Semiconductor Optoelectronics
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Lecture - 42
Semiconductor Photo-Diodes-I: PIN Diode

Okay, today we will discuss semiconductor photo diodes and in particular we will discuss about pin diodes. So, semiconductor photo diodes.

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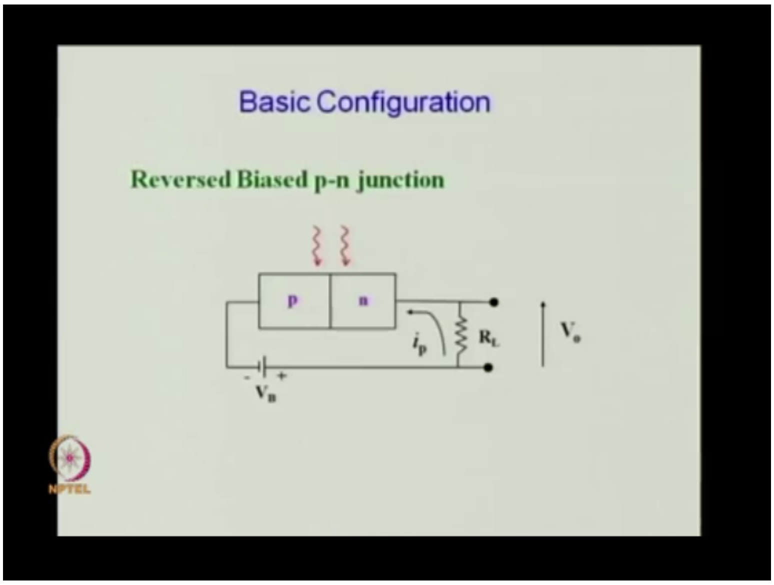

The basic configuration is a reverse biased p-n junction. We will see, why it is reversed biased. It is a reversed biased p-n junction. So, as you can see there is a p-n junction here and a load resistance and this is the bias supply here and output is measured here .

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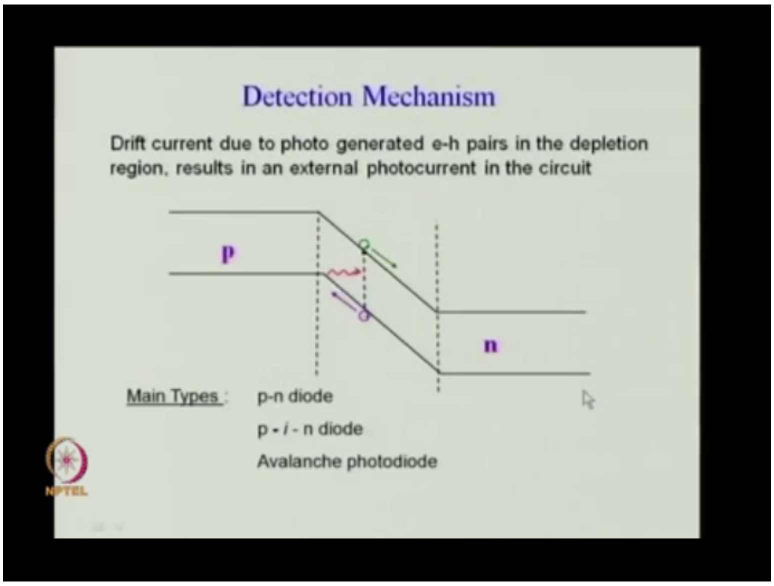

The deduction mechanism is illustrated here and incident photon in the active region, we will discuss what happens in the photons incident in other regions. But, an incident photon in the active region generates an electron hole pair p-h pair here and in this biased region, there is a potential region built 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 reversed biased and therefore the carriers are swept apart.

The carriers are swept apart immediately and that gives the reverse photo current. This is unlike the forward current of a diode where electrons are injected to the p side. In this case, as you can see, electrons go towards the n side and the reverse bias sweeps away the carriers resulting in a reverse photo current, I p is a reverse current.

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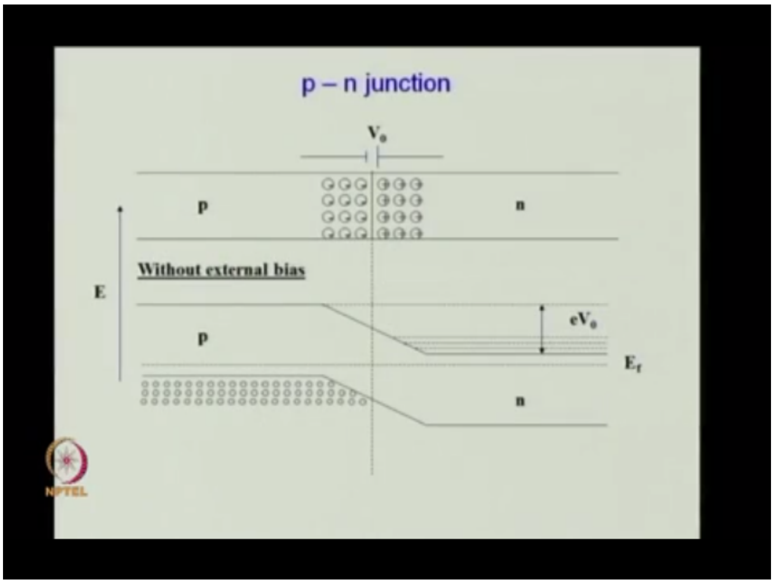

The p-n junction here, just to recall very quickly, we are seeing these in detail without any external bias a p-n junction is shown here. Plenty of electrons on the n side and plenty of holes on the p side and in any common region there is a no region where you have simultaneously plenty of electrons and holes.

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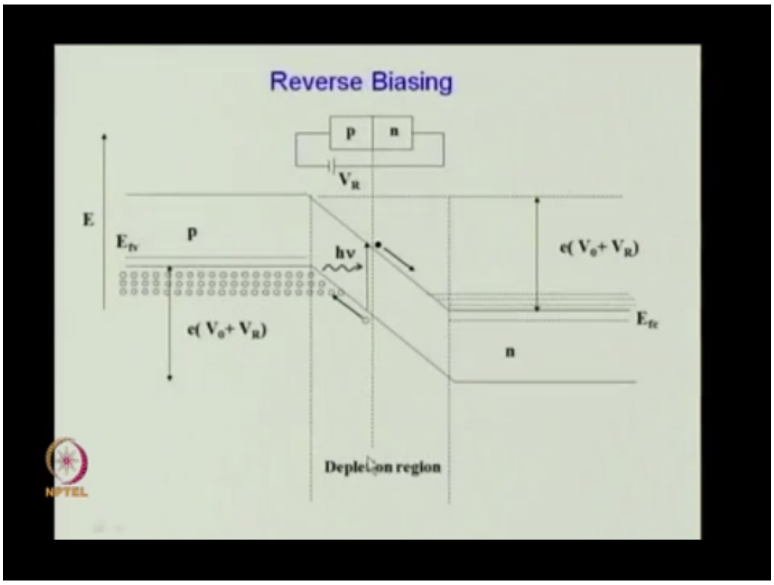

If you reverse bias the potential barrier increases, the height of the barrier increases, you can see here. Earlier it was e times V0, where V0 was the built in potential. Now it is e times V0+VR. E times because as you can see this is the energy axis and therefore, the built in potential is e times V0+VR. The slope is steeper now and therefore an electron as we discussed in the early part of the course can be imagined as water droplet. It rushes down here, down the slope and reaches this side. That is the n side.

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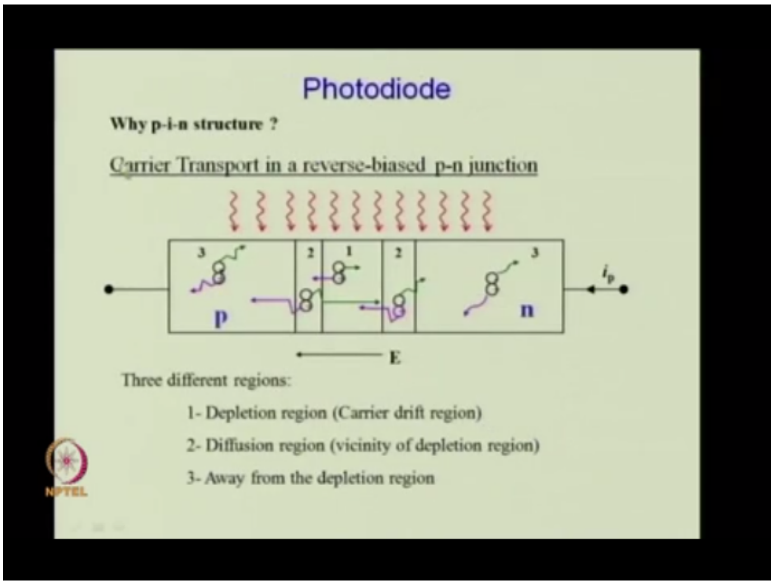

Then, why do we use p-i-n structures. Almost all detectors which are used in high speed applications are p-i-n photo diodes and why we go for a p-i-n structure? There are several reasons. So, let us just look at the carrier transport in a reverse biased p-n junction. So, this is the p-n junction p side n side. Assume that light is incident all over the p-n junction, this is p-n junction, all over the p-n junction and this is the junction region here. This is right now, this is not p-i-n, 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 freely wander around and they may recombine as well. But, the electrons which are incident in the active region or the depletion region, they, because of a potential there, 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 3 regions, the first region is the depletion region, where there is a potential difference between the p side and n side, 2 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 plenty of holes and therefore electrons tend to diffuse to 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 far away from the junction there is no electric field and this is called diffusion region.

Region number 2 is the diffusion region. If you find it difficult, we can draw it on the board and see this recall.

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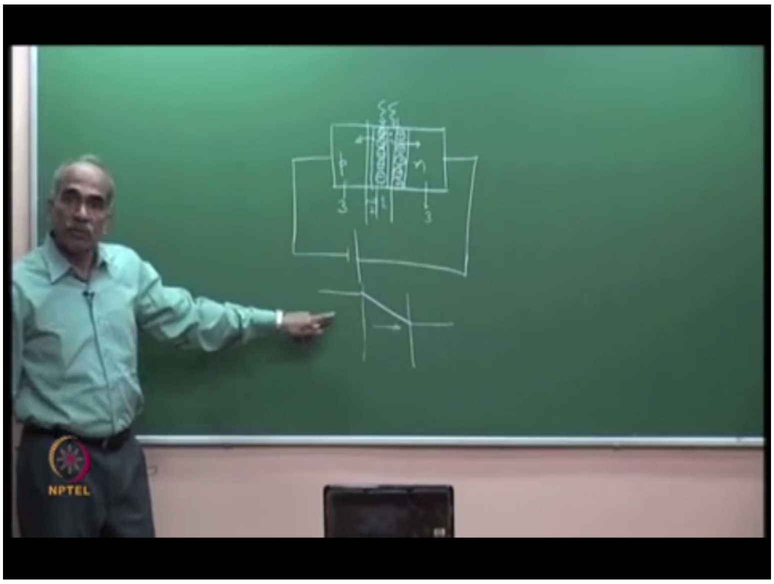

This is the junction region p n, this is the depletion region here. So, we have plenty of, this is the p side, plenty of immobile negative ions here and plenty of positive immobile ions here and this is the region now I am discussing. So, we have applied a reverse bias like this. So, this region, which is right at the junction is denoted as region number one. Far away from the junction, these regions are called 3, far away from the junction.

And those which are in the vicinity between depletion region and this one and 3, this is denoted as 2. 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 electrons. Therefore, the electrons which are generated here would like to migrate here by diffusion. So, diffusion region and drift region and far away from the region away from the depletion region where there is no field. There is a potential but there is no field that is dv/dx 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.

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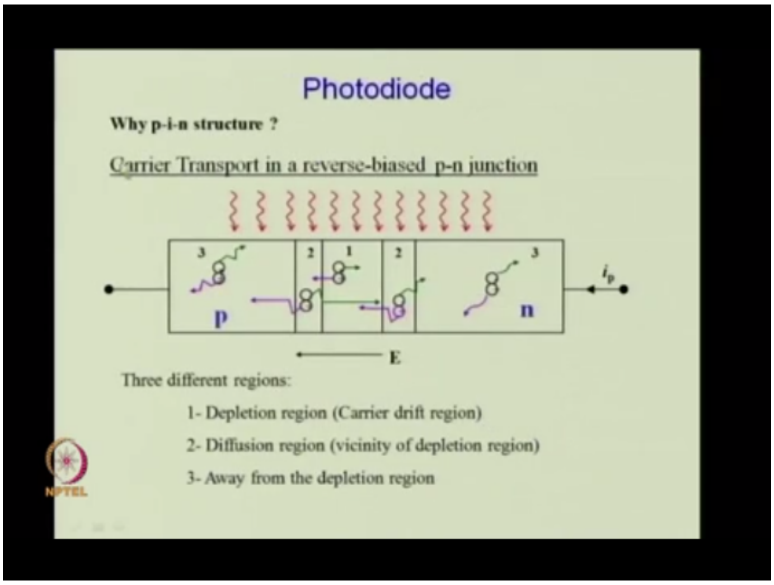

And what you see is, those carriers which are generated far away from the junction region are not swept away by any applied field. Those who are generated in the diffusion region are swept away because of the field, presence of the field. And in addition, the second mechanism which is there is diffusion 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 that is clear.

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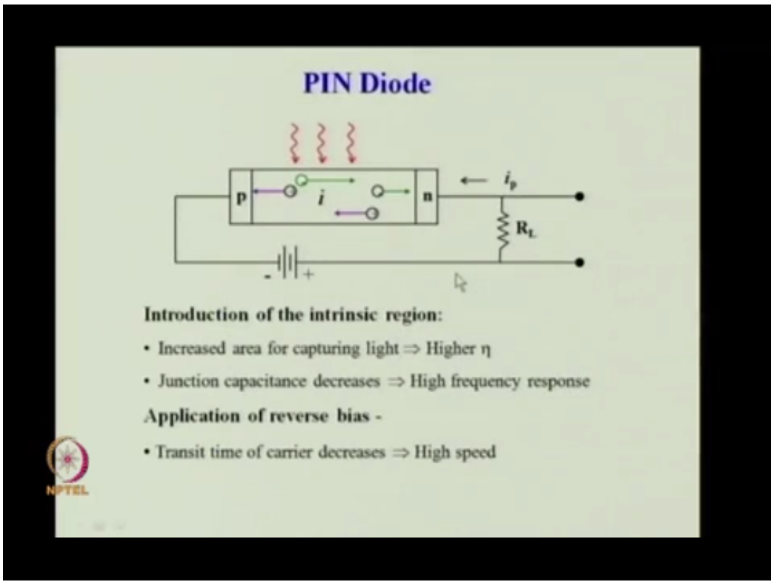

So, let us see more carefully the next slide. If we see the next slide, then now we have shown a PIN diode. Why do we go for PIN diode? I come back to this in a minute. Let me show the diagram again.

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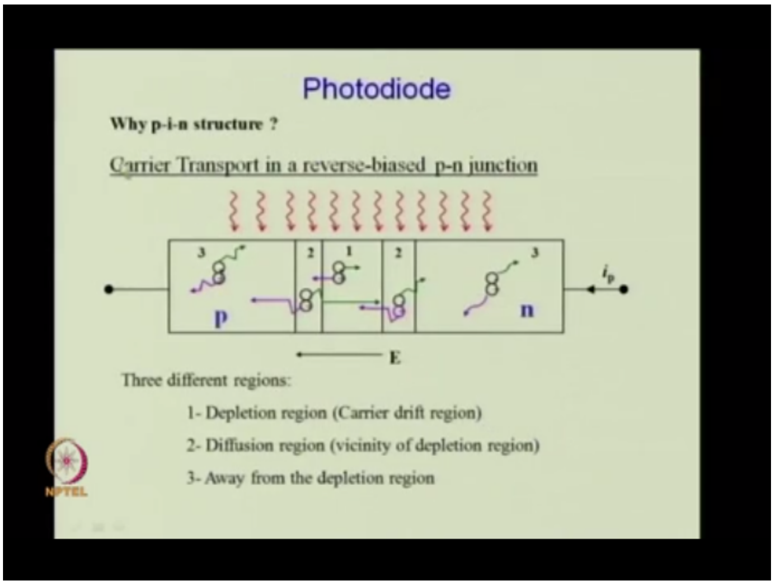

Carriers moving inside this region, inside the semi conductor carriers moving, that is electron moving in this direction hole moving in this direction constitutes a current in the external circuit. When? As I discussed.

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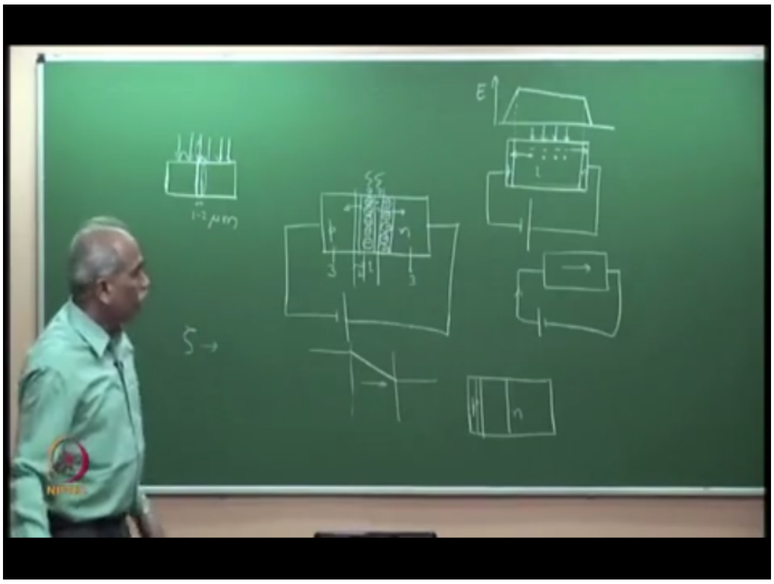

In an earlier class that when carriers move inside a semi conductor, that results in a current in the external circuit. In the external circuit, there is a current. Because, carriers are moving inside the semi conductor. So, carriers moving in this region here constitutes a current in the external circuit. Carriers are not moving drifting in this region, they are wandering 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 parameter zeta, which I said that it has 2 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 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 one to 2 micron. This is one to 2 micrometer, 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 reason why we went to p-i-n structures. So, we come to p-i-n.

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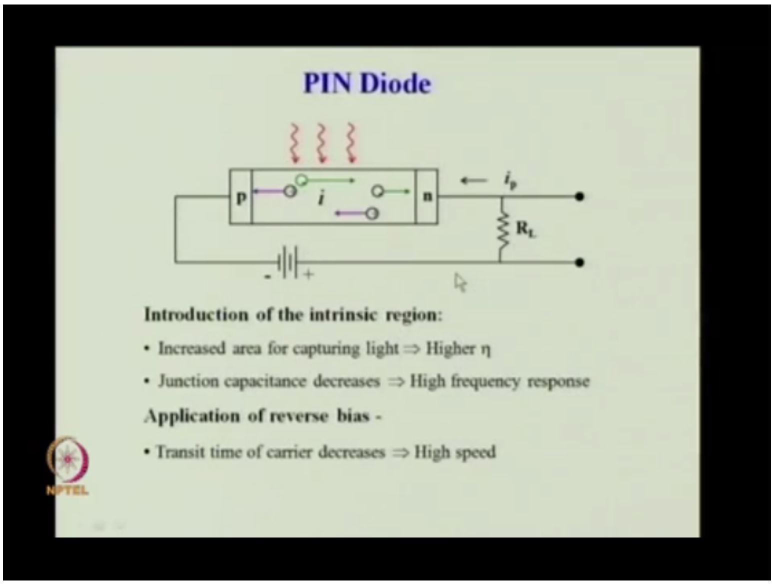

So, instead of a simple p-n junction, now we have a p, p doped region an intrinsic region or very lightly doped region and n, P-I-N. you can see in this schematic diagram, that the width of the p region is very small, width of the n region is very small, it is the i region which has a large width. So, because light captured in this region, what happens if you make a p-i-n structure. You make a thin p, here is the i and this is n. And now you apply a reverse bias, a strong reverse bias.

The entire i region 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 electric field here, the electric field will go up like this, then it will remain almost constant up to this, you can find this because of lack of time, let me not go into this. So, if you plot the electric field E, it would look like this. The entire I region has electric field.

Because that is now depleted, the region is extended, those of you were not able to get a good picture, see this, if I take a p+ region here, and an n region. P+ region means highly doped p region and lightly doped n region. What is the width of the depletion region? Here it will very small, here, it will be very large. Because the width of the depletion region depends on the doping concentration. If the doping concentration is high, width of the depletion region is small. So, the depletion region is extended up to this.

So, imagine instead of n doped, if I put intrinsic, the width of the depletion 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 a depleted region. And therefore, now the area of capture is very high. Light, which is incident here in this region, all of these will create electron hole pairs.

This not just creates, create, it was creating even 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, 2 things I 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 the 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 are 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 apart. So, this leads to higher eta.

Second, the junction capacitance decreases, this is also very important for us because we are interested in high speed photo detectors. Because we are more interested in optical communication and this is now done at very, very high bit rates and then the detector should be able to detect signals which are coming at such high signal speeds. So, the junction capacitance should be 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. I 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 the junction capacitance cj, the junction capacitance of the diode because of a reverse bias here. These are causing. Even if you do not apply a reverse bias, 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, this is as a junction capacitance. What is the junction capacitance in this case?

Here, you have the 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 is c. So, by having a i region, we have widened this d, this is d. So, in a simple capacitor, we have separated.

C is proportional to A/d or c=epsilon*A/d, where A is the area of the plates and d is the separation between them. 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 the junction capacitance drops, d has effectively become large, which means the junction capacitance drops. If the junction capacitance comes down, then the detector will become very fast.

We will see shortly that the frequency response is approximately 2 pi R*c and this c primarily comprises of the junction capacitance here cj. 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 high frequency high speed devices. Application of a reverse bias, the transit time of carriers decreases, because of high speed.

You are applying now a reverse bias and therefore everywhere there is electric field and the carriers are immediately swept apart, which means the transit time decreases. If we discuss the impulse response of a general semiconductor, you can show that the transit time decreases by application of an electric field. Alright.

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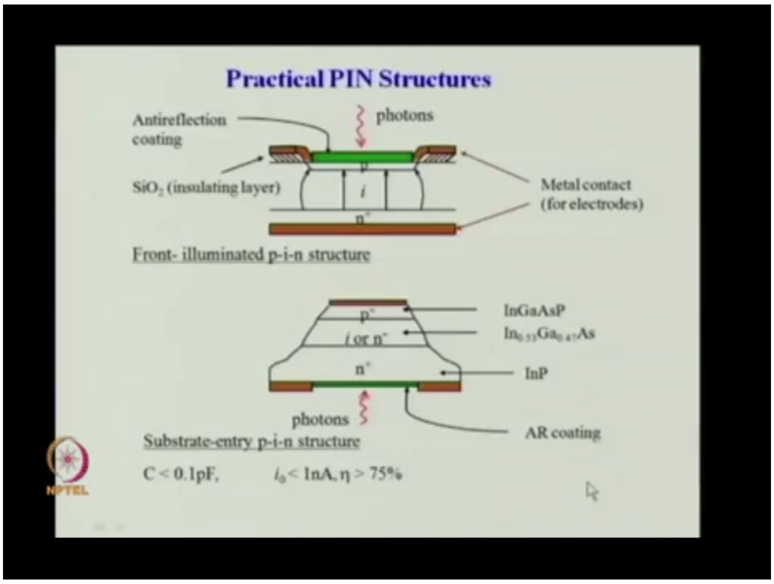

Lets us go to the next slide. This shows these are normally schematics, in practice, when you take a semiconductor, you cannot take a piece of semiconductor and eliminate it from size. In a practical situation, it is a chip, it is a semiconductor substrate on which we have to grow the detectors. So, what is done here is, you can see, there are 2 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+ region here. It is a p-i-n structure.

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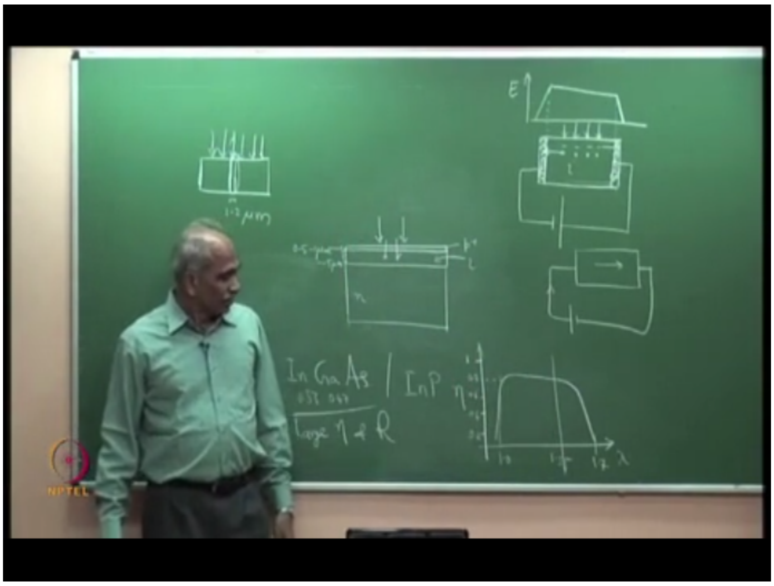

So, basically you have a substrate on which you deposit an n or i region here. So, this is the I region. Or you could start with an intrinsic substrate and have regions deposited on both the sides and then you deposit a thin layer here. So, generally the thicknesses involved are, these are very small 0.5 to 1 micro meter. And these are a few micro meter of the order of 5 micro meter. If you remember in one of the earlier classes, we had calculated the thickness of the semiconductor required for 90% absorption, it was just one micron.

One or 2 micron is sufficient to absorb almost 90% depending on the absorption coefficient. And therefore, typically the i region has a thickness of few microns, several microns and you have a p+ region here on top and this is the i and then this is the n region and the electrode contact. 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 0.5 to 1. 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 potentially and the detector, the light is incident from the top, which means when light enters this and penetrates in this region, we would like it to be absorbed. And that is why you can see the practical structure that is shown p, i and then +n metal contact. And always we have seen there is a diodes and photo detectors. Always, there is a glass window, which is antireflection coating so that light enters through the window and does not get reflected.

The need for anti reflection coating, we have discussed, the factor 1-R, to maximize the factor 1-R, R reflectivity should be 0. There is another structure, which is shown here and materials used as you can see indium gallium arsenate phosphate, indium gallium arsenate. This is the most widely used material indium gallium arsenate for several reasons, there are many reasons, we will see shortly. So, in almost all optical communication, the photo detector used is indium gallium arsenate. We know why this composition right.

The composition is because, this is lattes matched to indium phosphate. And lattes 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 the defects will act as recombination centers, which means the carriers will not contribute to the current in the external circuit. So, eta will go down. So, indium gallium arsenate has several reasons.

Yet, 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 micro meter 1 to 1.7. This is lambda versus eta. And the numbers here are eta is 1 here. So, it is about 80% it 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. You will see some numbers that have very large responsivity. So, why use indium gallium arsenate phosphate? One of the reasons is large responsivity, large eta and responsivity, large values. Second, why use in optical communication? It is very clear because our low loosed window is here, optical communication is around 1.55 micro meter and 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 finest detectors. There are more reasons. Let me also discuss very briefly.

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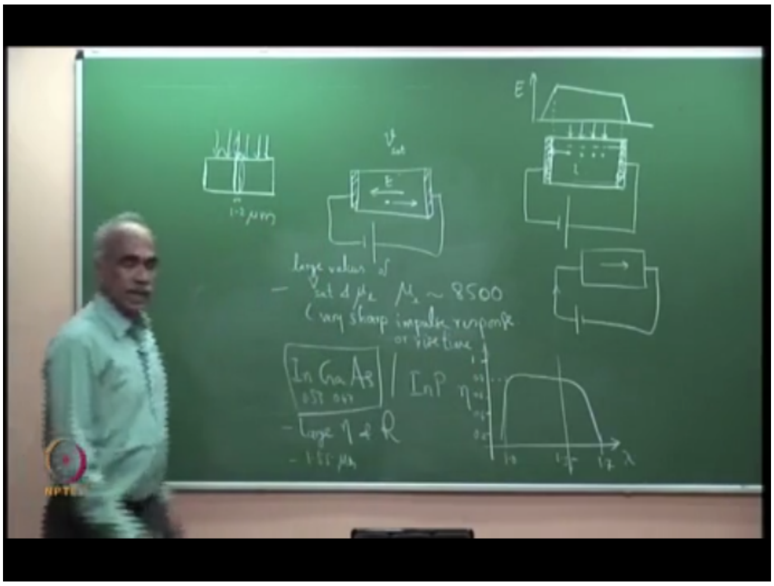

This material also has a very large v saturation. V saturation means, if you take the material and apply an electric field here. So, you apply a field. So, there is an electric field here E in this direction. A carrier electron, let us say electron or hole. A electron is getting accelerated towards this. 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 has 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, the third reason is, large values of v sat, saturation velocity and mobility mu e. which means the transit time is minimized and therefore the impulse response is very narrow in the case of a indium gallium arsenate detectors.

So, large values of eta and R, optical communication window and large values of mobility and v sat. Therefore, very small, very sharp impulse response or rise time okay. Let me come back from this to the structure here.

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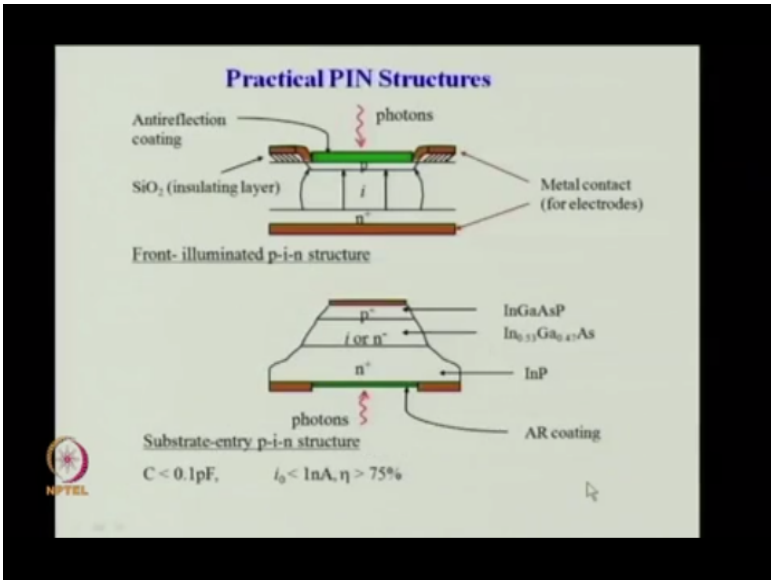

As you can see, this is grown on indium phosphate, just now I had written on indium phosphate because substrate is normally a binary compound. Either gallium arsenate or indium phosphate. So, on a binary compound, you grow the alloy. So, you can see, you start with the substrate here n+ and here is the indium gallium arsenate phosphate and then comes indium gallium arsenate phosphate. So, light enters from here.

These are typically the detectors used in optical communication. Indium light enters from here but, the substrate is thick 50 microns, 60 microns but does not absorb because optical communication is at 1.55 micro meter and indium phosphate has a band gap of E.g.=1.35 eV and optical communication is at 1.55, which means what is the e.g., corresponding band gap is very small 1.24/1.55. so, this is of the order of 0.7eV. so, if photons are coming at 0.7eV, they are going to get absorbed in indium phosphate.

So, as far as light at optical communication is concerned, indium phosphate 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 phosphate, which has a band gap of about 0.74. So, this has a band gap 0.73eV. 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 picofarad, very small junction capacitance okay. Let me go further.

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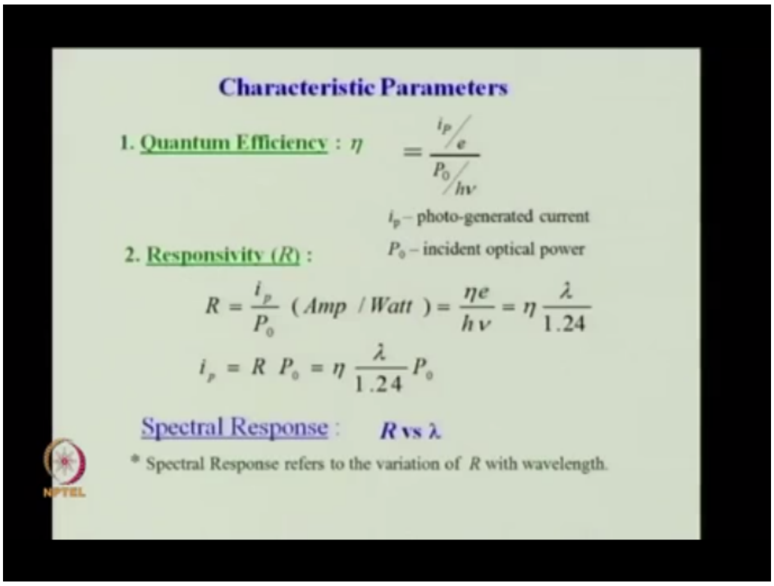

So, here are the characteristic parameters we discussed in one of the earlier classes, quantum efficiency eta is ip/e/ this. And therefore, responsivity R=ip/P0, which is given by eta*lambda divided by 1.24. You have already derived this. Therefore, given a material photo detector with a responsivity 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 verses wave length. Spectral response refers to responsivity versus wavelength.

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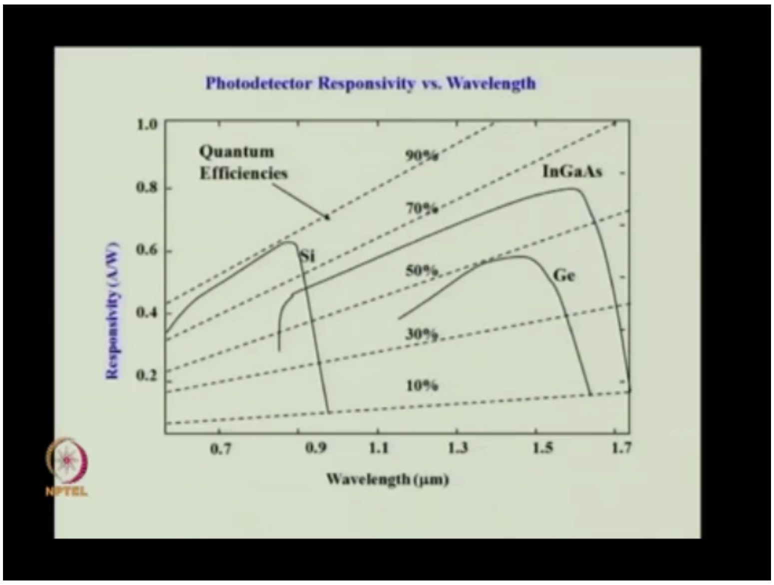

So, here are the typical responsivity of some of the photo detectors, you can see silicon, the dotted line corresponds to constant value of eta. So, indium gallium arsenate, you can see as efficiency this particular material here as efficiency of about 70% everywhere. Almost touching this line everywhere. But, the interesting part is you see, it is almost flat, that is 70% here silicon goes from about 1 micron or up to 1.1. It has a very good responsivity but, it is okay 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. This are the most important materials, the 3 materials which are most important are silicon, germanium and indium gallium arsenate.

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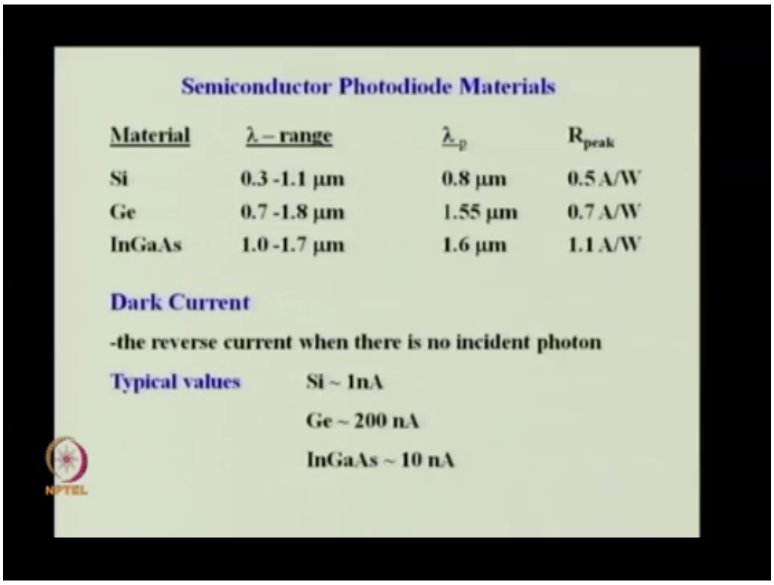

Semi conductor photo diode materials again this is what I have already mentioned, the wave length range peak responsivity is about 0.5 amps per watt for silicon. You can see again for indium gallium arsenate; it is 1.1 amps per watt. It is very good responsivity. The dark currents again some numbers 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.

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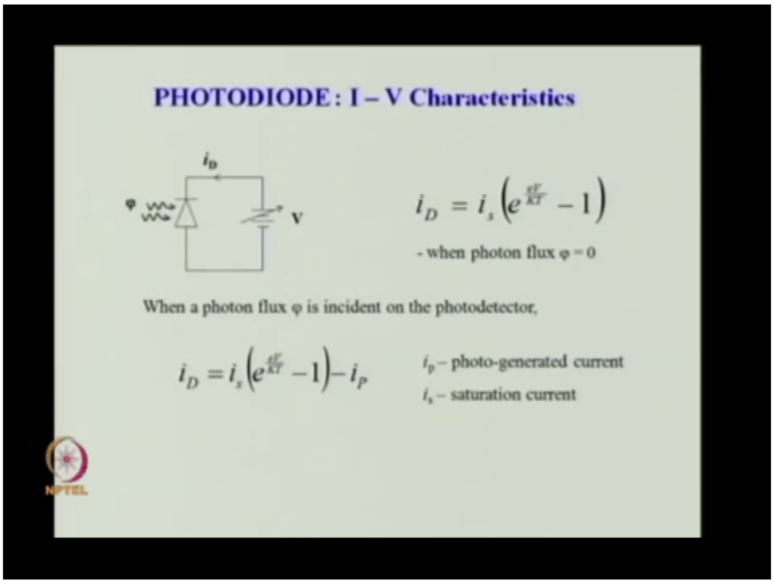

We move further to photo diode characteristics typical iv characteristics. All of you are familiar, the diode current is given by an equation of this sort. Where V is the applied potential difference KT is the same Boltzmann's constant. K and temperature. Is is the reverse saturation current. This is the normal diode equation without having any photocurrent. In the presence of a photo current, the equation is modified like this id=is*this-ip.

Because the photo generated current is a reverse current and therefore it is -ip. Ip is the photo generated current. Is is the saturation current. The picture will become clear when you see the characteristic here.

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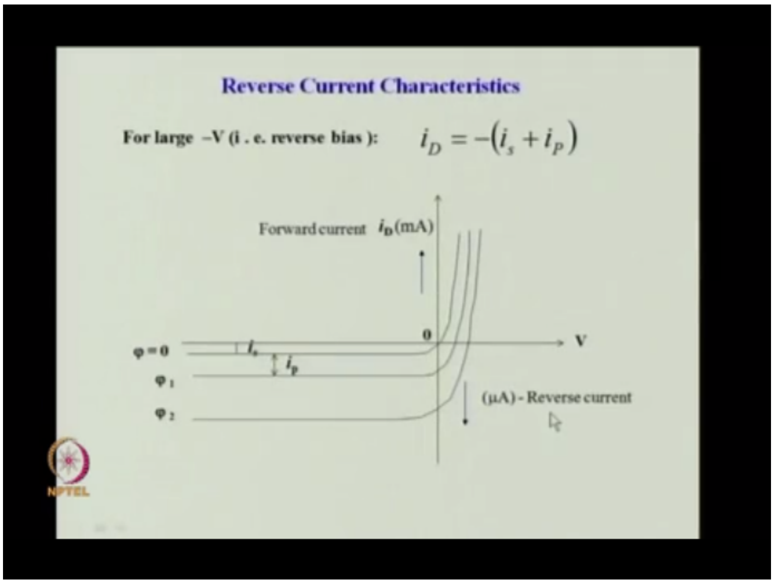

The familiar diode characteristic. The forward characteristic here V verses i forward characteristics and reverse characteristics V versus i. there is one difference though. The scales are different. The reverse currents are in micro amp here. So, you can see it is indicated, the reverse current is micro amp here. And this scale here is in milliamp here or tens of milliamp here. So, the reverse current is of course very small compared 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=0, 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 values. The total saturation will comprise of is, when there is no photon flux, phi=0+ip due to the presence of a photon flux. So, if you plot for a particular.

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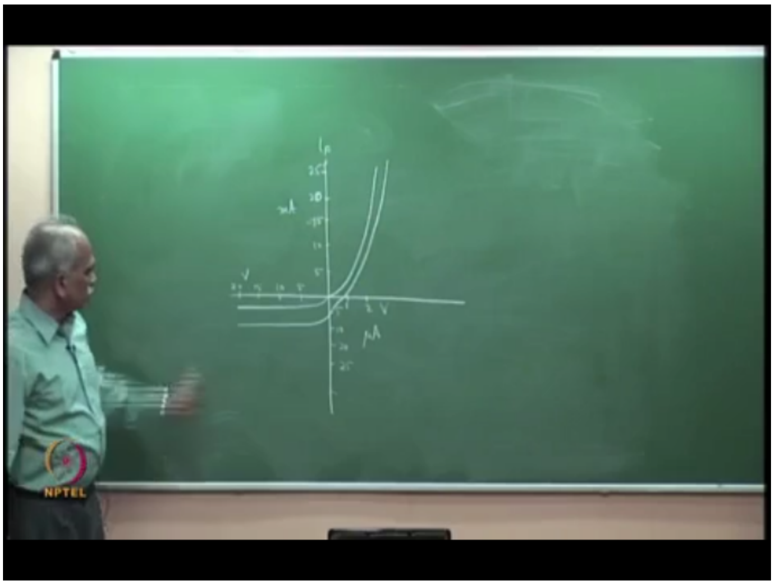

So, what is plotted here is our normal characteristic is like this here. And again recall that number are here micro amp here. May be 5,10,20,25 micro amp here. And here we are talking of milliamps. So 5,10,15,20,25 milliamps so this is the forward current if here. And the voltages this saturation takes place when the voltage is typical numbers I am just plotting 5,10,15,20 volts and the forward, just maybe 1 volt, 2 volt. So, this is 1 volt, this is 2 volt.

Even when you apply about 2 volt, it is already 10's of milliamps or maybe 50 milliamp current. So the scales are different but the shapes are just here. So, this is the normal diode characteristic, which we are familiar with. But, if you apply a photo 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 is + ip.

I have shown here, the reverse current for large values of V here -V, this is reverse large values of -V the diode current is –is + ip. Let us go further.

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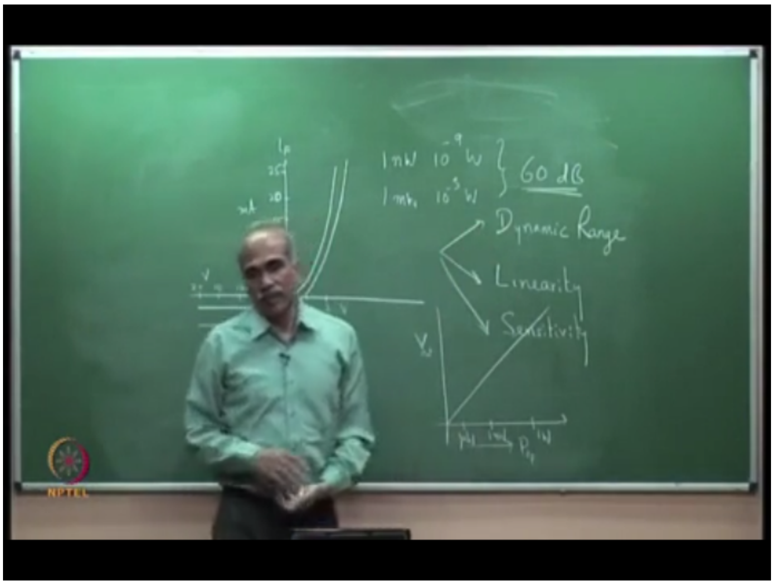

A little bit of a detector and design considerations. There are 2 configurations which are used in photo diode operation. Whenever one uses photo diode, 2 modes of operation. One is called the photo voltaic mode of operation here, which means this is the photo diode incident light generates a reverse photo current, which passes through a resistor and you measure the voltage across the resistor. That is the load resistor. So, this is photo voltaic, the incident photon flux generates an voltage across a resistance.

Hence the name photo voltaic. And the second one is photo conductive, that is you already have applied a reverse bias here and when the photon flux is incident, there is additional carriers 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.

Photo voltaic, no external bias is applied. 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 conductive. You can imagine that immediately that the photo conductive mode of operation is a high speed mode of operation. Because, there is a field, which is already applied. So, the incident photon flux generates carriers, which are immediately swept apart. Because you have applied a 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 or any signal processing, it is the photo conductive mode of operation which is employed. Alright. So, let us just do a little bit of design considerations. So, these are the 2 important detector characteristics.

If you plot load resistance versus linearity, that is a detector requires 2 things, one is dynamic range, when you use a detector, you look for 2 aspects. One is dynamic range and linearity. What does linearity mean? Linearity means, you have some output voltage, some voltage output, which is coming from the detector okay. Electrical signal V out, which we are measuring across a load resistance with optical power, incident is optical power.

This is detector output, which is in the form of an electrical voltaic let us say. Then, if this continues linearly over a large voltage, large power range, which means if I put 1 micro watt, it is here. If I put 1 milli watt, it is here. if I put 1 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 milli watt, what is the dynamic range? From 1 nano watt to 1 milli watt. 1 nano watt is 10 to the power of -9 watt. 1 milli watt is 10 power -3 watt. What is the dynamic range? Dynamic range is 60 dB. The dynamic range is 10 to the power of 6. -9 to -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 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, it is advisable to see certain data sheets of photo detectors. You will see, they will always give 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 these region, if the output voltage is proportional to the input power, then you call the detector a linear.

And of course, there is one more parameter that is sensitivity. We will discuss all these 3 issues in the design consideration.

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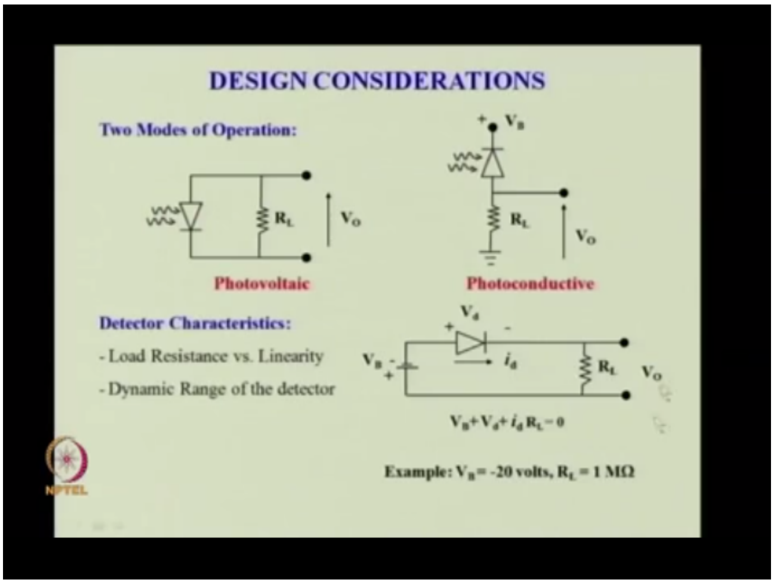

So, for the photo conductive, consider the photo conductive mode of operation here. A reverse voltage is applied, there is a load resistance RL. So, you apply the loop theorem for potential drops. So, VB + voltage across the diode + iD*RL. So, if you consider this loop like this, so VB+Vd+iD*RL=0. All the potential drops around a loop is the loop theorem. So, if you take a typical example of VB, reverse bias =-20 volt, RL load resistor=1 megohm.

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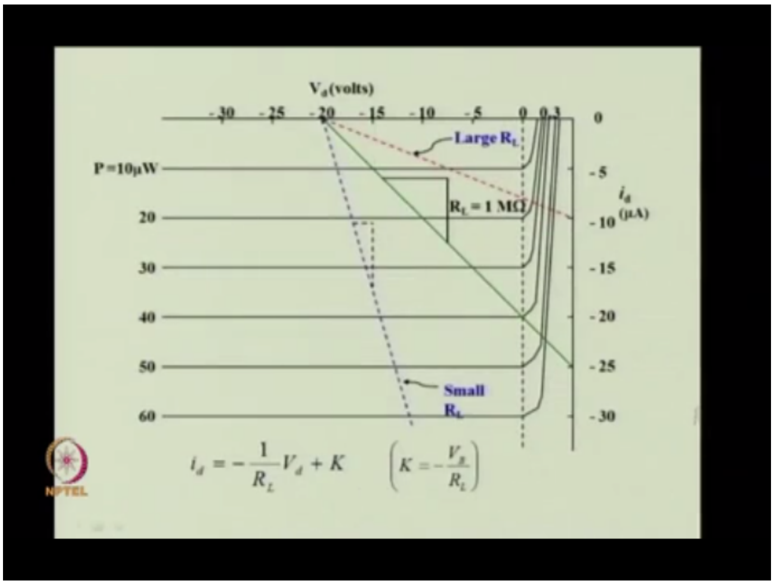

Then in the next graph, I have shown a plot of these, plot of the reverse characteristic for different photon flux is shown here. For a particular photo detector, what is shown is only the reverse part. The forward part is here. This will continue above. I have shown only this, this part the reverse part. Forget about the forward part. And what is drawn here is the load line. So, this is the load line. How do we get the load line?

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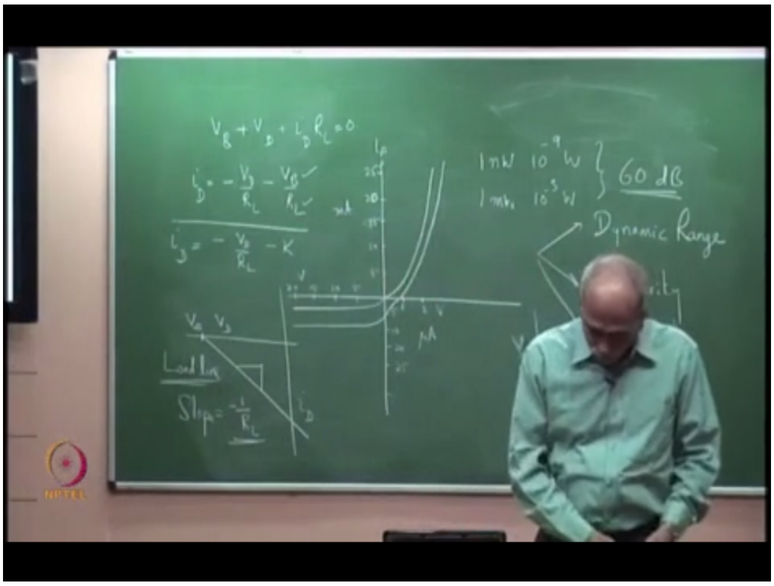

If you see this here, VB+VD, VD is across the diode + iD*RL=0. So, you take this to the other side. So, iD=-VD/RL-VB/RL. So, I said I take an example of VB=-20 volt and RL=1 megohm, which means this is fixed. So, I have indicated this as some fixed number K. please see the text. And this is -VD/RL. So, what is this? iD=-VD/RL. So, here is the graph. VD is here, this axis here is VD across the diode and this axis here is the current iD.

So, it is a VD versus iD is a straight line, equation of a straight line. Y=mx+c. m the slope is -1/RL. So, that is the load line. So, it is a straight line, equation of a straight line. So, this grows like this. It starts from VB. Why it starts from VB? If you put iD=0, then VD/RL=VB/RL. So, VD=VB. Therefore, this starts from VB and it is a straight line, which 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 -1 over R. so, this is the load line. What I want you to see is the following.

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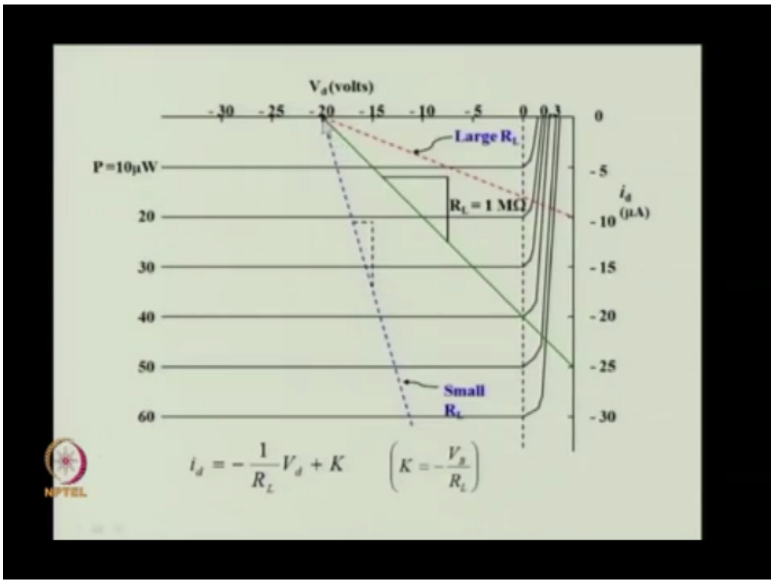

So, here is the load line for a resistance of 1 megohm. If you increase the resistance to let us say 10 megohm, the slope will be 1/RL so, RL is larger, which means the slope is smaller. This is the graph. So, there is a dotted line which shows the slope, the load line for a higher resistance. And if the resistance is smaller, this will be the load line. Some smaller number then you can see this is the load line. Now, what is the importance? Let us look at our case, the case that we have considered here.

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 tell you what is the voltage across the diode, VD is here. If the incident photon flux is 20 micro watt, come here and you get what is VD here, the intersection point here will give you VD, 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 varies from here to here like this. This is delta VV, 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 VDs here so, my VD will vary from about 15 here, -15 to 0.

The variation is very large, which means the variation, the diode voltage, 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 VD, which is 0. At 60, the load line intersects here and the VD 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 incident light level is very small, the changes are very large. In other words, this photo detector with this load line is very sensitive to change in optical power for incident small optical powers. But if the incident optical power is large, its output is fixed, it is not changing, it is saturated. The picture will become clear, if you see the next graph.

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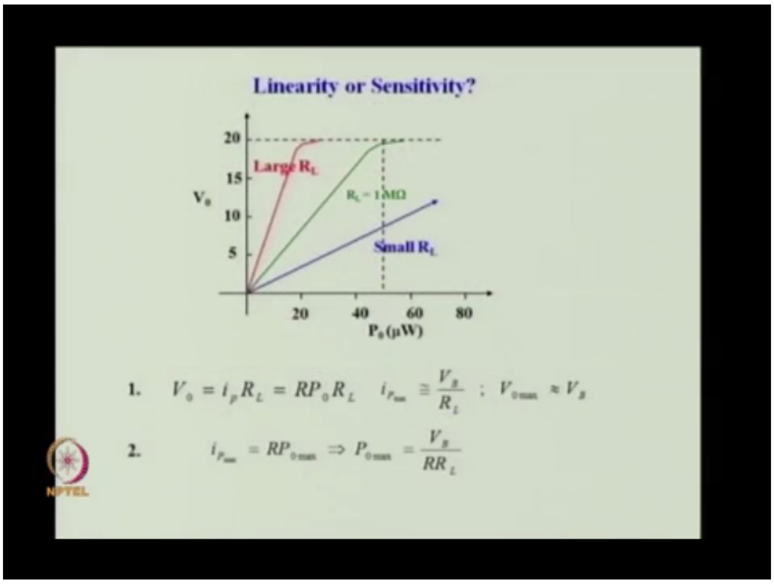

So, if you see this second graph here, what I have plotted is the same thing, same optical power 10 micro watt, 20 micro watt same thing. So, if I change incident optical power from 0 to 20 micro watt, the diode voltage goes from 0 to 15 or 17, 18 here. So, within 0 to 20 micro watt, the variation for RL for 1 megohm is very rapid here very rapid change. But, beyond 40 or here about 45, 50. You see this as saturated output is. Means it is no more sensitive.

It cannot go any beyond. Because why you have applied -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 your choice is 1 megohm, 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 a variation of optical power beyond 40 or 50 micro watt.

So, what is the meaning? If the resistance is large, it is a very sensitive detector but the range of power that you can measure is very small. If I put a small resistance R, I go back here.

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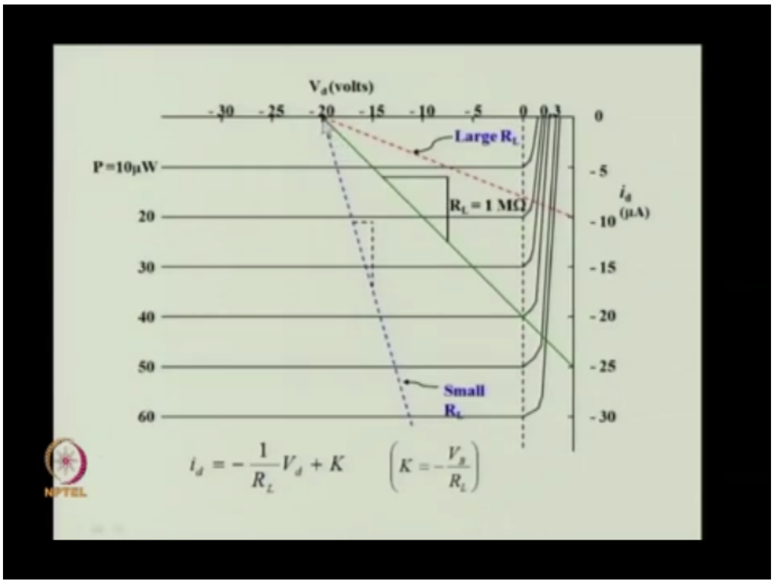

This is the slope please see when I change from 20 to 30. At 20, VD is somewhere here. At 30, VD is somewhere. There is a small change here VD, change in VD. When I change from 20 to 30. If I change from 40 to 50, then also, it is the same. Because, this line continues on the linear characteristic. It has not saturated. And therefore, if you see the next graph for small RL, this is continuing. This is linear. Even at 60, even at 80, it will not saturate it will continue like this.

Means it has a large dynamic range. Dynamic range refers to the useful range of measurement. So, what is the summary of this discussion? Summary is given here.

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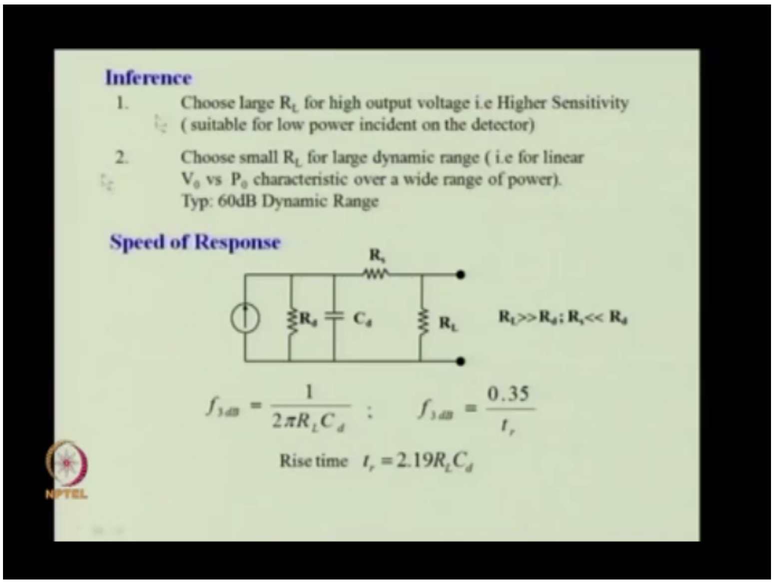

Choose large RL value so that you get high output voltage or higher sensitivity if you want to measure low powers incident. That is for small range of low power, why is this important for a designer engineer? You have an application where you need to measure very weak signal very low power. But, all your measurements are very low power only. Then I would put a large RL, 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 milli watt. This will not work. Because it is already saturated. So, you have to take small values of RL. So, with this example what I am illustrating is given a detector, choice of RL is very important. The choice of the load resistance will determine the dynamic range of measurement. We will also see that the choice of RL will also determine the band width of the detector.

The speed of response or the frequency bandwidth is also determined by RL. So, how to choose RL for given depends on the application. So, depending on the application, you may be having an application where you are not measuring very rapid changes but, you are almost measuring a DC at very low level. Which means large RL choose 10 megohm is very good. Because, you will get a large output voltage. And you are interested in bandwidth.

If you are interested in bandwidth it will be 2 pi RL*C. and if RL is large, then your bandwidth will be very small. If you see any data sheet of a photo detector, they will specify rise time tR=0.1 nano second typical example at RL=50 ohm. It will always be specified with the load resistance. When you put load resistance of 50 ohm, that is a very small load resistance, the rise time is 0.1 nano second. It is a high speed detector.

So, just because if you read only up to this and put 1 megohm with this detector it will not have that bandwidth. The bandwidth will be very small because bandwidth is given by 1 over 2 pi RL*C. So, RL the choice of RL 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 conclusions let me read again.

Choose small RL for large dynamic range, that is for linear V0 versus P0 characteristic over a wide range of power. Typically, 60 dB dynamically. The next we take a simple quiz. Quiz number 12.

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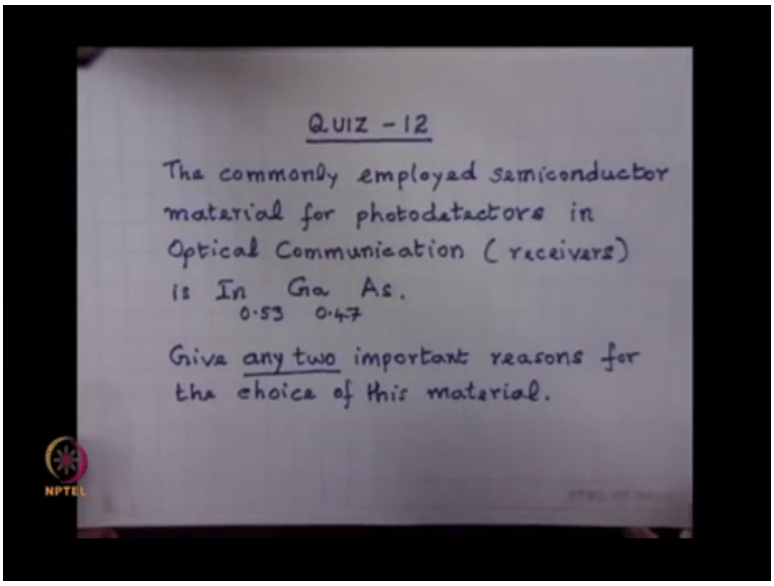

The commonly employed semi conductor material for photo detectors in optical communication receivers is indium gallium arsenate. Give any 2 important reasons for the choice of this material. Why we choose this material give any 2 important reasons for choosing indium gallium arsenate as detectors in optical communication. Only 2 minutes. Please answer in 2 minutes. Very brief no explanations are required.