Fiber Optics
Dr. Vipul Rastogi
Department of Physics
Indian Institute of Technology, Roorkee

Lecture - 37
Optical Sources and Detectors- V

In this lecture, we will now start discussion on Photodetectors. So, how do we detect an optical power? The idea is to convert optical energy into electric energy and we think about it the very first thing that comes to our minds is photoelectric effect.

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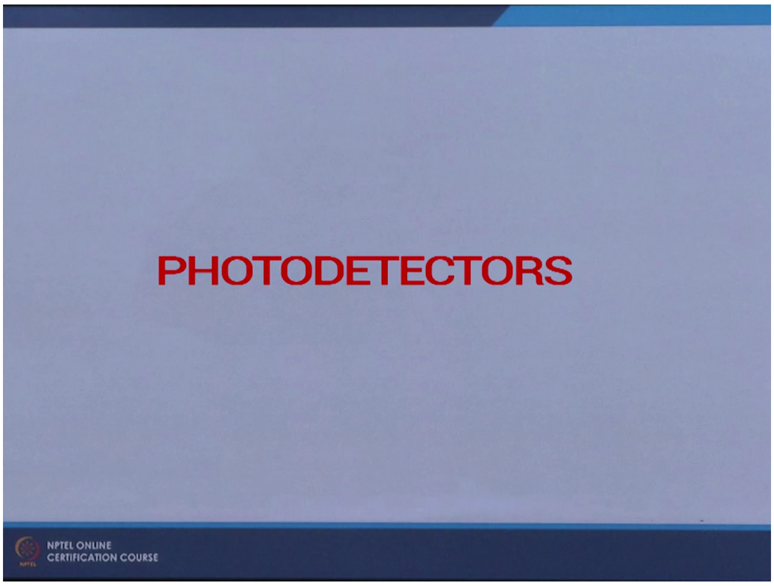

PHOTODETECTORS

So, what is photoelectric effect? We know that if we have a metal and we incident optical energy on to it, we incident some photons then these photons if their energy is sufficient then these photons can knock out the electrons out of the metal and then these electrons are available for conduction.

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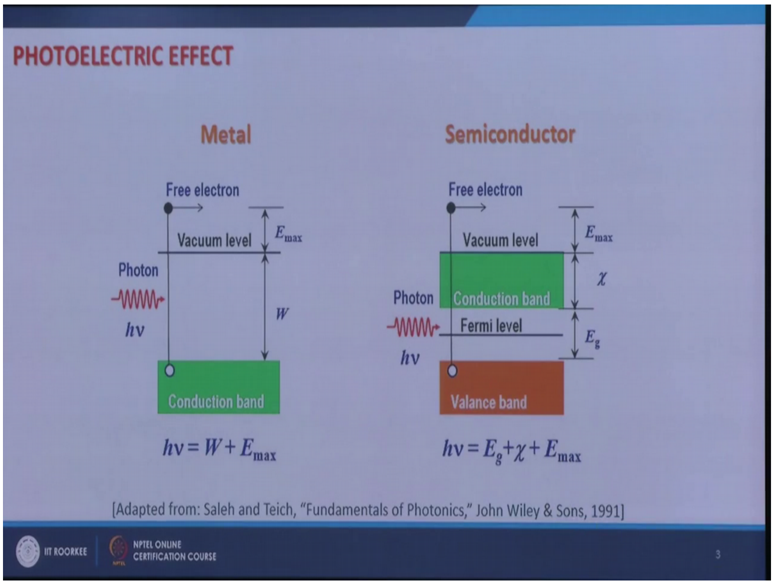

PHOTOELECTRIC EFFECT

$h\nu = W + E_{max}$

$h\nu = E_g + \chi + E_{max}$

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

These electrons are collected on an electrode and we and this can constitute a current in a circuit. So, we can convert optical energy into electric energy using photoelectric effect. Photoelectric effect occurs in metals where you have free electrons in conduction band and these electrons although we call them free electrons, but they are still attached to the material with certain energy which is known as the work function and this work function is W.

Now, if the energy of the incident photon is large enough which can overcome this work function, then this photon can knock out this electron and it can make it absolutely free, then it is not any longer attached to the material. The rest of the energy appears as the kinetic energy of the electron and by the equation of conservation of energy, we can have h nu is equal to W plus E max. E max is the maximum kinetic energy of an electron which occurs for the most loosely bound electron.

But if we do the same thing on a semiconductor, then what happens? In a semiconductor, we have a valance band and conduction band and these bands do not overlap. We have a band gap between them and most of the electrons are in the valance band. So, now, if you want to knock out an electron from a semiconductor, then you will have to incident a photon of energy which can overcome this band gap so that the electron can go into conduction band and then you have the work function chi. So, it has to overcome this work function also, then it can come out of the material. So, the equation of conservation of energy now is transformed to h nu is equal to E g plus chi plus E max. E max is again the maximum kinetic energy of the electron.

So, you would require; you can see, you would require much much more energy to knock out the electron from a semiconductor as compared to what you need in the case of metals. So, what do we do? Do we really use this effect which seems to be quite inefficient because you would require very high energy of the photon and this will have a consequence on the wavelength that you can detect.

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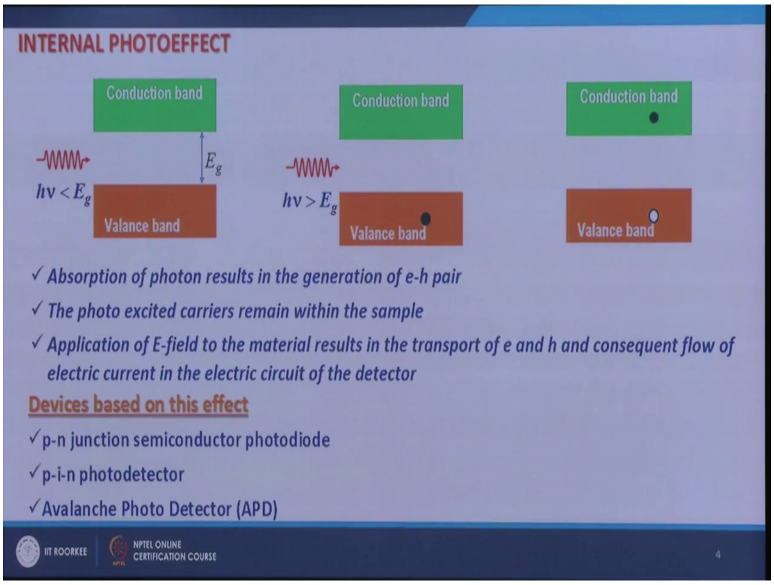

INTERNAL PHOTOEFFECT

- ✓ *Absorption of photon results in the generation of e-h pair*
- ✓ *The photo excited carriers remain within the sample*
- ✓ *Application of E-field to the material results in the transport of e and h and consequent flow of electric current in the electric circuit of the detector*

Devices based on this effect

- ✓ p-n junction semiconductor photodiode
- ✓ p-i-n photodetector
- ✓ Avalanche Photo Detector (APD)

Well, in semiconductors when we use semiconductors for photo detection purpose, then we usually do not require to knock out the electron, but we use what is known as internal photo effect.

What is the internal photo effect? Well, we incident a photon onto the semiconductor material and depending upon the energy of the photon, depending upon how the energy of the photon compares with the band gap energy this photon can be absorbed or this photon can go as it is or see this semiconductor material as a transparent material. So, if h nu is smaller than E g, then this photon will go as it is it will not be absorbed. However, if this h nu is larger than E g, then this photon will result in the generation of electron whole pair, the electron in the valance band will get this energy and will go to the conduction band.

So, the adoption of photon will result in generation of electron whole pair, but these photo excited carriers, they remain within the sample within the material. They do not leave it and then if we apply an electric field, then this would result in the transport of electron and hole and consequent flow of electric current in electric circuit. The devices which are based on this affect are p-n junction semiconductor photo diodes, p-i-n photo detector avalanche photo detector APD. So, we will study all the 3 in this lecture.

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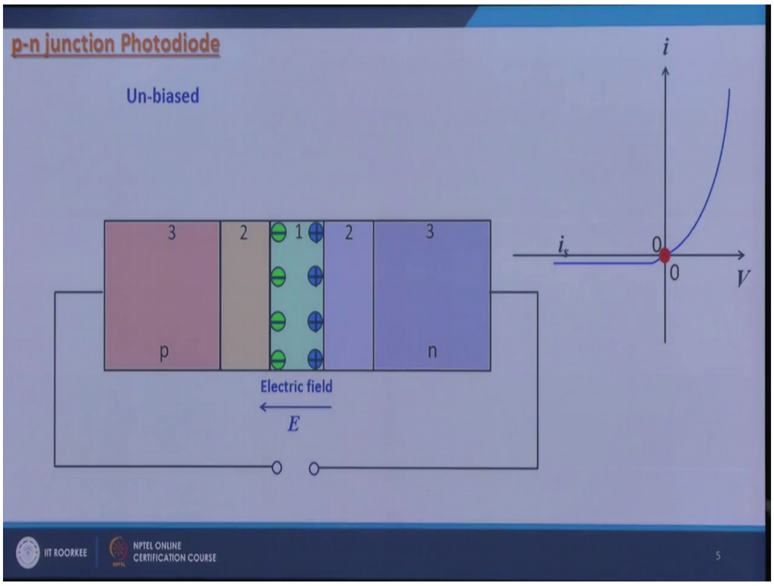

p-n junction Photodiode

Un-biased

If I look at p-n junction photodiode, how does it work? If I just take a simple p-n junction diode, then I know that in the junction region, there is an internal electric field which points from n type to p type because on n type; you have positive ions and on p side, you have negative ions. And if I look at i V curve of this p-n junction diode, then it is something like this if you do not apply any bias here, then you are somewhere here; no applied voltage, no current.

When you forward bias it, then you get a forward bias current like this and when you apply reverse bias, then you will have reverse saturation current like this very small amount of reverse saturation current.

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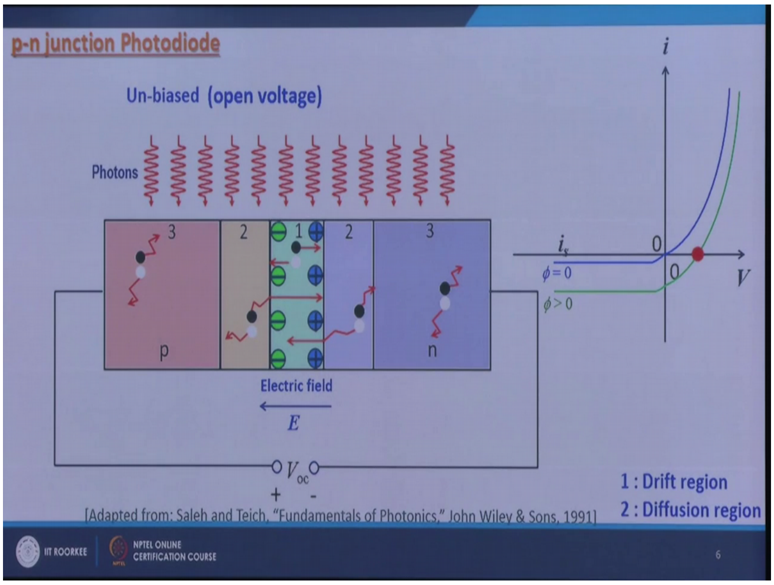

p-n junction Photodiode

Un-biased (open voltage)

1 : Drift region

2 : Diffusion region

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

Now, what you do? You incident photons on this, you incident optical energy onto this p-n junction diode. Now if the energy of these photons is sufficient to generate electron whole pair, it is larger than the band gap, then this will result in generation of electron whole pairs everywhere.

Now, I have divided this into 3 regions; 1, 2 and 3 on either side and see what happens. Still, I have not applied any bias on to this, please see, this plus minus do not indicate any bias, I will explain what it is. Now let us look at an electron whole pair which is generated in this region, since you have an electric field which points from n to p, then this electron will be drifted towards n type and whole will be drifted towards p type. Any electron whole pair which is generated in this region, then electron will move to this side and whole will move to this side.

The electron whole pairs which are generated in these regions; they will wander randomly unless, they come in the vicinity of this electric field and when they come in the vicinity of electric field that they; we will be drifted electron on this side and whole on this side similarly this one. While the electron whole pairs which are generated here, they will wander randomly and they have very less chances to come in the under the influence of this electric field because they are very far from here and then ultimately they will recombine, so what do I see that electron whole pairs which are in this region or which are in these regions; they have the probability of constituting an electric current.

If the circuit is closed, but if the circuit is not closed, then what happens; that electrons gather on this side and whole gather on this side. So, basically, what I have done by incidence of optical energy? I have generated electron whole pairs and because of this electric internal electric field, there are charge separation electrons on n side wholes on p side and then there is charge separation, then it works like a battery depending upon how much charge has been created. I will have an open circuit voltage. So, it will become a battery, you have a p-n junction semiconduc tor diode, you incident optical power on it and it becomes a battery; this is nothing, but the solar cell.

So, if I look at i V curve, then the i V curve in the presence of photon, flux phi represents the photon, flux becomes like this and since I have not applied any voltage here bias voltage. So, V is 0. So, I have not applied any bias voltage, but because of the charge separation, a voltage occurs; a voltage appears across the terminals which is V o c and it is known as open circuit voltage this is open circuit voltage.

Now, what happens if I short circuit it? If I close the circuit, then electrons will start flowing in this direction, whole will start flowing in this direction and it will constitute a current, but this current would be larger than the reverse saturation current in the absence of any optical energy. So, the optical energy increases the reverse saturation current and this reverse saturation current is a measure of whatever optical power is incident and that is how we can measure optical energy or optical power.

This is nothing, but the short circuit operation of an unbiased p-n junction diode. You can also bias it; if you bias it and you reverse bias it; when you reverse bias it, then what you do you basically increase the width of this region depletion region and you have this region wider depletion region which has electric field across it and since this region is now wide, so you will have more electron whole pairs here generated which contribute towards photo current.

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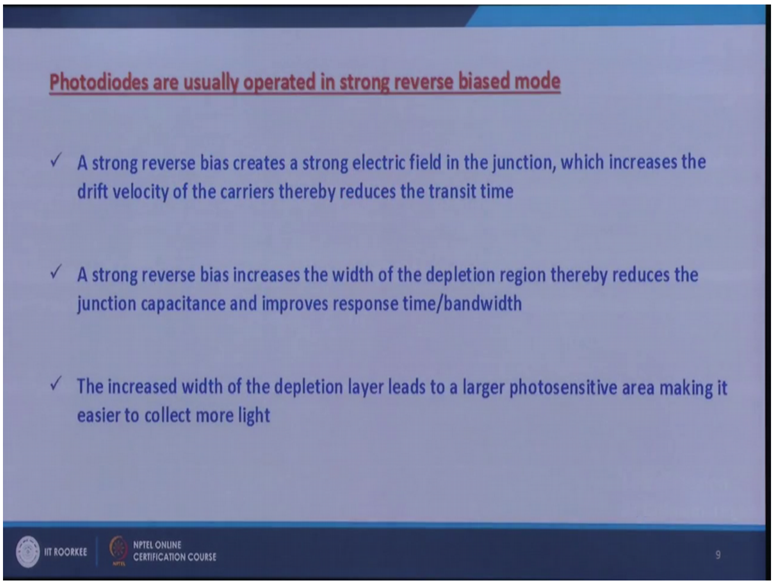

Photodiodes are usually operated in strong reverse biased mode

- ✓ A strong reverse bias creates a strong electric field in the junction, which increases the drift velocity of the carriers thereby reduces the transit time
- ✓ A strong reverse bias increases the width of the depletion region thereby reduces the junction capacitance and improves response time/bandwidth
- ✓ The increased width of the depletion layer leads to a larger photosensitive area making it easier to collect more light

So, this reverse biased operation of a photodiode results in a Photodetector; a photo detection process. So, you operate somewhere here. So, these photo diodes are usually operated in strong reverse biased configuration, what are the advantages of reverse biasing. It is strongly well a strong reverse bias will create strong electric field across the junction and since the electric field is strong. So, it will increase the drift velocity of the carriers and consequently and consequently, it will reduce the transit time also as we had seen the reverse bias will also increase the width of the depletion region and because of that the photosensitive area would increase. So, depletion region layer width will increase. So, photo sensitive area would increase because it is that region where the generated electron whole pairs will constitute a current.

Another thing is that when you increase the width of the depletion region by strong reverse bias, then the junction capacitance decreases and this decreasing junction capacitance will improve the response time or the band width. So, these are the advantages of the strongly reverse biasing p-n junction diode for photo detection process another important photo diode is p i n or pin photodiode; what has been done here is that you insert an intrinsic region or lightly doped region between p type and n type.

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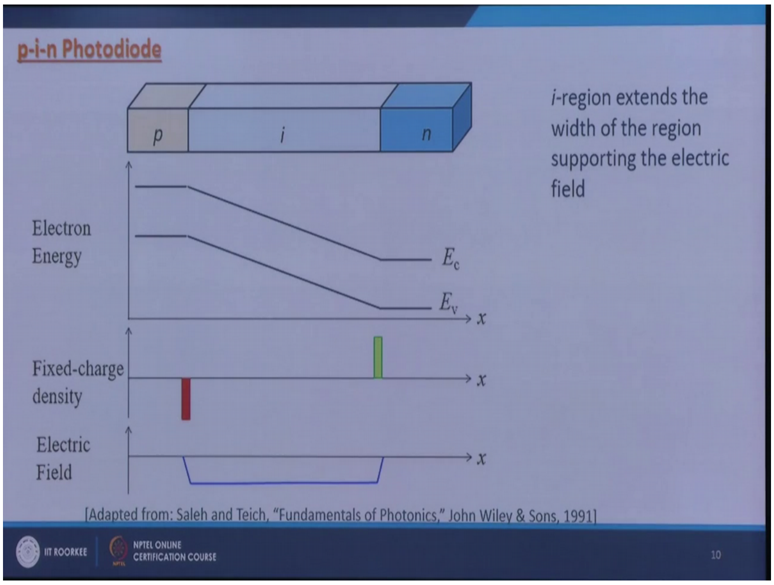

p-i-n Photodiode

i-region extends the width of the region supporting the electric field

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

What is the advantage of this? Well, with this you extend the width of the region which supports the electric field and thereby you increase the area of photosensitive region. So, if I look at it when this is by electron energy as a function of distance. So, you have p type you have n type and this is the junction region where you have an electric field.

If I look at the fixed charge densities which are negative ions on the p side and positive ions on the n side; so, this is the fixed charge density which creates an electric field like this and since this region is very wide. So, the electric field is now over a very wide width very wide region and it increases the photosensitive area.

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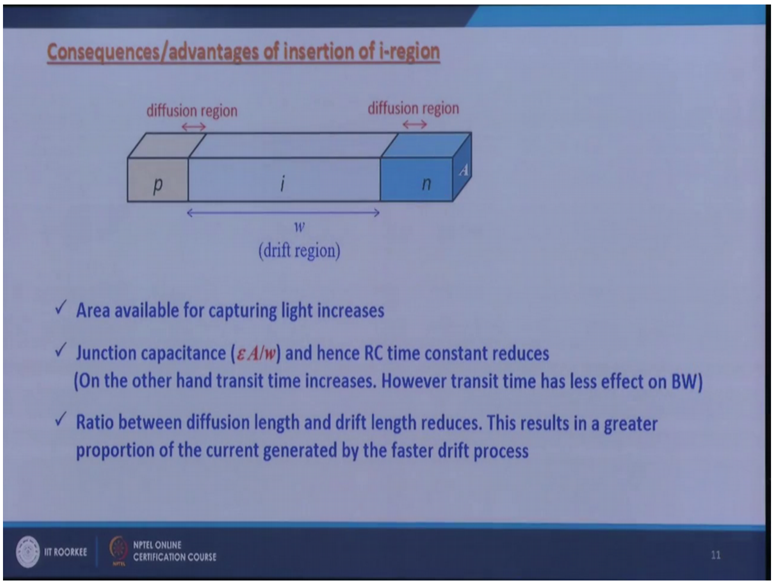

Consequences/advantages of insertion of i-region

- ✓ Area available for capturing light increases
- ✓ Junction capacitance ($\varepsilon A/w$) and hence RC time constant reduces (On the other hand transit time increases. However transit time has less effect on BW)
- ✓ Ratio between diffusion length and drift length reduces. This results in a greater proportion of the current generated by the faster drift process

So, what are the advantages or consequences of inserting an i region? Well as I had explained in the previous slide that the area available for capturing light increases because now this area becomes photosensitive, this is the drift region because the electric field is over this region and then this is the diffusion region where the electron whole pairs wonder randomly and then they come under the influence of the field here and get drifted later on. So, the area of the level for capturing light increases again the junction capacitance will decrease because now the width of the junction region increases considerably. So, the junction capacitance will decrease because junction capacitance goes as epsilon A over w where a is the area of cross section and epsilon is the dielectric permittivity of the medium there.

So, the RC time constant also reduces; however, you will say that you have increase the width this region. So, now, electrons will have to travel longer distance in drifting from here to here. So, it will increase the transit time as compared to the transit time in the case of simple p-n junction diode. Yes, it will increase the transit time, but increasing transit time has very less effect on band width as compared to this RC time constant. So, it is not of major concern, also, what I see that now drift region is much longer as compared to diffusion region and of course, drift process is much faster than the diffusion process. So, you will have faster response of the photodiode p i n diode.

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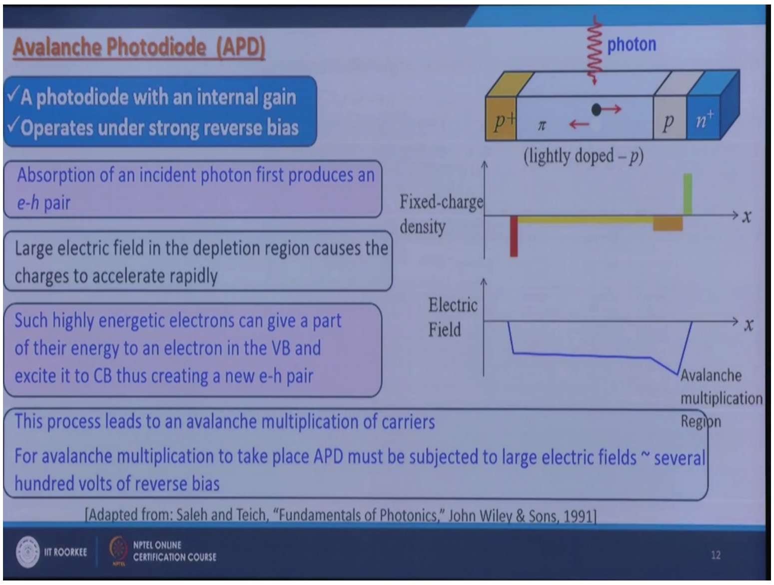

Avalanche Photodiode (APD)

✓A photodiode with an internal gain
✓Operates under strong reverse bias

Absorption of an incident photon first produces an *e-h* pair

Large electric field in the depletion region causes the charges to accelerate rapidly

Such highly energetic electrons can give a part of their energy to an electron in the VB and excite it to CB thus creating a new e-h pair

This process leads to an avalanche multiplication of carriers

For avalanche multiplication to take place APD must be subjected to large electric fields ~ several hundred volts of reverse bias

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

There is another device which is known as avalanche Photodetector or avalanche photodiode; APD. This device is a very sensitive device because it has an internal gain mechanism and it operates under a very strong reverse bias; what it is, let us look at the structure; the structure is you have a highly doped p region, then you have a pi region which is nothing, but lightly doped p region, then you have a p doped region and highly doped n region.

If I look at the fixed charge density across various layers, then you have very high negative charge density here in the p plus region and the lightly doped p region will give you moderate fixed charge density then this is the charge density of p region and this is in n plus 1 region positive charge density this kind of charge distribution will result in the electric field which looks like this. So, I have electric field which extends over a very wide region and then very strong electric field here.

Now, if I operate it under very strong reverse bias, then in this region, you have very strong electric field and this strong electric field will accelerate the charges rapidly what is happening basically you incident photon, it will generate electron whole pairs. So, these electrons when they come under the influence of such a large electric field, they are accelerated and since they have very high energy; so, these electrons now have impact with the electrons in valance band and they give a part of the energy to an electron in valance and then this electron goes to conduction band. So, another electron whole pair is generated.

This electron from the newly generated electron pair again is accelerated and knocks out another electron from sends another electron from valance band to the conduction band. So, another electron whole pair is generated to this of avalanche multiplication of carriers and this gives the internal gain, but to have this avalanche multiplication what you need is very strong reverse bias.

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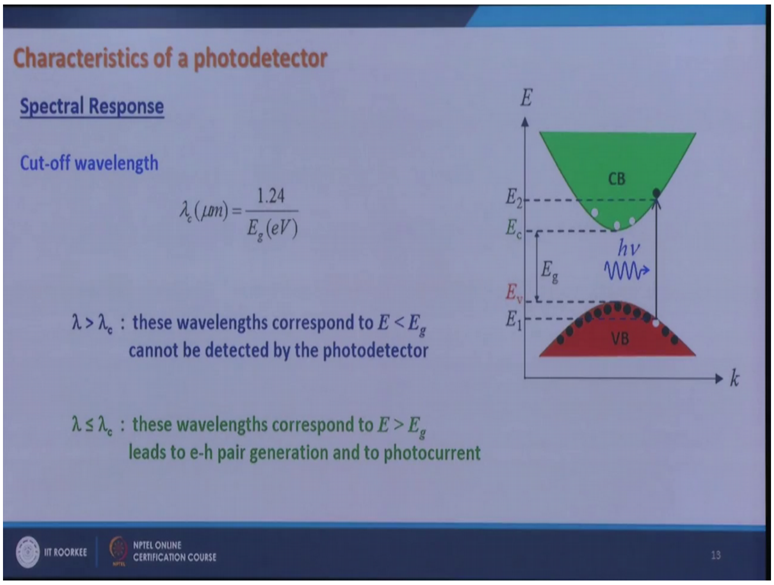

Characteristics of a photodetector

Spectral Response

Cut-off wavelength

$$\lambda_c(\mu m) = \frac{1.24}{E_g(eV)}$$

$\lambda > \lambda_c$: these wavelengths correspond to $E < E_g$
cannot be detected by the photodetector

$\lambda \leq \lambda_c$: these wavelengths correspond to $E > E_g$
leads to e-h pair generation and to photocurrent

So, you need hundreds of volts of reverse bias for this what wavelengths would be detected by a particular material of a photodiode for that if I look back to this E k diagram; what happens is that only the photons which have energy larger than the band gap energy can create electron whole pairs. So, it will have a cut off, if the photons have smaller energy than E g, then they will go through; they will not be absorbed and they will not contribute for photo current. So, there is a cut off wavelength which is given by lambda c is equal to 1.24 over E g where E g is in electron volts and lambda c micrometer.

This we had seen earlier also. So, for all the wavelengths longer than lambda c, they cannot be detected by the Photodetector because their energy would be smaller than band gap energy while all the wavelengths which are shorter than lambda c, they will have energy larger than E g and they will lead to generation of electron whole pair and photo current.

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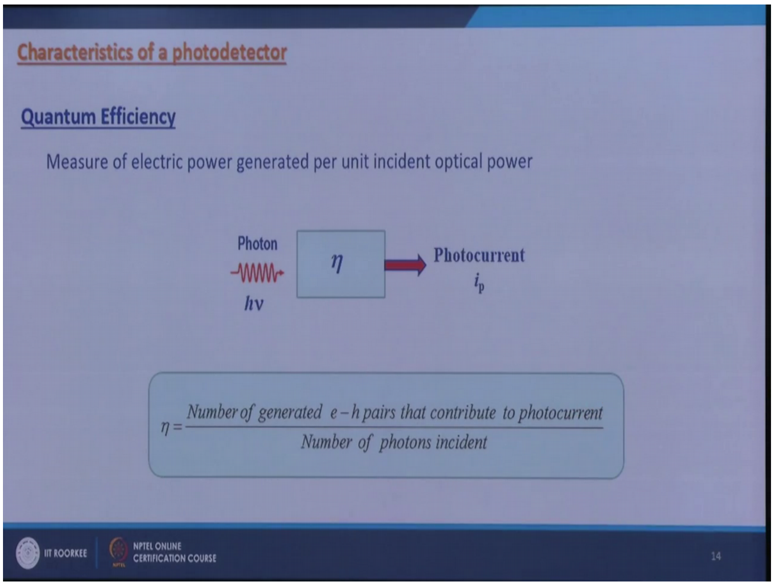

Characteristics of a photodetector

Quantum Efficiency

Measure of electric power generated per unit incident optical power

$$\eta = \frac{\text{Number of generated } e-h \text{ pairs that contribute to photocurrent}}{\text{Number of photons incident}}$$

What are the various characteristics of Photodetector? Well, one is quantum efficiency, how efficiently I can convert optical energy into electric energy. So, it is a measure of electric power generated per unit incident optical power. So, you have the semiconductor material, you incident photon and you generate photocurrent well. So, the quantum efficiency is defined as number of generated electron whole pairs that contribute to photo current divided by number of photons incident because each photon will generate one electron whole pair, but not all the electron whole pairs will contribute to photocurrent some of them are lost and re-combination. So, there is a finite quantum efficiency let us work out the expression for it.

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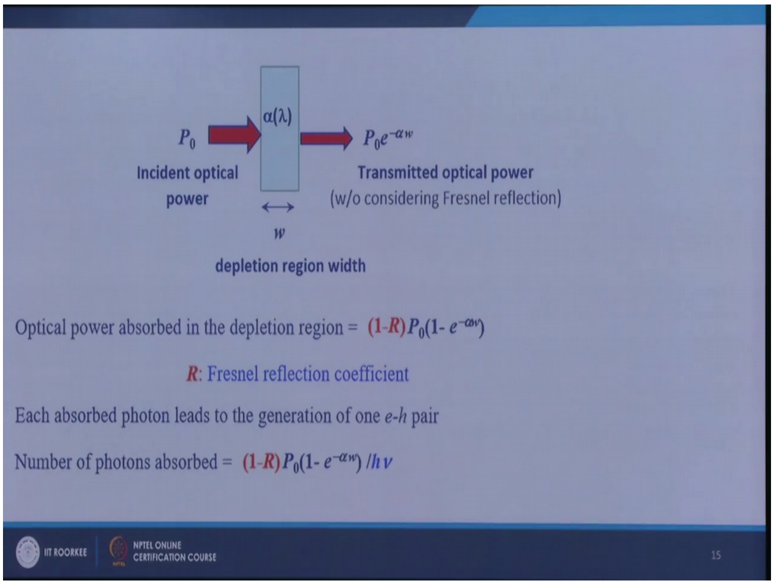

Optical power absorbed in the depletion region = $(1-R)P_0(1- e^{-\alpha w})$

R: Fresnel reflection coefficient

Each absorbed photon leads to the generation of one *e-h* pair

Number of photons absorbed = $(1-R)P_0(1- e^{-\alpha w})/h\nu$

If I have a semiconductor material which has absorption coefficient alpha at wavelengths lambda and it has got a width w, if I incident optical power P naught here and if I do not take into account any final reflection, then the transmitted power would be P 0 e to the power minus alpha w, if alpha is the absorption coefficient right. So, what is the power which is absorbed the power absorbed would be P 0 minus P 0 e to the power minus alpha w which means P 0 times 1 minus e to the power minus alpha w. Now basically P 0 is not the power which enters the material because a fraction R will get reflected because of Fresnel reflection. So, the power that goes inside is 1 minus R times P 0.

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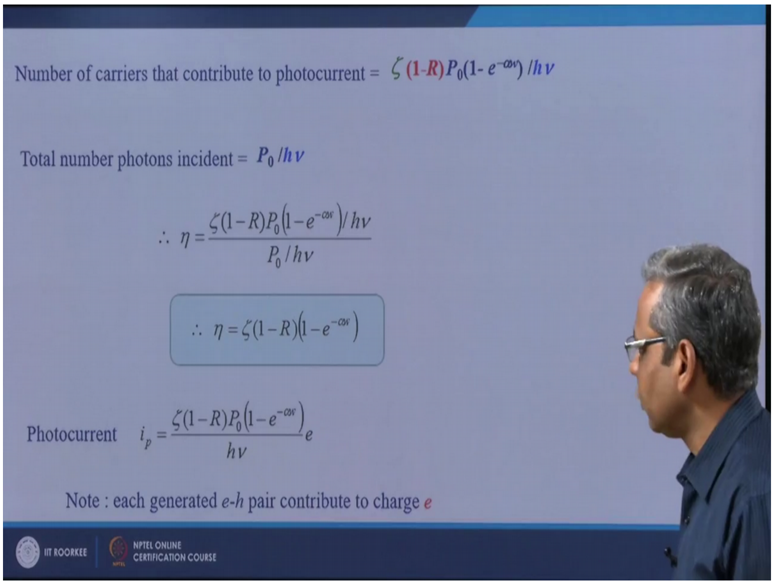

Number of carriers that contribute to photocurrent = $\zeta(1-R)P_0(1- e^{-\alpha w})/h\nu$

Total number photons incident = $P_0/h\nu$

$$\therefore\ \eta = \frac{\zeta(1-R)P_0\left(1-e^{-\alpha w}\right)/h\nu}{P_0/h\nu}$$

$$\boxed{\therefore\ \eta = \zeta(1-R)\left(1-e^{-\alpha w}\right)}$$

Photocurrent $i_p = \frac{\zeta(1-R)P_0\left(1-e^{-\alpha w}\right)}{h\nu}e$

Note : each generated *e-h* pair contribute to charge e

So, this would be the power absorbed and this will result in generation of electron whole pair. So, the number of photons absorbed would be now this divided by h nu number of photons absorbed per unit time and each of these photons will generate electron whole pairs and if only zeta fraction of generated carriers contribute to photocurrent, then the number of carriers that contribute to photocurrent would be zeta times this. Again, this is per second. Now, what is the total number of photons incident? Total optical power incident divided by energy of 1 photon. So, these are the total number of photons incident per unit time. So, the quantum efficiency would be this divided by this. So, eta would be this and this is simply zeta times 1 minus R times 1 minus E to the power minus alpha w.

What would be the photocurrent? Well, the number of carriers that contribute to photo garage per unit time times the charge of one photo generated carrier. So, this would be given by this you should note that each generated e h pair contribute to charge e. So, this would be the photocurrent.

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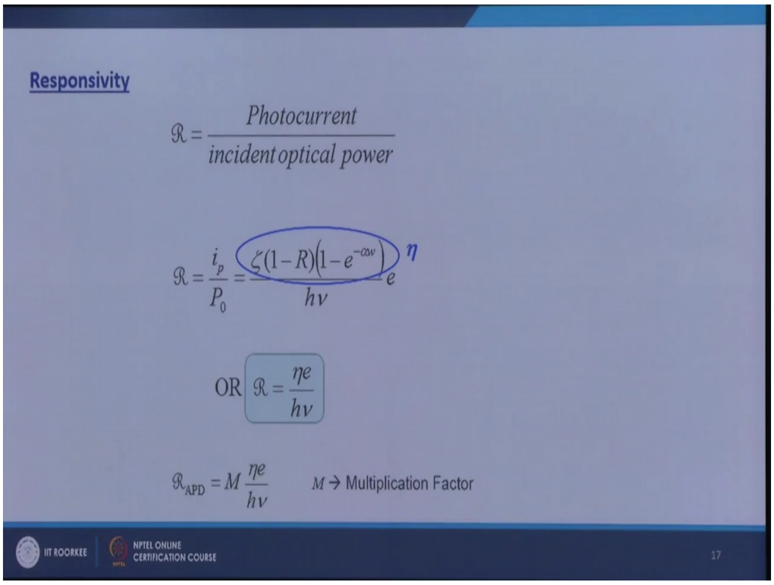

Responsivity

$$\Re = \frac{\text{Photocurrent}}{\text{incident optical power}}$$

$$\Re = \frac{i_p}{P_0} = \frac{\zeta(1-R)\left(1-e^{-\alpha w}\right)e}{h\nu} \quad \eta$$

$$\text{OR} \quad \boxed{\Re = \frac{\eta e}{h\nu}}$$

$$\Re_{APD} = M\frac{\eta e}{h\nu}$$

M → Multiplication Factor

Then another important parameter is responsivity. Responsivity is output versus input of a device output here is photo current and input is incident optical power. So, R would be i p over P 0. So, simply it would be this and since this is eta; so, it can be represented in terms of quantum efficiency as eta e over h nu.

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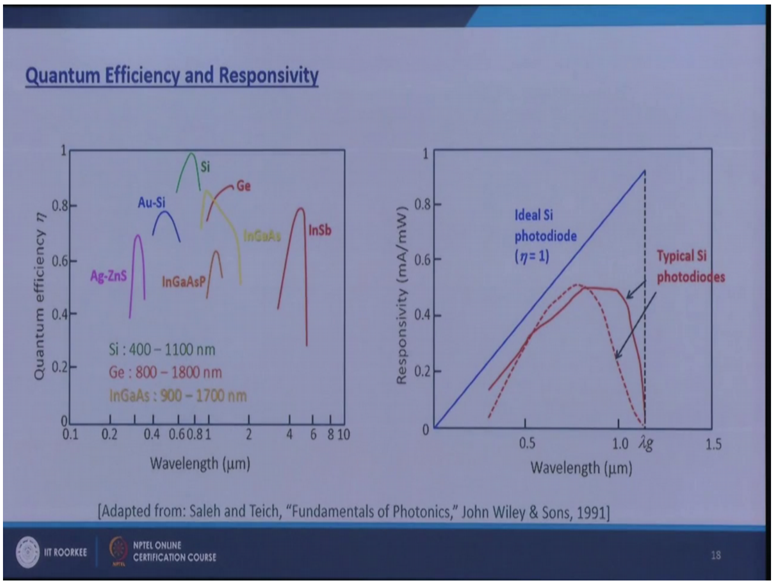

Quantum Efficiency and Responsivity

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

In case of APD, you will have a multiplication factor because of internal gain. So, this will become m times eta you over h nu. These are the quantum efficiency and responsivities at various wavelengths, as I can see that not one material can work in the entire wavelength range. So, you have different materials to work in different wavelength ranges and they have different quantum efficiencies. Also for example, silicon can work from 400 nanometer to 1100 nanometer; germanium from 800 nanometer to 1800 nanometer and indium gallium arsenide from 900 to 1700 nanometers. This is the responsivity of silicon, this corresponds to eta is equal to one which is ideal photodiode and this is typical silicon photodiode.

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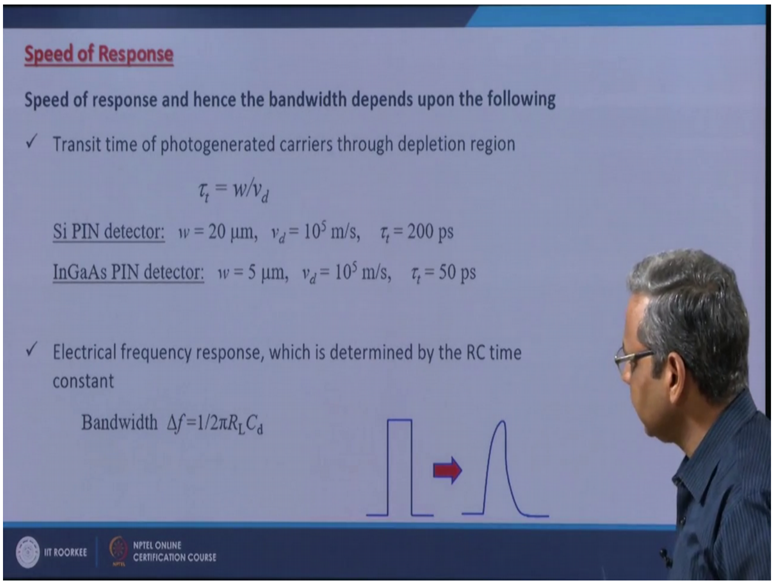

Speed of Response

Speed of response and hence the bandwidth depends upon the following

- ✓ Transit time of photogenerated carriers through depletion region

$$\tau_t = w/v_d$$

Si PIN detector: $w = 20\ \mu m$, $v_d = 10^5$ m/s, $\tau_t = 200$ ps

InGaAs PIN detector: $w = 5\ \mu m$, $v_d = 10^5$ m/s, $\tau_t = 50$ ps

- ✓ Electrical frequency response, which is determined by the RC time constant

Bandwidth $\Delta f = 1/2\pi R_L C_d$

Then, the speed of response speed of response and hence a bandwidth; it depends on transit time; how fast the carriers transit across the junction and transit time is nothing, but the width of the junction region divided by the drift velocity for silicon pin detector. W is typically 20 micron, drift velocity of electron is 10 to the power 5 meters per second. So, the transit time would be 200 picoseconds in case of indium gallium arsenide pin detector W is 5 micron. So, transit time would be 50 picoseconds.

And the electrical frequency response is determined by RC time constant because if you incident this optical pulse, then the electric pulse will follow this because there would be finite rise time and finite fall time which depends on RC and this band width because of this, the bandwidth would be limited by RC time constant and is given by 1 over 2 pi R L C d R L is the load resistor C d is the junction capacitance junction capacitance is given by epsilon over w. So, of course, the smaller the junction capacitance larger would be the bandwidth.

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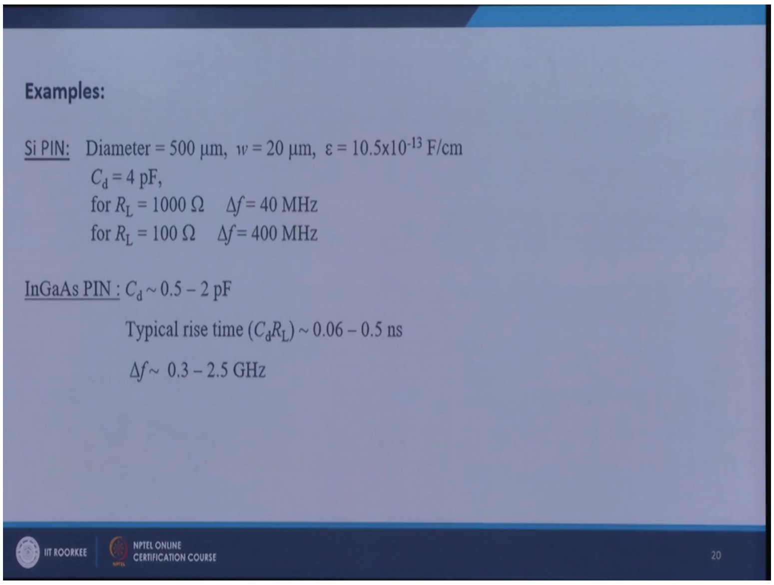

Examples:

Si PIN: Diameter = 500 μm, w = 20 μm, $\varepsilon = 10.5\times10^{-13}$ F/cm

C_d = 4 pF,

for R_L = 1000 Ω Δf = 40 MHz

for R_L = 100 Ω Δf = 400 MHz

InGaAs PIN : $C_d \sim 0.5 - 2$ pF

Typical rise time ($C_d R_L$) ~ 0.06 – 0.5 ns

$\Delta f \sim$ 0.3 – 2.5 GHz

So, in the end let me work out an example. So, if I have silicon pin Photodetector with diameter 500 micron junction, width 20 micron and epsilon this much C d would be 4 pico farad. If I have a load resistor of 1 kilo ohm, then band width would be about 40 megahertz in case of indium gallium arsenide pin detector, C d would be around 0.5 to 2 pico farad, typical rise time is 0.06 to 0.5 nanoseconds and it will give you the bandwidth of about 0.3 to 2.5 gigahertz.

So, with this, I complete discussion on optical sources and detectors and in the next lecture I will now consider the system design aspects.

Thank you.