deletion region will completely go over the entire region that is what is happening. When you have a high doped p region and an n region here and very lightly doped this one, the entire intrinsic region becomes like it depleted region. And therefore, now the area of capture is very high, light it is incident here in this region, all of this will create electron hole pairs. Is not just create, it was creating E 1 here, but they are under an applied field and therefore, immediately this end is negative. So, the holes immediately rush to this side and electrons rush to this side, drifting the carriers are drifting apart very rapidly because there is a strong electric field here. The carriers are swept in opposite directions very rapidly.

So, by introducing this i region two things have achieved; one there is a strong electric field in the entire region, point number one I have a large capture area for photons light incident to capture the light, which will contribute to current in external circuit, I have a large area. And second is there is a strong field which I can apply and the electrons and holes will be swept to both the sides very rapidly. So, see the points which are written there. So, introduction of the intrinsic region, increased area for capturing light this gives you higher quantum efficiency. Because, out of the total flux of photons incident, how many of them will create electron hole pairs that will contribute to the current in the external circuit, this will determine eta.

And therefore, now the capture area is large and in this large capture area whatever electron hole pairs are generated or contributing to the current. Because, they are immediately swept they are not recombining again because of the high electric field. So, they are immediately swept upend, so this leads to higher eta. Second the junction capacitance decreases this is also very important for has because we are interested in high speed photo detectors. Because, we are more interested in optical communication and this is now done at a very very high bit rates and then the detector should be able to detect signals which are coming at such high signal speeds.

(Refer Slide Time: 17:18)

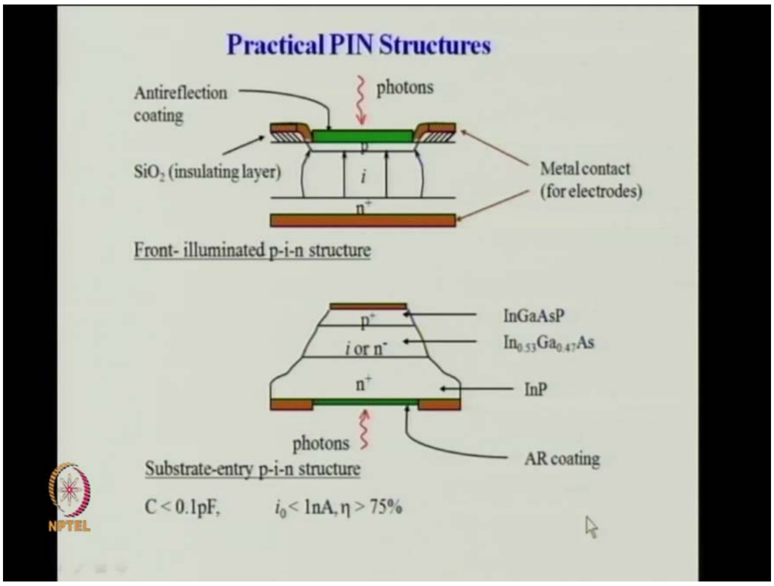


So, the junction capacitance should very small, please see if you take a normal diode and if you apply a reverse bias here. So, this is p side, this is n side have drawn this, but I am again drawing it. So, we have immobile ions here sitting so, this is now like a capacitance. So, this is responsible for junction capacitance C j, the junction capacitance of the diode, because of a reverse biased here these are causing. Even if you do not apply a reverse bias there is a there is a junction capacitance because of charge migration due to concentration difference. But now, when you apply a reverse bias there is in addition there is drift. So, it is there is a junction capacitance, what would what is the junction capacitance, in this case here you have to immobile ions are sitting here and the positive ions are sitting here.

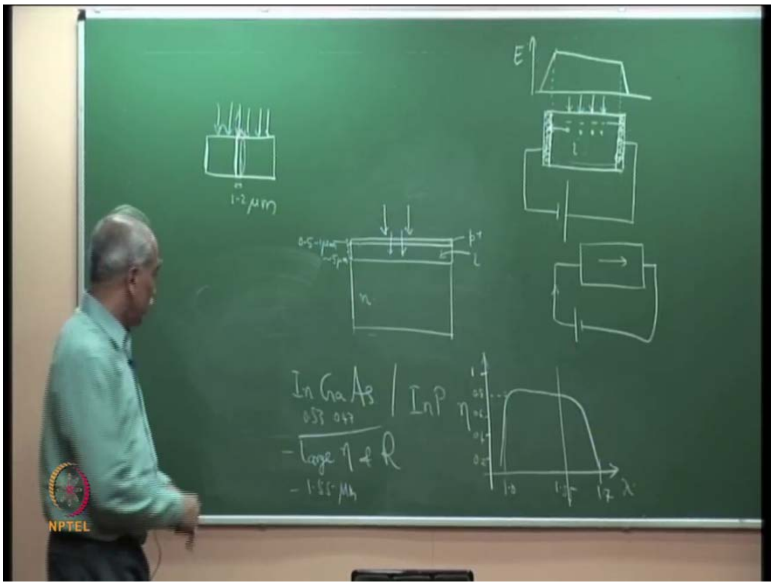
So, the separation between the plates it is like a plate with separation of d, you know that capacitance is proportional to area and inversely proportional to d, larger the separation smaller e C. So, by having a i region we have wider to this d, this is d. So, in a simple capacitor is separated, C is proportional to A by d or C is equal to epsilon into A by d. Where A is the area of the plates and d is the separation between the plates. By introducing an i region, again let me repeat one we have got a larger capture area for photons which will increase eta. Second the separation here that is a junction capacitance drops d has effectively become large which means the junction capacitance drops. If the junction capacitance comes down then the detectors will become very fast, we will see shortly.

That the frequency response is approximately 2 pi R into C and this C primarily comprises of the junction capacitance here C j, smaller the junction capacitance larger is the cut off frequency. And this is the second important advantage of using i and therefore, high frequency response these detectors are highest frequency, high high speed devices. Application of a reverse bias the transit time of carriers decreases because of high speed, you can you are applying now a reverse bias. And therefore, everywhere there is electric field and the carriers are immediately swept a part which means a transit time decreases. If we discuss the impulse response of a general semiconductors, you know that the transit time decreases by application of an electric field.

(Refer Slide Time: 20:55)



(Refer Slide Time: 21:39)



Let us go to the next slide this shows these are the normally schematics in practice, when you take a semiconductor you cannot take a piece of semiconductor and eliminate it from slides. In an practical situation it is a chip, is a semiconductor substrate on which you have to grow the detectors. And so, what is done here is you can see there are two different configurations which are shown. So, you have an n substrate here and there is an i region which is deposited and then a thin p plus region here it is a PIN structure. So, basically you have a substrate on which you deposit an n or i region here. So, this is the i region all you could start with an intrinsic substrate and have regions deposited on both the sides and then you deposit a thin layer here.

So, generally the thicknesses involved are these are very small 0.521 micro meter and these are a few micro meter of the order of 5 micro meter. If you remember in the in one of the earlier classes we had calculated the thickness of the semiconductor required for 90 percent absorption it was just 1 micron, 1 or 2 micron is sufficient to absorbed almost 90 percent depending on the absorption coefficient. And therefore, typically the i region as a thickness of few microns several microns and you have a p plus region here on top and this is the i and then this is n region and the electrode contract. Light is incident from the top and because this layer is very thin the incident light literally penetrates into this region. This is a very thin layer may be 0.1 micron, I have written 0.521 it could be very small, very thin region.

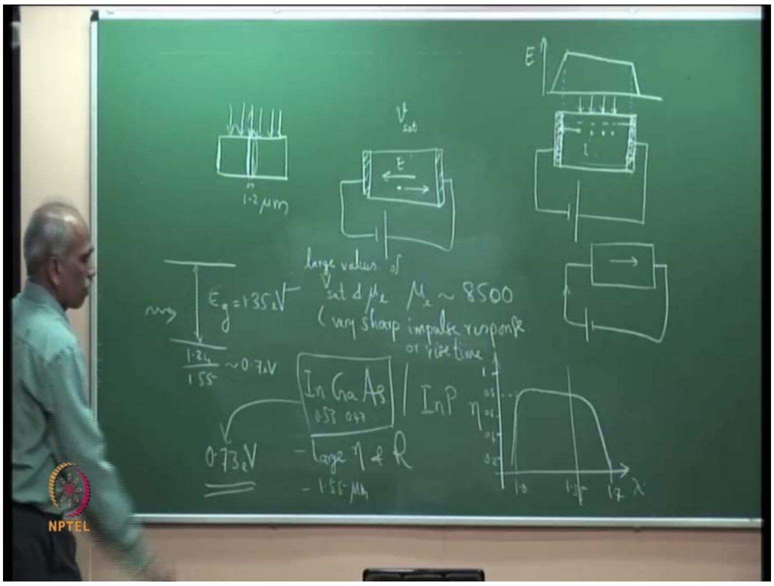
Because, we want all the light to get absorbed here in a practical structure the layers are grown epitaxially and the detector the light is incident from the top, which means when light enters this is an penetrates in this region we would like it to be absorbed. On that is why you can see the practical structure that it shown PIN and n plus contact. And always we have seen laser diodes and photo detectors always there is a glass window which is a or anti reflection coating. So, that light enters through the window and does in get reflected. The need for anti reflection coating we have discussed factor 1 minus r to maximize in the factor 1 minus r or the reflectivity should be 0.

There is another structure which is shown here and a materials used as you can see indium gallium arsenate phospide, indium gallium arsenate. This is most widely used material, indium gallium arsenate for several reasons there are many reasons we will see shortly. So, in almost all optical communication we use the photo detector used is indium gallium arsenate, we know why this composition. The composition is because this is lattice matched to indium phospide and lattice matching is very very important in the case of detectors. Because, there should not be any both in detectors and in sources you want to have very little defects, defects should be minimum, so that the component zeta is very large.

Otherwise they the detect will be act as a recombination centers which means a carriers cannot contribute to the current current in the external circuit. So, eta will go down. So, indium gallium arsenate has a several reasons, at another reason is we will discuss this I will show you the responsivity curve. If you see the eta for indium gallium arsenate because, the material appears I thought I will explain it here, it is typically like this goes from approximately 1.7. So, what I have plotted is eta quantum efficiency to approximately 1 micron meter 1 to 1.7, this is lambda versus eta and the numbers here are eta is one here. So, it is about 80 percent goes to about 0.8 and 0.4, 0.6, 0.2.

So, very high quantum efficiency eta is very high if eta is very high responsivity is also very high. We will see some numbers that is very large responsivity. So, why use indium gallium arsenate phospide, one of the reasons is large responsivity large eta and responsivity, large values. Second why use in optical communication is very clear because our low loss window is here, optical communication is around 1.55 micro meter, you see the response is flat and very good response. So, that is a second reason that optical communication is in this window where this is one of the finalist detectors.

(Refer Slide Time: 26:53)



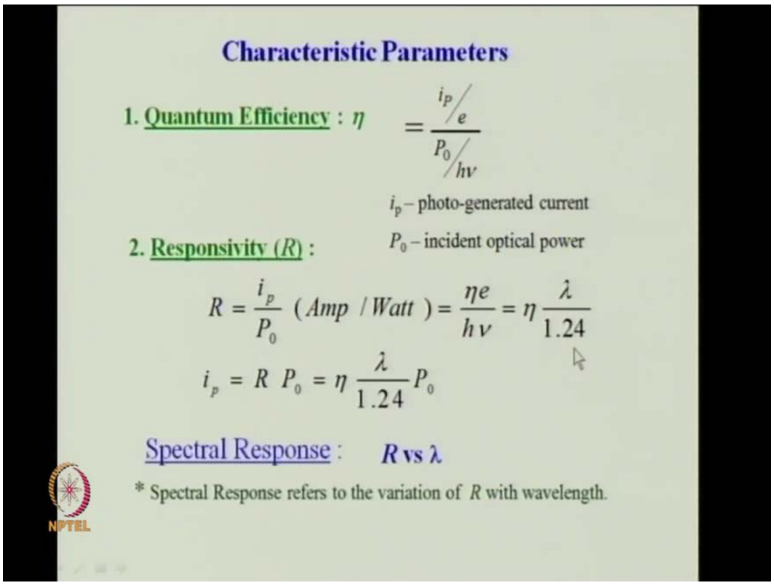
There are more reasons let me also discussed briefly, this material also has a very large V saturation. V saturation means if you take the material an apply an electric field here so, you apply a field. So, there is an electric field here E in this direction, a carrier electron let us say electron or hole a electron is getting accelerated towers this. V sat here refers to the velocity, saturation velocity of carriers in the presence of an applied electric field, the saturation velocity can be very large in the case of indium gallium arsenate. So, indium gallium arsenate as a very large V sat, which means the mobility and the mobility values are very high. I do not have the number I think the mobility mu E, mobility is about 8500 units, I will give you in a later this one.

But a third reason is large values of V sat, large values of saturation velocity and mobility mu E and mobility, which means the transit time is minimized. And therefore, the impulse response is very narrow in the case of indium gallium arsenate detectors. So, large values of eta and are optical communication window and large values of mobility and V sat therefore, very small, very sharp impulse response or rise time impulse response or rise time or rise time. Let me comeback from this to the structure here, as you can see this is grown on indium phospide, just now I had written on indium phospide. Thus because, substrate is normally a binary component either gallium arsenate or indium phospide. So, on a binary compound you grow the alloy. So, you can see you start with the substrate here n plus and here is the gallium arsenate phospide and then comes indium gallium arsenate phospide.

So, light enters from here these are typically the detectors used in optical communication indium light enters from here, but this substrate is thick 50 microns 60 micron. But does not absorbed absorbed because, optical communication is said 1.55 micro meter and indium phospide has a band gap of indium phospide as a band gap E g equal to 1.35 e V. And optical communication is said 1.55, which means what is the E g corresponding band gap is very small 1.24 by 1.55. So, this is of the order of 0.7 e V.

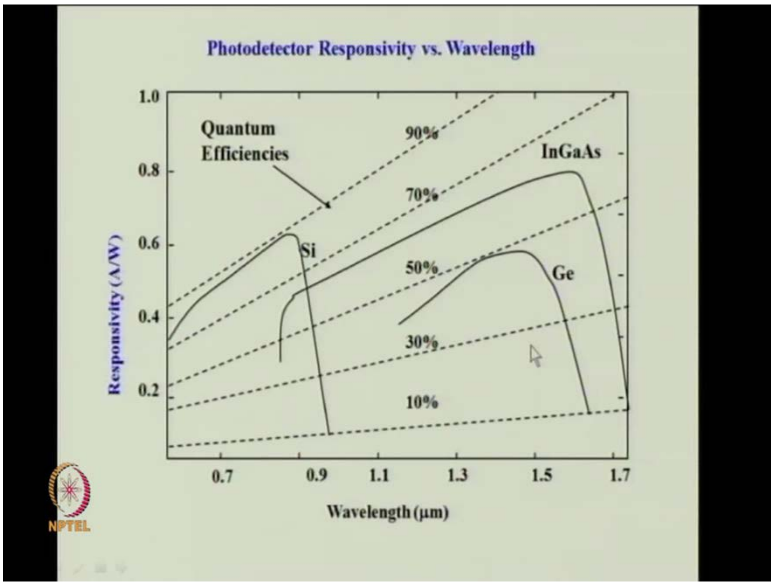
So, if photons are coming at 0.7 e V there not going to get absorbed in indium phospide. So, as for as light at optical communication is concerned indium phospide is transparent and therefore, this is called substrate-entry p-i-n structure. So, light enters from here and gets absorbed in this region indium gallium arsenate phospide which has a band gap of about 0.74 so, this as a band gap 0.73 e V. So, it gets absorbed here and then leads to carrier generation and high speed detection. Typical values of eta are given typical junction capacitance is 0.1 pico fared very small junction capacitance. Let me go further.

(Refer Slide Time: 31:08)



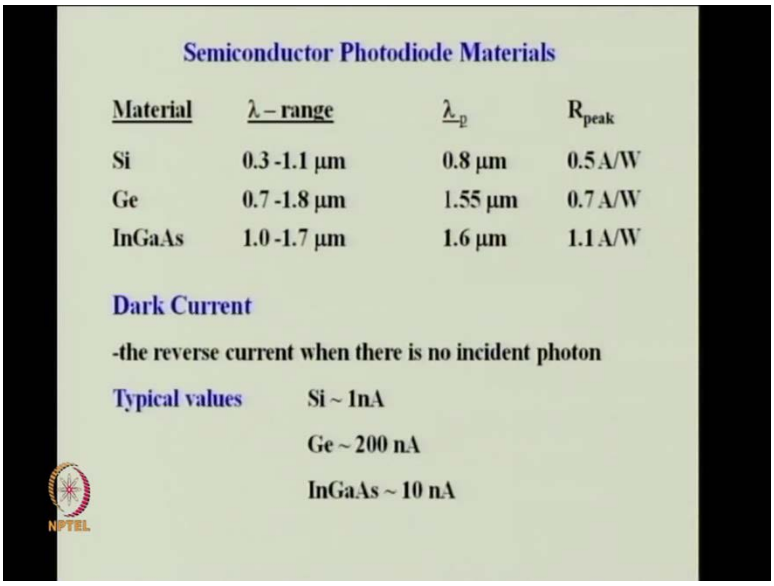
So, here are the characteristic parameters we discussed in one of the earlier classes quantum efficiency eta is i p by e by this. And therefore, responsivity R is equal to i p by P 0 which is given by eta into lambda divided by 1.24, we have already derived this. Therefore, given a material photo detector with a responsivity R, the photo current corresponding to an incident optical power P can be determined. The spectral response of a photo detector is nothing but the responsivity versus wavelength, spectral response refers to responsivity versus wavelength.

(Refer Slide Time: 31:55)



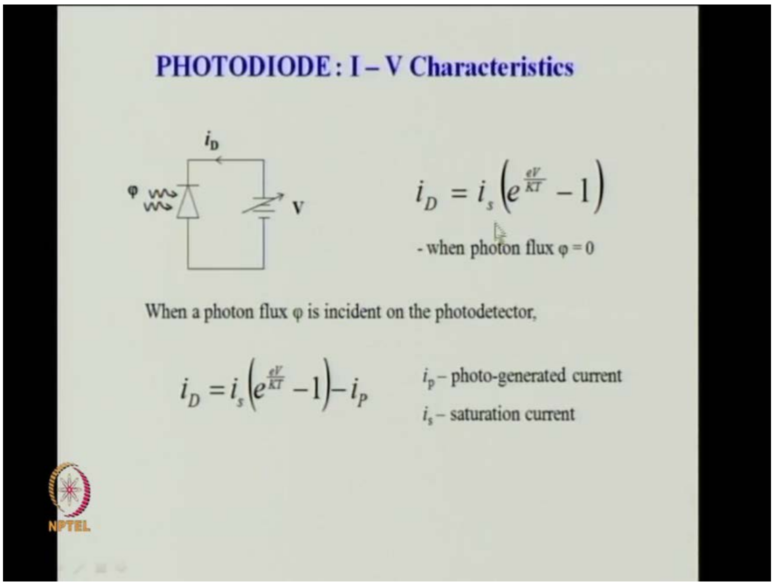
So, here are the typical responsivity of some of the photo detectors you can see silicon the dotted line corresponds to constant value of eta. So, indium gallium arsenate you can see has efficiency this particular material here has efficiency of about 70 percent everywhere almost touching this line everywhere. But the interesting part is you say it is almost flat that is 70 percent here. Silicon goes from about 1 micron or up to 1.1 it has a very good responsivity, but it is in this region, but for optical communication either you can use germanium or indium gallium arsenate. But for all the reasons that I have specified one would prefer indium gallium arsenate. These are the most important materials, the three materials which are most important are silicon, germanium and indium gallium arsenate.

(Refer Slide Time: 33:00)



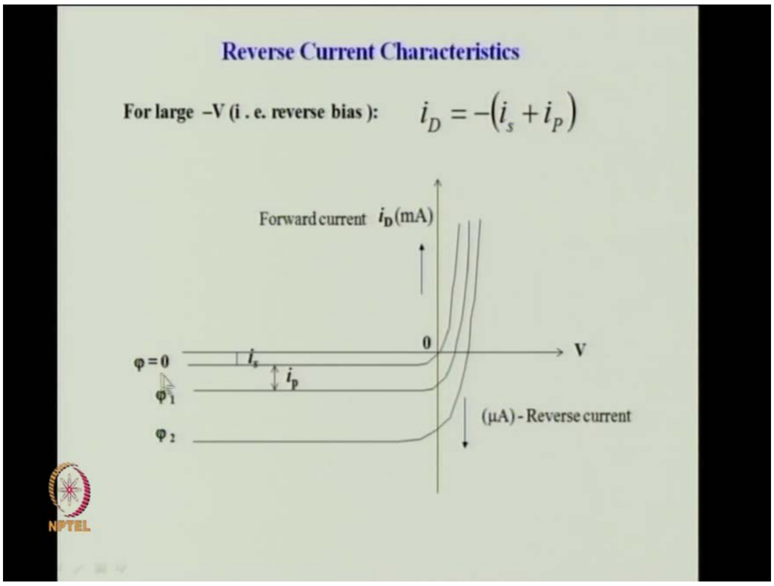
Semiconductor photodiode materials; Again this is what I have already mentioned the wavelength range, peak responsivity is about 0.5 amperes per watt for silicon. You can see again for indium gallium arsenate it is 1.1 amperes per watt, it is a very good responsivity. The dark currents again some numbers here silicon has typically dark current, dark current refers to the reverse current when there is no light incident on the detector. So, it is primarily due to thermally generated carriers and the numbers germanium is alright for 1.55, but you see the dark current is very large, large dark current will lead to a large noise power in the system. And therefore, usually one prefers indium gallium arsenate of course, silicon is a very good detector better than indium gallium arsenate, but it will not work in the optical communication window.

(Refer Slide Time: 34:07)



We move further to photodiode characteristics, typical I – V characteristics all of you are familiar the diode current is given by an equation of this sort. Where V is the applied potential difference K T is the same Boltzmann constant, K and temperature, i s is the reverse saturation current. This is the normal diode equation without having any photo current, in the presence of a photo current the equation is modified like this i D is equal to i s into this minus i p. Because, the photo generated current is a reverse current and therefore, it is minus i p. i p is the photo generated current, i s is the saturated saturation current.

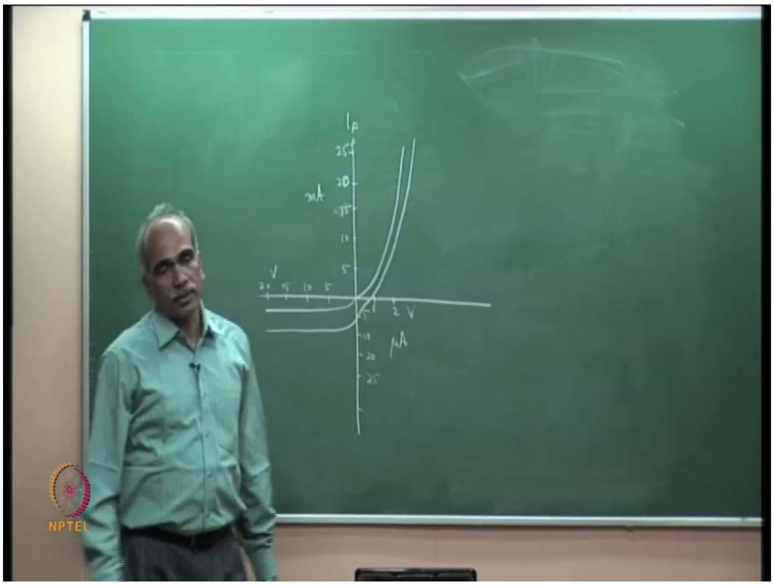
(Refer Slide Time: 34:56)



The picture will become clear when you see the characteristic here the familiar diode characteristic. The forward characteristic here V versus i forward characteristic and reverse characteristic V versus i. There is one difference though the scales are different the reverse currents are in micro ampere. So, you can see it is indicated the reverse current is micro ampere and this scale here is in mile ampere what tends of mile ampere. So, the reverse current is of course, small compare to the forward current. One important point that we see is normal diode is this forward and reverse because, there is no light incident. phi is equal to 0, phi is the photon flux phi is the photon flux and there is no photon flux incident we look at the normal diode.

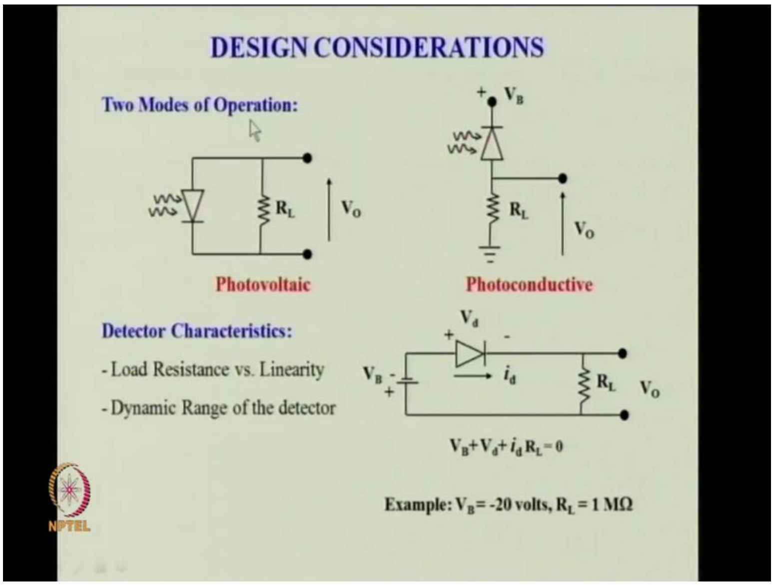
In the presence of a photon flux in addition to the thermally generated dark current or reverse current, we also have photo generated reverse current. That is reverse current generated due to light and that reverse current adds to the minority carrier dark current and gives you the total current. And therefore, the photo detector characteristic will have different saturation current values the total saturation will comprise of i s when there is no photon flux, phi is equal to 0 plus i p due to the presence of a photon flux.

(Refer Slide Time: 36:39)



So, if you plot for a particular. So, what is plotted here is our normal characteristic is like this here and again recall that numbers are here micro amperes may be 5, 10, 20, 25 micro amperes. And here we are talking of mile amperes so, 5, 10, 20, 25 micro amperes 15, 20, 25. So, this the forward current i f here and the voltages this saturation takes place when the voltages typical numbers, I am just plotting 5, 10, 15, 20 volts. And the forward just may be 1 volt, 2 volt so, this is 1 volt, this is 2 volt. Even when you apply about 2 volts already tens of mile amperes are may be 50 mile ampere current. So, the scales are different, but the shapes are just. So, this is the normal diode characteristic which we are familiar, but if you apply a photon current in the presence of a photon flux we have additional. So, you will have a characteristic normally like this the saturation value changes to i s plus i p, had shown here the reverse current for large values of V here minus V this is reverse, large values of minus V the diode current is minus i s plus i p.

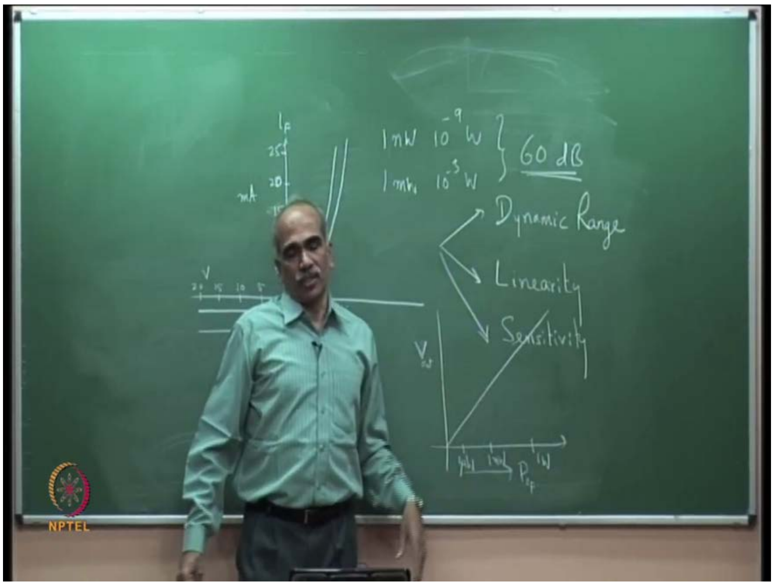
(Refer Slide Time: 38:27)



Let us go further, a little bit of detector and design cons. There are two considerations which are used in photo diode operation, whenever one users photo diode two modes of operation. One is called photovoltaic mode of operation here, which means this is the photodiode, incident light generates a reverse photo current, which passes through a resistance, you measure the voltage across the resistance that is the load resistance. So, this is photovoltaic, the incident photon flux generates an voltage across a resistance hence, a name photovoltaic. And the second one is photo conductive that is you already have a applied reverse bias here and when the photon flux is incident there is additional carrier flowing. Which means there is an additional current which is passing through this, which means the device becomes more conductive in this case this device here becomes more conductive due to the incident photon flux and hence the name photoconductive mode of operation.

Photovoltaic no external bias is apply photo conductive you apply a reverse bias, it is ready with a reverse bias. The incident photon flux increases the conductivity hence, the name photo conducting. You can imagine that immediately that the photo conductive mode of operation is a high speed of mode operation because, there is a field which is already applied. So, the incident photon flux generates carriers which are immediately swept upon because, you have applied reverse bias. In this case there is no field and therefore, it will generate a current because, there is always a potential difference at the barrier, but this is a slower device, this is a faster device. And therefore, all high speed applications with special emphasis on optical communication are any signal processing it is the photo conductive mode of operation which is employed. So, let us just consider to a little bit of design considerations. So, the detector characteristics a detector characteristics are these are the two important detector characteristics if you plot load resistance versus linearity.

(Refer Slide Time: 41:03)

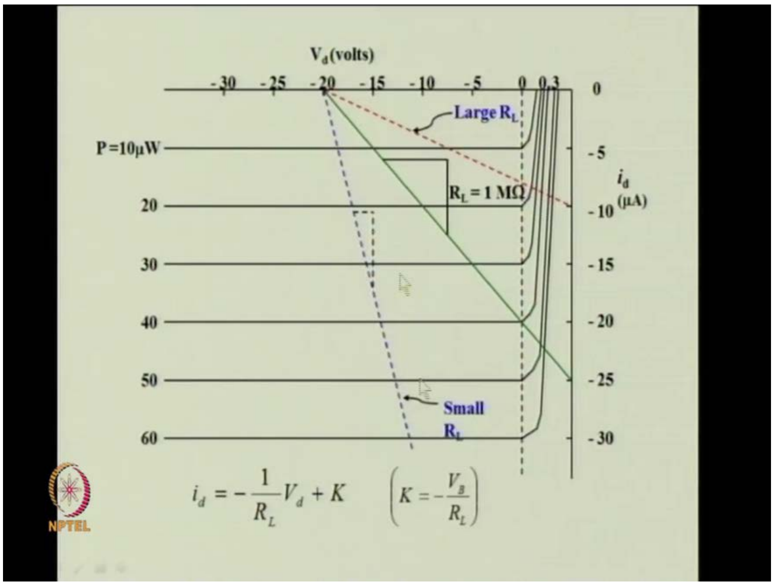


That is the detector requires two things; one is dynamic range, when you use a detector you looks for two aspects; one is dynamic range and linearity. What does linearity mean? Linearity means you have some output some output voltage some voltage output, which is coming from the detector. Electrical signal V out which you are measuring the load resistance, with optical power incident is optical power, this is detector output which is in the form of an electrical voltage let us say. Then if this continues linearly over a large voltage, large power range which means if I put one micro watt it is here, if I put one mile watt it is here, if I put one watt if it is still remaining linear the output voltage is all the while if it is remaining linear this is called linear characteristic. And this has a large dynamic range dynamic range refers to the useful range of measurement where the detector could be used.

The range of powers over which you can use the detector, if it remains linear to measure 1 nano watt and also 1 mile watt what is the dynamic range. From 1 nano watt to 1 mile watt, 1 nano watt is 10 to the power of minus 9 watt, one mile watt is 10 to the power minus 3 watt. What is the dynamic range is dynamic range is 60 dB. The dynamic range is 10 to the power of 6 minus 9 to minus 3 is 10 to the power of 6, 10 to the power of 6 is 60 dB, 10 to the power of 1 is 10 dB and 10 to the power of 6 is 60 dB. So, if you have if it you can go up to 1 watt this will become 90 dB dynamic range, most of the photo detectors when applied in the photo conductive mode of operation, you more it is advisable to see certain data sheets of photo detectors. You will see there will always give you dynamic range, dynamic range is typically this number 60 to 70 dB is the dynamic range of a photo detector.

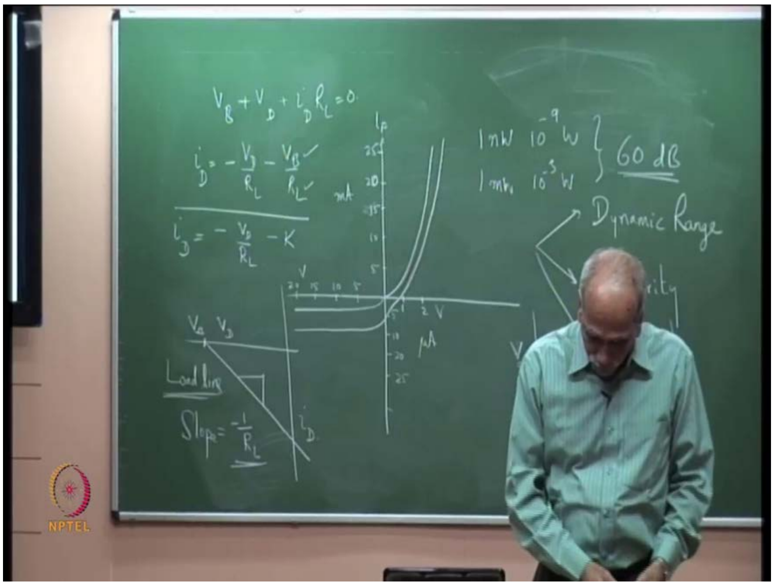
Typically anywhere from 50 to 70 dB is the dynamic range. What is linearity, over this region if the output voltage is proportional to the input power then you call the detector a linear. And of course, the there is a one more parameter that is sensitivity. We will discuss all these three issues in the design consideration. So, for the photo conductive consider the photo conductive mode of operation here, a reverse voltage is applied there is a load resistance R L. So, you apply the loop theorem for potential drops. So, V B minus voltage across plus voltage across the diode plus i d into R L, so if you consider this loop like this. So, V B plus V d plus i d into R L equal to 0, all the potential drops across around a loop is 0 in the loop theorem. So, if you take a typical example of V B reverse bias equal to minus 20 volt R L load resistor equal to 1 mega ohm.

(Refer Slide Time: 45:00)



Then the next graph I have shown of plot of these, plot of the reverse characteristic for different photon flux we shown here. For a particular photo detector what is shown is only the reverse part, the forward part is here this will continue above. I have not shown I have shown only this part the reverse part, forget about the forward and what is drawn here is the load line.

(Refer Slide Time: 45:35)



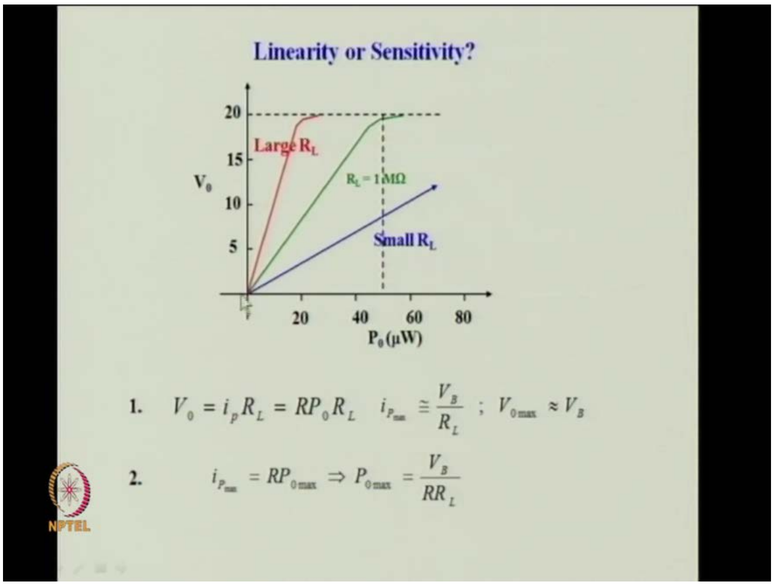
So, this is the load line how do we get the load line, if you see this here V B plus V B plus V D, V D is across the diode plus i D into R L equal to 0. So, you take to the other side. So, i D is equal to minus V D by R L V D by R L minus V B by R L. So, I said I take an example of V B equal to minus 20 volt and R L equal to 1 micro ohm, which means this is fixed. So, I have indicated this as some fixed number K, please see the text wait, so and this is minus V D by R L. So, what is this i D is equal to minus V D by R L. So, here is the graph V D is here, this is this axis here is V D across the diode and this axis here is the current i D. So, it is a V D versus i D is a straight line equation of a straight line y is equal to m x plus c. M is the slope is minus 1 by R L, so that is the load line.

So, it is a straight line equation of a straight line. So, this goes like this it is start from V B why it start from V B, if you put i D is equal to 0 then V D by R L V D by R L equal to V B by R L. So, V D equal to V B therefore, this start from V B and it is a straight line goes like this. This is of course, elementary for those of you have done load lines in electronic circuits. So, the slope of this line here, so if you find out the slope this is minus 1 over I, so this is the load line. What I want you see is the following; so, here is the load line for a resistance of 1 megohm. If you increase the resistance to let us say 10 mega ohm the slope will be 1 by R L. So, R L is larger which means the slope is smaller this is the graph.

So, there is a dotted line which shows the slope the load line for a higher resistance and if the resistance is smaller this will be the load line, some smaller number then you can see this is the load line. What is the importance, let us look at our case that the case we have consider here. When the photon when the incident photon flux please understand this, when the incident photon flux is 10 micro watt come on this line here the load line tells you what is the voltage across the diode V D is here. If the incident photon flex is 20 micro watt, come here and you get what is V D here the intersection point here, will give you V D. Which means if I change the photon flux from 10 micro watt to 20 micro watt, please see this 10 micro watt to 20 micro watt, if I change the incident optical power from 10 micro watt to 20 micro watt the voltage across diode various from here to here like this.

This is delta V D the change in diode voltage for this change in optical power. If I change the incident optical power from 10 to 40 here, then I would get the corresponding V D is here. So, my V D will vary from about 15 here, minus 15 to 0 to variation is very large, which means the variation to the voltage diode voltage. Because, we are measuring the change in voltage the change in voltage due to change in photon flux is very large, but if I go from 40, let us say my incident photon flux was 40. Now, I increase it to 60 at 40 this is the V D which is 0 at 60 the load line intersects here and the V D is here, which is about 0.2 or 0.3 volt. The change in volt is very small what does this tell, this indicates that when light levels, incident light level is very small the changes are very large. In other wards this photo detector with this load line is very sensitive to change in optical power for small optical powers, incident small optical powers. But if the incident optical power is large it is output is fixed is not changing it is saturated.

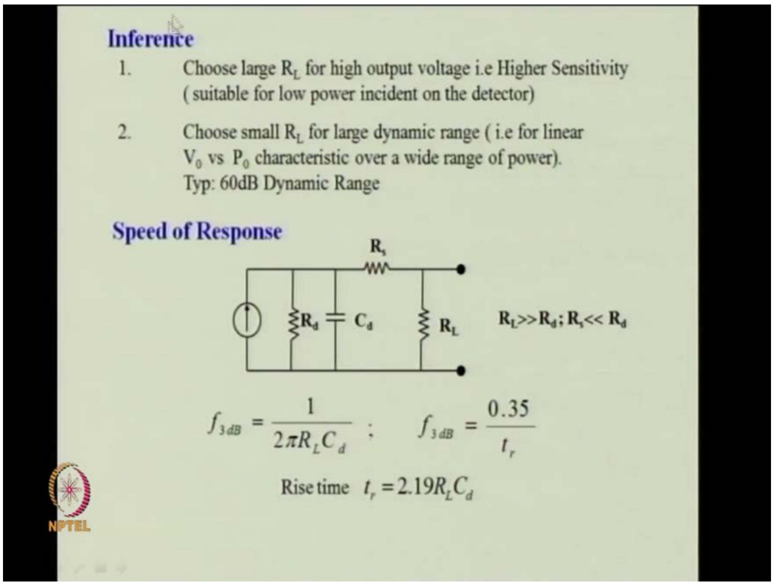
(Refer Slide Time: 50:53)



The picture will become clear if you see the next graph. So, if you see this second graph here what I have plotted is the same thing same optical power 10 micro watt, 20 micro watt same thing. So, if I change incident optical power from 0 to 20 micro watt the diode voltage goes from 0 to 15 or 17, 18 here. So, within 0 to 20 micro watt, the variation for R L for 1 mega ohm is very rapid here, very rapid change. But beyond 40 are here about 45, 50 you see this is saturated output is, means it is no more sensitive, it cannot go any beyond because why we have applied minus 20 volt. So, it cannot give more than 20 volt the diode bias is only 20 volt. So, it cannot give you any further and therefore, it is a very good detector if you are choice is 1 mega ohm then it is a very sensitive detector from 0 to 40 micro watt variation.

But beyond that it is simply saturated which means it will not be able to detect the variation of optical power beyond 40 or 50 micro meter. So, what is the meaning if the resistance is large, which it is a very sensitive detector, but the range of power that you can measure is very small. If I put a small resistance are I go back here this is the slope please see when I change from 20 to 30, let 20 V D somewhere here at 30 V D is somewhere here. This is small change here V D change in V D, when I change from 20 to 30, if I change from 40 to 50 then also it is the same. Because, this line continues on the linear characteristic, it has not saturated. And therefore, if you see the next graph or small R L this is continuing, this is linear even at 60 even at 80 it will not saturated it will continue like this. Means it as a large dynamic range, dynamic range refers to the useful range of measurement.

(Refer Slide Time: 53:23)

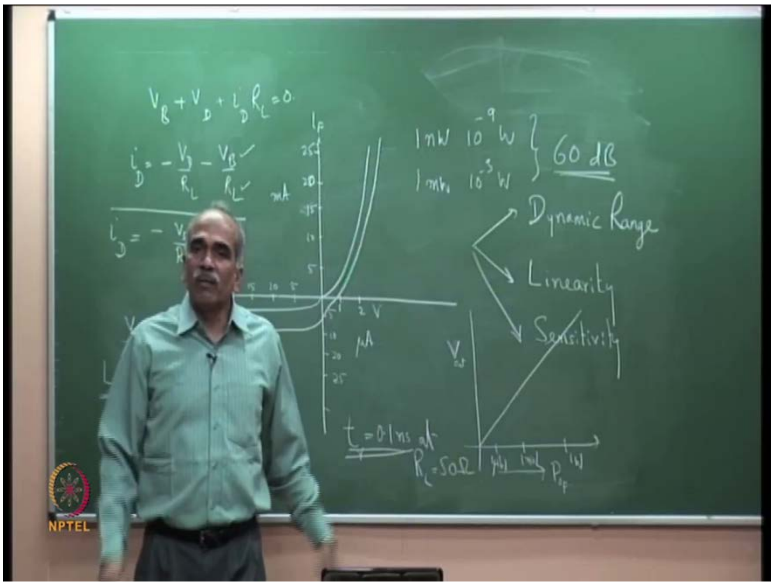


So, what is the summary of this discussion, summary is given here choose large R L value. So, that you get high output voltage or higher sensitivity if you want to measure low power incident. That is for small range of low power, why is this important for a designer engineer, you have an application where you need to measure very weak signal very low power. But you are all you are measurement are very low power only then I would put a large R L because, I need high sensitivity. But there may be another application like the power meter where you want to measure from 1 nano watt up to 10 mile watt, this will not work because it is already saturated. So, you have to takes small values of R L. So, with is example what I am illustrating is given a detector choice of R

L is very important, the choice of the load resistance will determine, the dynamic range of measurement.

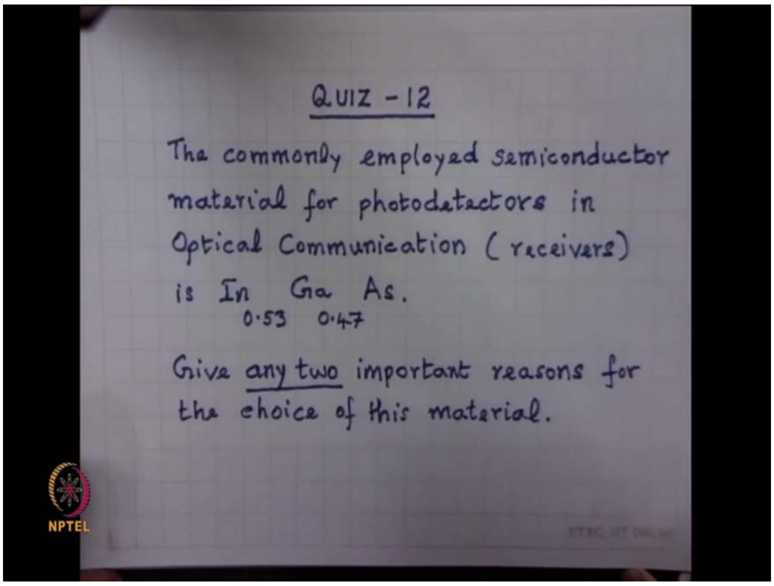
We will also see that the choice of R L would also determine the bandwidth of the detector, the speed of response or the frequency bandwidth is also determined by R L. So, how to choose R L for a given it depends on the application. So, depending on the application, you may be having an application where you are not change measuring very rapid changes, but you are almost measuring a d C at very low level. Which means large R L choose ten mega ohm is very good because, you will get a large output voltage. And you are not interested in bandwidth if you are interested in bandwidth 2 pi R L into C and if R L is large then your bandwidth is very small.

(Refer Slide Time: 55:18)



If you see any data sheet of a photo detector, they will specify rise time t r equal to 0.1 nano second. Typical example at R L is equal to 50 ohm, it will always be specified with the load resistance. When you put load resistance of 50 ohm that is the very small load resistance the rise time is 0.1 nano second is a high speed detector. So, just because if you read only up to this, and put one mega ohm with this detector, it will not have that bandwidth. The bandwidth will be very small because the bandwidth is given by 1 over 2 pi R L into C, so R L the choice of R L is very important. So, that is the objective of showing this graph. So, I have discussed about the dynamic range linearity and sensitivity. So, here are the conclusion let me read again, choose small R L for large dynamic range, that is for linear V 0 versus P 0 characteristics over a wide range of power, typically 60 dB dynamic range.

(Refer Slide Time: 56:45)



The next we take a simple quiz, quiz number 12 here, the commonly employed semiconductor material for photo detectors in optical communication receivers is indium gallium arsenate. Give any two important reasons for the choice of this material, why we choose this material, give any two important reasons for choosing indium gallium arsenate as detectors in optical communication. Only two minutes, please answer in two minutes. Very brief, no explanations are required.