Introduction to Semiconductor Devices

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Lecture - 11.4
Types of Photodetectors

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Hello, everyone. Let us get started. So in the last lecture, we have seen the fundamentals of solar cells. We have analyzed the operation and we identified a few key parameters that are essential for optimizing the efficiency of a solar cell. So today, we will turn our attention to another class of optoelectronic devices namely photodetectors.

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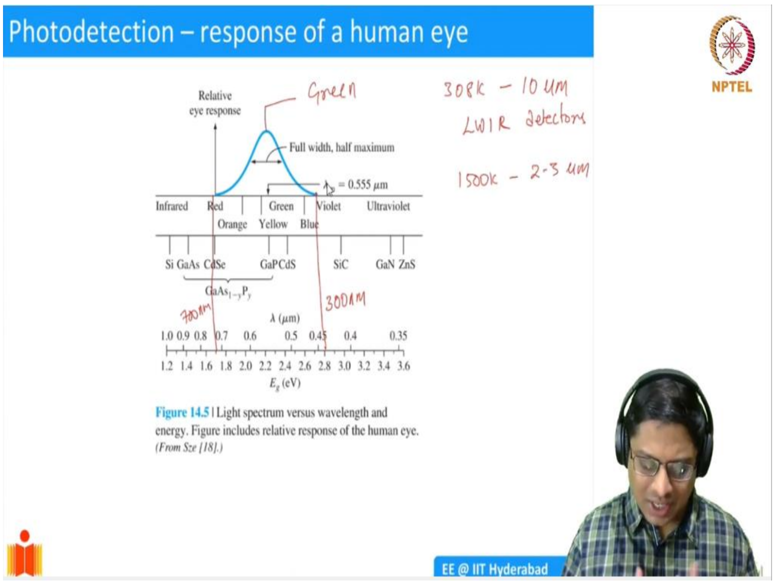

Photodetection – response of a human eye

Figure 14.5 | Light spectrum versus wavelength and energy. Figure includes relative response of the human eye. *(From Sze [18].)*

So, if you look at, you know our daily lives, the most common photodetector that all of us are aware is the human eye. So, it is sensitive to light. So, it turns out that; human eyes sensitive to the visible part of the spectrum. The visible part of the spectrum will lie in wavelengths 300 nanometers to 700 nanometers. So, that is what I am showing here. So, if I draw a line here, let us say here, so, this is about 700 nanometers and on the lower wavelength range it is about 300 nanometers.

So, the axes are actually showing you both energy and wavelength. So, it is increasing in energy and increasing in wavelength this way. So, you see that human eye, if you look at the relative response of the eye, it is having a peak in the visible spectrum. So that is ranging from about the blue region or you know; which is about 350 nanometers to the red which is about 700 nanometers.

So, this is the visible part of the spectrum. And you can see that it has a peak at, let us say green, in the green region of the spectrum; it is very, very efficient. So, small signal in the green spectrum can actually be detected by the human eye very, very efficiently. So, if you think about it, human eye is a very, very versatile system. So we can actually look at the sun directly.

And you know, the pupils will contract and you are still able to even if you have a large amount of light we are able to detect or you go into a dark room, you switch off all the light sources. After some time your eye edges and you can actually see even when if there is some faint light we will be able to see. In fact, recently there were some scientific experiments that were done.

And it was shown that a human eye is So we can actually get it a single photon, if you think about it that is a very amazing thing. Because, if you just think about a regular laser pointer that we use in our presentations. This small battery operated laser pointer, if you shine that typically the power that is emitted by that is about few milli-watts.

And you have seen that and if you hit that you know, if you shine that light, you will see that it is bright and follow the presentations. So in that spot, there are about 10 power 15 photons and we are able to see it quite clearly. Now, you start reducing the number of photons by 15 orders of magnitude and we still can see with the human eye. It is a very, very fantastic is of you know fantastic photo detector in that sense.

So, in some sense, we would like our ideal photo detector has to emulate response a human eye. But is that sufficient for us? Well, it turns out that it is not enough because human eye for all its versatility it is still limited. For example, you cannot see very well in the dark I mean, single photon level it can detect but you need to have you know, it takes a long, long time to detect that.

For example, you know in the Army or you know in the counter insurgency operations, soldiers want to have night vision goggles. You might have seen that they were these goggles which can actually show them in a show the images in the night. How are they operating? Well, it turns out that if you take a human body, we have a temperature of about 38 degrees centigrade.

So that translates to about 308 Kelvin. So, for that particular temperature all of us are continuously emitting IR radiation. So, we emit a radiation in the peak about 10 microns approximately. So, all of us are emitting this IR radiation and if you build a photo detector that can actually measure this IR radiation 10 microns then we can actually see in the dark and this is a technology that we use, you know in the for the night vision we use a technology which is called as long wavelength IR, LWIR it is called.

So, we have LWIR detectors which can enable us to actually see what is there in the dark. So this is what soldiers use in the field. So these are also some sort of semiconducting materials. We will talk about it later on. Another application could be that you know, there are a lot of industrial processes that have temperatures in the range of 1000 to 1500 Kelvin. So, you heat up you know for example, let us say oxidation.

We want to heat it up 900 Kelvin and 900 centigrade actually or you know there is melting on steel and things like that when you have 1000 1500 degrees Kelvin. So, if you have such temperatures, how do you measure that? Well you know you can put a thermometer and measure the temperature because the moment you put a thermometer it is going to melt.

So, for those ranges also for example, if you have 1500 Kelvin, again we have seen the blackbody radiation. So, we said that if you have an object that is heated up to about 600, 6000 Kelvin that will have a peak in the visible. If you have a lower amount of heat for example 1500 Kelvin, its peak radiation would be about you know in the range somewhere between 2 to 3 micrometers.

So, if you are able to build a photo detector that can detect 2 to 3 micrometer radiation, then it can be used in industrial applications. I mean, another common example you might see is an automatic door openers. They operate in the near infrared. So, whenever you go near an object, it has an IR and then that IR will be detected and the detector detects that there is a person and it opens the door.

So, these are all different applications of a photo detector. And so, today, we would like to understand the basic principles of these photo detectors.

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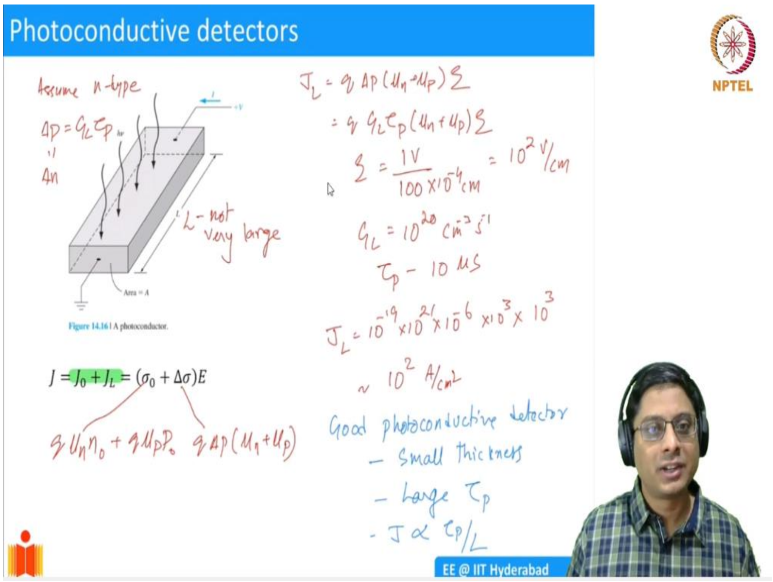

Photoconductive detectors

Assume n-type

$\Delta p = G_L \tau_p$

Δn

L - not very large

Figure 14.16 | A photoconductor.

$J = J_0 + J_L = (\sigma_0 + \Delta\sigma)E$

$q\mu_n n_0 + q\mu_p p_0$ $\quad q\Delta p(\mu_n + \mu_p)$

$J_L = q\Delta p(\mu_n + \mu_p)\mathcal{E}$

$= q G_L \tau_p (\mu_n + \mu_p)\mathcal{E}$

$\mathcal{E} = \frac{1V}{100 \times 10^{-4} cm} = 10^2 V/cm$

$G_L = 10^{20} cm^{-3} s^{-1}$

$\tau_p - 10 \mu s$

$J_L = 10^{-19} \times 10^{21} \times 10^{-6} \times 10^3 \times 10^3$

$\sim 10^2 A/cm^2$

Good photoconductive detector

- Small thickness
- Large τ_p
- $J \propto \tau_p / L$

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So, to start with let us look at you know, the one of the simple photo detectors which is a photo conductive detector. What it does is; you take a piece of silicon or any semiconductor. Silicon is the most common one. So, you take a piece of silicon and you shine light on it. What happens? Well, if you know the light produces electron hole pairs. This is a story, we have been telling many, many times during this course.

So what happens if you produce an electron hole pairs? Well, you can actually detect the change in the conductivity of that piece of silicon. So for example, if I shine right here, I am showing an image of its semiconductor and you have some light incident on it. There is some light incident on this and we are applying a certain voltage to the semiconductor. So, this is a bar of semiconductor of an area A and length L.

So, if you apply voltage, there will be some current. We have already seen this. This is the drift current that flows in the semiconductor. So, the drift current I can write it as you know, σE, which is in the Ohms law. The σ would be, we have seen it multiple times. So, q times mobility of the carriers times the concentration of the carriers.

$$J = J_o + J_L = (\sigma_o + \Delta\sigma)E$$

Let us say, there is n_o of electrons there. Mobility is μ_n and times charge + $q\mu_p P_o$.

$$q\mu_n n_o + q\mu_p p_o$$

So these are the equilibrium concentration of the semiconductor. There will be some cons, you will see some current flows in the semiconductor. Now, when you shine light, they are going to produce additional electron hole pairs. And they are also going to cause current.

So how many electron hole pairs are produced? Well that depends on you know, how much light you are shining? Let us say you know, there are equal you know, amount of electrons and hole pairs. So, let us say we will assume n type semiconductor. So, if I assume that and shine light, let us say the minority carriers will be basically the holes.

The excess minority carriers will be proportional to the generation rate times the minority carrier lifetime τ_p. So, this is the number of holes that are produced this case. And of course, this will be equal to Δn which is the number of electrons and after some time, they are going to recombine. So, because of these excess minority carriers, what is the conduction that is achieved? Well that turns out to be if I can write it here.

$$q\Delta p(\mu_n + \mu_p)$$

So this you know, since Δ n and Δ p are equal, I just mentioned only Δ p. So, this will be q Δp times mobility of n times + mobility of p. So, this is the conductivity for excess connectivity. So, this is what is produced in a semiconductor. So, what we can do is we can detect this light induced current and what will this light induced current be?

Well, you have you know, I have separated out the DC or you know, the background current and the light induced current. So, the light induced current J_L will be equal to q times Δ p times μ n + μp times electric field. And this Δ p of course, is equal to G l times generation times, τ p, times μ n + μp times electric field.

$$\begin{aligned} J_L &= q\Delta p(\mu_n + \mu_p)E \\ &= qG_L\tau_P(\mu_n + \mu_p)E \end{aligned}$$

So, since we know the semiconductor physics, we can actually think about it you know qualitatively what should happen.

When will this detector be good? One of the conditions is that the length of the detector must be small. The reason for that is, if you have a large length, let us say know 500 microns length. What happens to the generated electron hole pairs? We know that they will quickly be combined. So we do not want that recombination to happen before they can recombine. We want current to actually flow into the external circuit.

So for this, we have to for a photoconductive detector to work efficiently, we need to make sure that the length of the photodetector L is you know, reasonable you know, it is not very large. L is not very large. The reason is, if it is large, it is going to the minority carriers are going to recombine. For example, in the center of the silicon, you generate the electron hole pairs but they will recombine before they reach the terminals.

We do not like that so, the L should not be large. There is another reason why L should not be large. That is, we are having the electric field here E. So electric field will simply be the voltage dependent divided by the length. So, for example, if I say apply electric voltage of 1 volt and I take my detector length to be let us say 100 microns just as an example, 100 microns will be how much? It will be 10 power – 4 centimeter.

So, how much will this be? 1 – 10 power – 2. So basically 10 power 2 volts per centimeter.

$$E = \frac{1V}{100 \text{ x } 10^{-4} cm} = 10^2 \, {}^{V}\!/_{cm}$$

And we have already seen when studying drift current that 10 power 2 is not really a large amount of electric field. We saw that in the PN junctions the field is about 10 power 4 volts per centimeter. So, there is not a large field. So, if you want to increase the field strength you have to reduce the size of the; detector maybe choose 10 microns or even 1 micron.

So, that is one aspect of it. The other aspect of it is that if you choose a very, very thin detector. First of all it is mechanically difficult to fabricate even if you manage that the problem would be you need to have significant amount of light absorption. And light absorption is going to be proportional to the length of the detector. You cannot have a very very small detector and expect to produce a lot of electron hole pairs.

So that also comes into picture. So, the overall performance of the detector will be you know dependent on these parameters. Let us take some simple examples and try to estimate how much is a current that is produced by such a photodetector? Let us say now we know generation rate let us assume the generation rate to be let us say you know 10 power 20, per centimeter cube per second. This is the rate that I am assuming.

So, how many photons will it give per you know, in this case, what is the photon flux? The photon flux with the amount of photons that are producing photons or rather the number of minority carriers that produce is going to be G times τ τ_p will be typically about you know in the semiconductors. It will in silicon it will be 10 microseconds maybe. That is typical number in indirect band gap semiconductors.

So, we can compute you know. So, let us say here, if you try to directly estimate J. J_L is going to be, I will just do an order of magnitude estimation 10 power – 19 Q and this is 10 power 21, τ_p will be 10 power – 6. Mobility is you know for n type it is 1350, n for p type it is 400 I will say again, I will just roughly put 10 power 3 1000. And electric field let us say I managed to make 10 micron thickness of the semiconductor.

So, I will make 10 power 3. So, what will be the order of magnitude of this type? So, 3 + 3 6, 6 will go out here. So essentially you have 10 power 2 per centimeter square. Well, this is kind of you know, the range that you will expect. What you need to realize is? This is much more significant of course, if you design this optimally choose the length to be small and you have a large amount of light incident then you can get large connects.

This is much, much stronger than the reverse saturation current that you had have seen in the PN junctions. So, what do we need to make sure that you know there is a good photo conductive detector? Well, for a good photoconductive detector, you need small thickness. This is one of the requirements and you need large τ_p. So, if you have small thickness, basically the kind of the current that you produce J is proportional to τ_p.

Because, if you have larger minority carrier lifetime it will stay longer recombination not happened. So they will actually go into the terminals. And then it is inversely proportional to the length if you have a small length and actually will get large current. So both of these things, this is the typical expression that you can have. So, this is photoconductive detectors.

But you know, these are good but it is very difficult to design some of these in some light applications we use, we like them, we actually the high speed applications, we like photoconductor detectors. But we have another mechanism that we can use to build photo detectors. Now, for example here, if you make the thickness very small, you are not generating sufficient number of electron hole pairs.

Because the thickness is small, the absorption of photons will be small. And so electron hole pairs will be small. Sometimes we might want to actually generate larger number of electron hole pairs. So how can we do that? We do not have that much of control. So, what we do is? We extend this we actually build at it instead of a simple piece of silicon; we can build a detector out of a PN junction.

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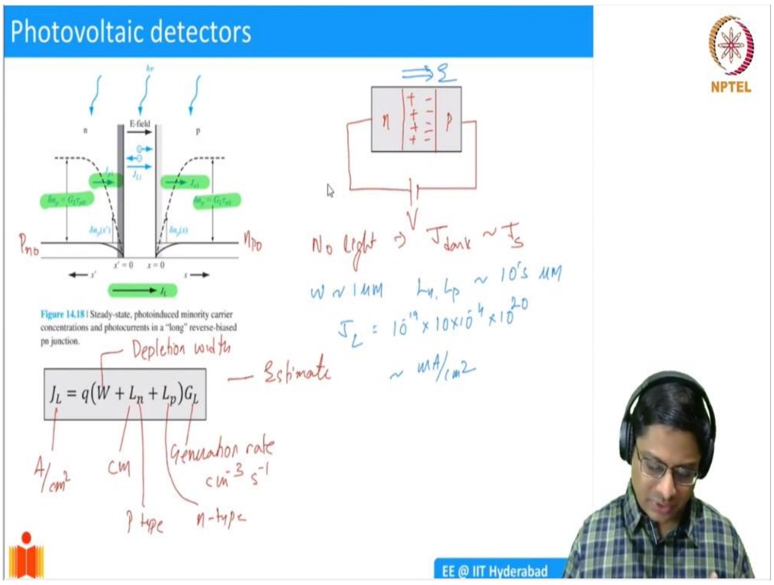

Photovoltaic detectors

Figure 14.18 | Steady-state, photoinduced minority carrier concentrations and photocurrents in a "long" reverse-biased pn junction.

$$J_L = q(W + L_n + L_p)G_L$$

Depletion width

— Estimate

A/cm^2 cm p type n-type

Generation rate $cm^{-3} s^{-1}$

No light ⇒ $J_{dark} \sim J_s$

$W \sim 1 \mu m$ $L_n, L_p \sim 10's \ \mu m$

$J_L = 10^{-19} \times 10 \times 10^{-4} \times 10^{20}$

$\sim mA/cm^2$

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And those detectors are called as photo volatile detectors. So, for example, I can take a PN junction, we have already studied this in great detail. Let us say, I take a PN junction. I do not like the shape. So, if you take a PN junction and you know, so I want to refer to this diagram, so I will basically write it in the same way. So, I will take n and p here. So I will have positive charges here.

And negative charges, just reverse the polarity that we have typically taken. So, because I want to be consistent with the diagram on the left. So I can apply a reverse bias to this. When I apply reverse bias, I can control my depletion width and I can increase my depletion width. So what happens in this case? Well, you will see that there is you know, a strong electric field in the positive x direction.

So now, if you do not do anything. Let us just apply this voltage and wait, what happens? Well, we have studied you know, the reverse bias operation of the junction. So what happens is? Let us say this is your x = 0 is the edge of the n region and this is the edge of the p region. So, you have the depletion region but add let us say this is a p type on the right.

So, this should be the equilibrium concentration of electrons which I can write it as n_{po}. Let us say equilibrium concentration of electrons in the p region. And you can have in the n region you will have minority carriers P_{no}. And we have seen that closer to the edge of the depletion region the minority carrier concentration reduces. That is because; there is an electric field which will sweep the holes to the right and electrons to the left.

Causing the you know, over a certain diffusion that we saw that the minority carrier concentration will reduce. So, this is what happens when you know, have simply have no light present or just you know, a PN junction. So, there is amount you know of no light. Let us say, no light implies, we call it the certain current which flows which is called as J dark. Dark current we say without any light.

So, this will be for roughly equal to the J reverse saturation. If you do not apply any voltage or you know small voltage, do not go to the breakdown, then essentially yes, it will be roughly flattered. We have seen the PN junction highly characteristic that will the be dark current in a photo detector. Now, if you shine light, what happens? Well, if you shine light, you are going to introduce minority carriers.

And how many minority carriers are you going to introduce? Well, in this region, you are going to introduce the light whatever you know generation rate, times the minority carrier lifetime which is τ_n. And on the left, you are going to introduce generation rate times, the minority carrier lifetime may be. But because of the electric field present, these carriers are again driven away the electrons will be sorry, the holes will be driven in this direction, the electrons will be driven in this direction.

Sorry, minority carriers are electrons here, so electrons will be driven in this direction that is why the electron current is in this direction. And similarly the whole current is in this direction. So current flows in the plus x direction. So that is what we are showing here. And the total amount of current for this detector, it turns out that it will be this expression here in the bottom.

We are not deriving it. I do not think we need to derive it. The current is going to be equal to the generation rate this is generation rate. This will be the units of per centimeter cube, per second of course. And this is length this will be centimeter. And so, this is charged that is how you get this to be in the amps per centimeter square. So, this is how I remember usually.

So, what you see is? The current that you are producing in such a scenario is dependent on the width of the depletion region of course.

$$J_L = q\left(W + L_n + L_p\right)G_L$$

This is depletion width and the minority carrier diffusion length and the majority carrier deficient rather not minority carrier diffusion length in the sorry I should say majority carrier. It is both minority carrier diffusion length but this Lp is for the n type region Ln is for the p type region. These are both minority carrier diffusion lengths.

This is for p type region minority diffusion lengths. N is a minor carriers and that in here it is for the n type region. So, now what will this current be typically? Well, we know some estimates. We know that W, let us say is also order of our micrometer, L_n and L_p you know, L_n, L_p are typically in the range of 10s of micrometers for silicon. So, if you take a similar situation as last time whatever we are taking generation rate to be 10 power 20.

The J_L turns out to be equal to this is 10 power – 19 times, I will take 10s. 10s of micrometers so, 10 into 10 power – 4 centimeters into 10 power 20. So, this is roughly what you will see? Well they should also be time you know this is directly the generation rate but of course there is going to be some absorption coefficient. That we will anyway discuss later on. So, you can estimate how much the current is going to be?

This is going to be roughly 10 power – milliamps or something like that you know, roughly about milliamps per centimeter square. But the beauty is that because you have a large depletion, now I can increase my reverse bias. If I increase my reverse bias, I am going to extend my depletion region and thereby collect more photons. The absorption you know, we have not accounted for absorption.

In the photoconductive case, we said that you know, we implicitly assume that all the photons are absorbed in that region which is not going to be true but if you the thickness is small then might be valid. But in the case of photo volatile devices, you can adjust the depletion width and thereby increase the number of photons absorbed. So, that is how we want to use this.

So, this is a simple photovoltaic device. And by the way, I mean this expression is an estimate because you know, there are certain assumptions. So that are made, we will discuss that later. This is a rough estimate; it is not like a very perfect number. Alright, so if you have such a scenario, what will be the current?

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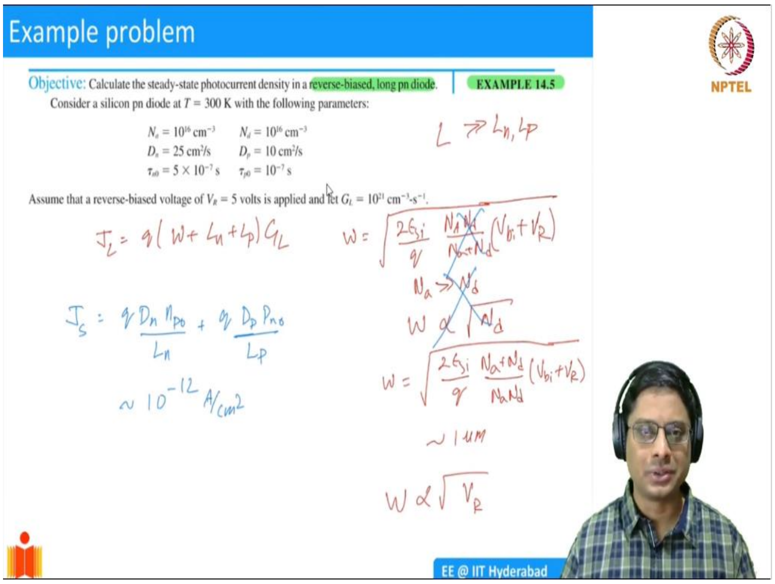

Example problem

Objective: Calculate the steady-state photocurrent density in a reverse-biased, long pn diode. EXAMPLE 14.5

Consider a silicon pn diode at $T = 300$ K with the following parameters:

$N_a = 10^{16}$ cm^{-3} $N_d = 10^{16}$ cm^{-3}

$D_n = 25$ cm^2/s $D_p = 10$ cm^2/s

$\tau_{n0} = 5 \times 10^{-7}$ s $\tau_{p0} = 10^{-7}$ s

Assume that a reverse-biased voltage of $V_R = 5$ volts is applied and let $G_L = 10^{21}$ cm^{-3}-s^{-1}.

$L \gg L_n, L_p$

$J_L = q(W + L_n + L_p) G_L$

$W = \sqrt{\frac{2\epsilon_{si}}{q} \frac{N_A N_d}{N_a + N_d} (V_{bi} + V_R)}$

$\cancel{N_a \gg N_d}$

$\cancel{W \propto \sqrt{N_d}}$

$J_s = \frac{q D_n n_{p0}}{L_n} + \frac{q D_p p_{n0}}{L_p}$

$\sim 10^{-12}$ A/cm^2

$W = \sqrt{\frac{2\epsilon_{si}}{q} \frac{N_a + N_d}{N_a N_d} (V_{bi} + V_R)}$

$\sim 1 \mu m$

$W \propto \sqrt{V_R}$

Let us try to take an example problem here. So, this is again from the textbook. So, you can go back and look at 14.5 of even. So, calculate the steady state photocurrent density in the reverse biased, long PN junction. That is the kind of assumption we are making implicitly. We are saying that the length of the photodetector is greater than or, much greater than L_n L_p and so on.

So we want it to be long so that you know, it is the minority carrier diffusion length is smaller than the length of the detector. And you are given some parameters and you are asked to calculate. Well, what we have to do? We have seen the expression was you know, in this case, photo voltaic device. So PN junction, so,

$$J_L = q\left(W + L_n + L_p\right)G_L$$

is one way to calculate.

So how do you calculate the width? Well, we know the width of the junction for a PN junction. In the PN junctions we have

$$\cancel{W = \sqrt{\frac{2\varepsilon_{si}}{q}\frac{N_A N_D}{N_A + N_D}(V_{bi} + V_R)}}$$

In this case, we are reverse biasing. So, let us see some reverse bias. So, this is a width of a junction. Well, is this expression correct? How do we analyze this? So, I always get confused whether $N_A + N_D$ should go on the top or in the bottom.

So, if it goes in the bottom like this, will this be correct? Well, the way to check that would be, let us assume that you know $N_A >> N_D$. So, what should you determine your width of the minority carrier, how if you do this scenario what will happen? So, if you do this, your width will be proportional to root of N_A is much greater so N_A will cancel out, N_D
So, what we are saying is, if p type is heavily doped N type is going to determine your width and as you increase the width of the sorry doping concentration of the N region your width is going to increase and clearly, this is wrong. This should not happen. Because we saw that as an increase the doping of the N type, the width of the depression return should reduce.

And that is our basic understanding of PN junctions. So, this expression is wrong, I should correct it. So, I mean so, you see, you do not have to remember these expressions, by q should be N a + N d divided by N a N d times V bi + V r.

$$W = \sqrt{\frac{2\varepsilon_{si}}{q}\frac{N_A + N_D}{N_A N_D}(V_{bi} + V_R)}$$

So, if you substitute and we have done it you know many, many times, so this will be in the range of 1 micrometers let us say. So, I leave you to estimate how I mean, we have done this indirectly? Well, this is what the current is going to be.

One significant point that I want to make is, if you compare this to the saturation current, remember J_s. This was your saturation current in a diode and that was proportional to the minority carrier concentration. So q I think there was a D n and N p0 divided by. I think it was L L n + please verify this formula D p P n alpha P n0 divided by L p.

$$J_s = \frac{qD_n n_{po}}{L_n} + \frac{qD_p P_{no}}{L_p}$$

So, here you saw that this was typically in the range of 10 power – 12 amps per centimeter square.

So, this was Pico amps kind of current, where as you see that if you have light induced current you have about millions amps or even hundreds of microns amps or even higher. So, these are very, very efficient detectors. So, we saw that if you use a simple photodetector there is not much flexibility we had too many constraints. So, to overcome those constraints we have gone to PN junctions, wherein you can control the width of the depletion region.

But what is a typical range over which you can control the width of the depletion region, it is not really that much Again, because it can go from about you know, 0.1 micron to about 1 micron maybe 1.5 microns, it is you know large voltage. Basically, the width is going to be proportional always to the square root of voltage. If you do not have any voltage, typically about you know, 0.1 micron. Even if you increase the voltage, you are not going to get that much of benefit.

We still want to increase it further. And the way we achieve that is actually by using another type of photodetectors which are called as avalanche photodetectors. So, I will talk about that in the next video. Since it is already 30 minutes, I would like to stop the video here. And I will record another video where I talk about the avalanche photodetectors and also the various metrics that can be used to analyze the photodetectors. So, I will see you in the next video. Thank you very much for your attention. Bye