Introduction to Semiconductor Devices
Dr Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology – Hyderabad

Lecture - 11.5
PIN and Avalanche Photodectectors

Welcome back. So, in the previous video we discussed the 2 basic types of photo detectors: the photoconductive photo detectors and photo voltaic photo detectors. So, in this video we would like to go forward. So, we were talking about improving the current the photocurrent that we produce in a photo detector and one of the key parameters was to increase the width of the depletion region in a PN photo voltaic detector or in the detection region we want to increase.

So, we saw that if you take a simple photo simple PN junction, we cannot really increase the width that much because of the inherent limitations.

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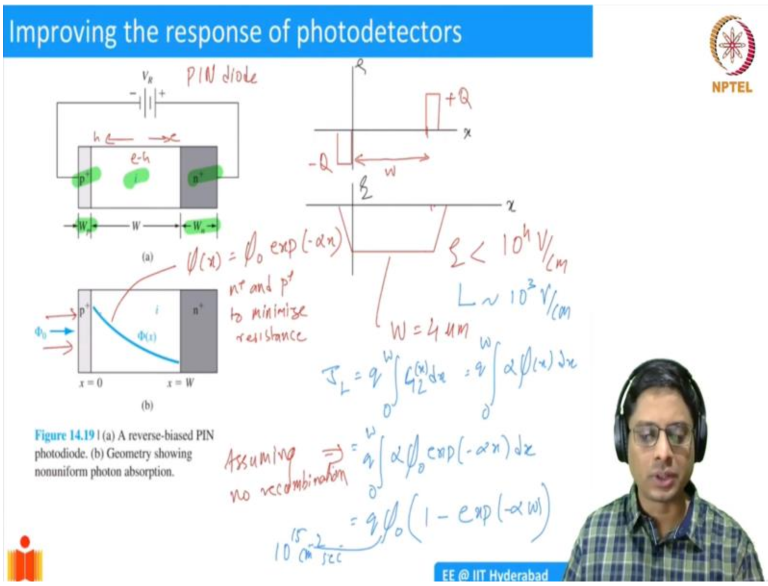

Improving the response of photodetectors

Figure 14.19 | (a) A reverse-biased PIN photodiode. (b) Geometry showing nonuniform photon absorption.

So, one of the alternatives is to actually use what are known as PIN junctions, you know PIN photodiodes. So, we have already studied this in the context of PN junctions, if you use a PIN diode. So, you have a p type region and then n type region and a sandwich in between that you have intrinsic region. What is the advantage of this structure? Whether we have the simple PN junction? Well, we will see that so, the widths are this much these are the standard numbers.

So, let us say, if you have a PIN junction and we applied some reverse bias. So, what would be the field in this system? So, well to analyze that we have done it multiple times in our PN junction analysis. So, let us say you have the x and then the row, the charge density I want to plot. So, you have a p type region on the left, so I will have it now when it is depleted you have charge space charge which looks like this.

And then you have the width of this somewidth and then after that you have basically a balancing charge, positive charge which is coming because n type semiconductor be depleted. So, what you have is + Q here and a − Q here and the separation between them now is going to be the width of the intrinsic region. Why is this useful? Well, if you have such a scenario, we have also computed the electric fields and the electric field should look like you know, you should remember this

We have even done a Nanohub exercise on this. So, x let us say this is electric field, we know that electric field is going to be you know, pointing in the minus x direction. So, it has to be a negative field. And it will essentially show sharp rays here linear in the depletion region. But because there is no charge in the intrinsic region, it is neutral by definition, it is basically n = p there and there is nothing to deplete there is no space charge in that region.

So, what you are going to get is a flat electric field there is no change in the electric field in this region. And then there is going to be linear variation again in the n type region. So, this is the type of electric field and we have seen that this is electric field is definitely smaller than you know 10 power 4 volts per second that you see in a typical PN junction. This might be of the order of you know maybe I do not remember now but 10 power 3.

I think 1000 volts per centimeter is what we have seen, I think for some 3 to 4 micrometer widths. So, back what we are essentially doing is, we are creating this electric shield which will make the carriers move in opposite directions. For example, if I have electron hole pairs which are produced right in the center here e h, what happens the electric field in this direction.

So, holes will go in this direction and electrons will go in this direction and this electric field immediately separates the electron holes. And because of that the recombination of electron hole pairs is less probable. That is why we like photovoltaic detectors because the recombination is reduced still of course, you know there are going to be some recombination where we cannot completely avoid it. But the probability is reduced because we are making the carriers drift in opposite directions.

So, now that is one advantage of a PIN diode compared to a even PIN diode has it but now the width is you know, in the PIN junction case, the width was only you know limited to the depletion rates which is micrometers. Now, this width of the depletion sorry intrinsic region can be anything that I designed it. Now I can choose a 4 micrometer depletion width. There is nothing that stops me from doing that.

If I do this then I can have more absorption. Now, for example one of the ways to build a photo detector would be to choose a thin layer of p +. The reason we are making it p plus is we want it to actually connect to the external circuit. So, we do not want resistances in the minimize resistances. I will say, n + and p + to minimize resistance, when you connect to the external circuit it is finally electrons that are flowing.

So, once they reach the end, we just want to quickly go into the external circuit, we do not want to have contact resistances. That is why we want to heavily dope the p and n regions. And now, if you have photon flux, let us Φ_o which is incident on this. What will happen? Now, we have discussed optical absorption already. So, if you have this photon flux incident, as you know, let us say there is not much of absorption in the p plus region, it is a very thin region.

And so, what you will see is that there is a gradual decay in the photon count. And this decay is because of absorption. The photons are getting absorbed and that is why the number of photons is reducing. And how is this, this function $\Phi(x)$ is going to be equal to Φ_o which is my incident flux times exponential minus αx. This is going to be my photon flux as a function of position.

So, now, what will be the current? In the previous case, we assume that the electron poles are you know, produced uniformly. But once you have a sufficiently long depletion or you know intrinsic region, it is not going to be true anymore. And that is why I said that in the expression

J_L equal to you know, Q times the width plus Lp and plus Ln times the G_L is an estimation, it is not really correct, because we are ignoring the decay of the photons.

So, what will be the current? Well, in this case, we will have to calculate by you know J_L, let us say, this is simply going to be the charge times the number of photons. And the number of photons, or rather the number of electrons produced that is going to be proportional to the number of photons at a particular distance with the total amount of current is going to be

$$q\int_0^W G_L dx$$

Or rather I should say, if you have G_L is the rate, this is going to at each location is going to produce slightly different number of photons. Because, there is a decay in the photon flux. So, this is going to be equal to $q\int_0^W \alpha\Phi(x)dx$, alpha which is absorption coefficient times the flux at that point. phi of x and dx. So, this is going to be equal to $q\int_0^W \alpha\Phi_0 \exp(-\alpha x)dx$

And so this is going to be equal to $q\Phi_o\left(1-\exp(-\alpha W)\right)$. So, if you have a certain flux incident, let us say this is going to be 10 power 15 per centimeter square per second. So, this will be the discharge will be the current experience will measure in this.

By the way, this is assuming that is no recombination of course, which is an approximation. So, what will this be? What will this current be in a PIN junction? Well, let us try to do a small problem for that.

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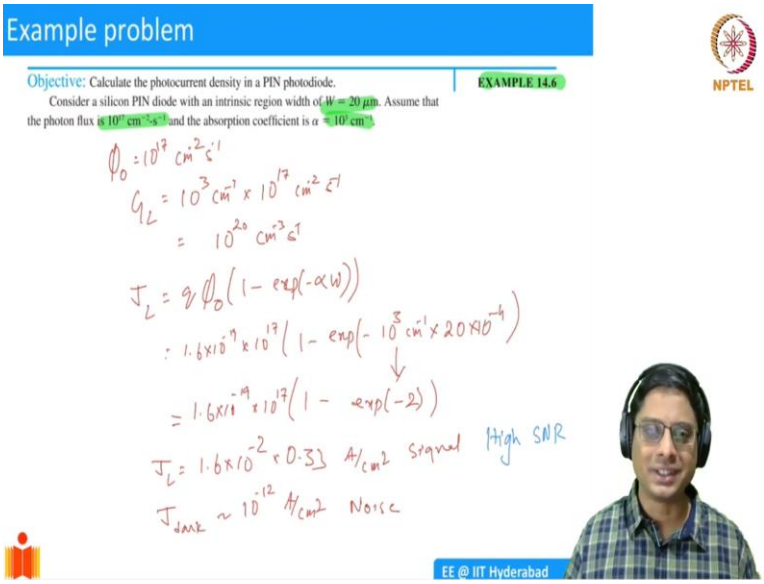

Example problem

Objective: Calculate the photocurrent density in a PIN photodiode. **EXAMPLE 14.6**

Consider a silicon PIN diode with an intrinsic region width of $W = 20\ \mu m$. Assume that the photon flux is $10^{17}\ cm^{-2}\text{-}s^{-1}$ and the absorption coefficient is $\alpha = 10^3\ cm^{-1}$.

$$\phi_0 = 10^{17}\ cm^{-2} s^{-1}$$

$$G_L = 10^3\ cm^{-1} \times 10^{17}\ cm^{-2} s^{-1}$$

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

$$J_L = q\phi_0(1 - \exp(-\alpha W))$$

$$= 1.6 \times 10^{-19} \times 10^{17} (1 - \exp(- \underset{\downarrow}{10^3\ cm^{-1} \times 20 \times 10^{-4}}))$$

$$= 1.6 \times 10^{-19} \times 10^{17} (1 - \exp(-2))$$

$$J_L = 1.6 \times 10^{-2} \times 0.33\ A/cm^2 \quad \text{Signal} \quad \text{High SNR}$$

$$J_{dark} \sim 10^{-12}\ A/cm^2 \quad \text{Noise}$$

So, this is again from the textbook 14.6. So, PIN diode is given to you silicon, it has an intrinsic region of width 20 microns that is wonderful, you have larger amount of collection capability there. Photon flux is 10 power 17. Alpha is this much. So, I mean, this is just plug and chug there is no reason for me to actually do it. So, the incident flux phi not is going to be 10 power 17.

I am leaving the units rather you know, let me write it always remember flux is going to be per centimeter square. The rate is going to be per centimeter cube. So, the current J_L or rather, if you want to write G_L, G_L is going to be what? Alpha times the absorption, what is the absorption coefficient which is now in this case? 10 power 3 per centimeter times the flux which is going to be 10 power 17 centimeter square per second.

So, this is what going to be 10 power 20 per centimeter cube per second. So, similar number as what we have taken in the photovoltaic devices. So, with that what will be the current? So, J_L is basically $q\Phi_o\left(1 - \exp\left(-\alpha W\right)\right)$. This is going to be 1.6 x 10 power – 19 times 10 power 17 times 1 – exponential alpha. Alpha is 10 power 3 per centimeter inverse times W width is 20 microns.

Just please remember you should always put it in centimeters 10 power minus 4 centimeters. So that will be the same thing this bracket, this guy will be exponential – 10 power 3, 10 power – 4, so 2 exponential – 2, 1 – exponential – 2 times this. So, you will calculate it and you see what it is. I do not want do it. Alright, exponential – 1, x 0. 3, 1.66 – 2 will be determine that, square of that.

So, I guess it should be 0.3 or so. 0.3 and so, this is 0.6. Well, I mean yeah 10 power – 2. So, I think 1.6 into 10 power – 2 into this will be somewhere between point 3 something. Check it out. So, this is going to be my amps per centimeter square current. Again, this current is much more significant than the reverse saturation current. So, the reason I am pointing this out is this is the light induced correct.

But in my devices, it turns out that my background is a dark current, without any light. That is J dark that is going to be 10 power – 12 amps per centimeter square. So, this is good for us, signal to noise ratio is going to be high. This is noise, dark current is basically without anything you are getting this current. So that is noise and this is my signal.

So, I like to have high from my detector. Any detector for that pattern, you would like to have high SNR we say signal to noise ratio. You want to have larger signal and smaller noise. So, this is one way of achieving higher SNR. So, there is one more class of photodetectors that we have. We can actually further improve it, now we can even get higher current.

How do we get that? Well, it turns out that we can achieve that by what is known as an avalanche photodiode.

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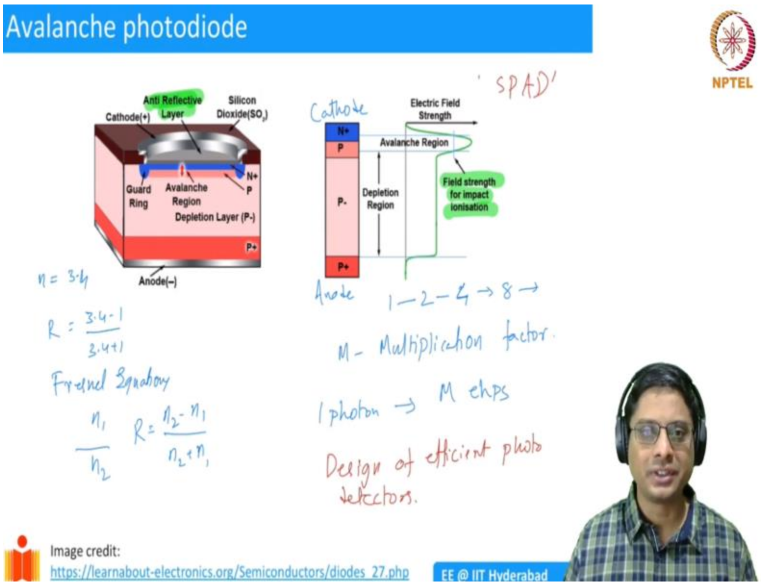

Avalanche photodiode

'SPAD'

$n = 3.4$

$R = \frac{3.4-1}{3.4+1}$

Fresnel Equation

$\frac{n_1}{n_2}$ $R = \frac{n_2 - n_1}{n_2 + n_1}$

1 — 2 — 4 → 8 →

M - Multiplication factor.

1 photon → M ehps

Design of efficient photo detectors.

Image credit:
https://learnabout-electronics.org/Semiconductors/diodes_27.php

So, in this, we will try to exploit the avalanche multiplication process that we discussed. So, before I do that this is basically a structure for a junction you know that an PIN avalanche photo detector that you can make. This is what it is going to look like? You are going to have the basic you know, well anode and cathode when we say anode and cathode. This is called anode and n + is called cathode for historical reasons.

So, you have these things. And then you actually have a top layer which has to be transparent. And we want it to actually transparent as much as possible. We are actually talking about silicon here. Silicon has a refractive index of 3.4. So, if you directly shine light on for silicon from air, it turns out that a lot of light will be reflected and the reflection coefficient is (3.4 – 1) /(3.4 + 1)

So, how much is that? I am not sure, it will be about 40% or so. So, about 40 to 50% of light will be reflected. And rest of it is transmitted and we do not like that. So that is why you know, we can do some techniques by which we can reduce the reflection. So that all of the photons that are incident actually going into the photodiode. This is Frenel equation, I assume that you might have studied somewhere, if not, you can just check it out.

If you have an index, refractive index 2 materials with no refractive index n 1, n 2, the reflection coefficient is going to be

$$R = \frac{n_2 - n_1}{n_2 + n_1}$$

. So, I am assuming light is incident from air on silicon. So, roughly this is going to be the reflection coefficient. It is a different matter. That is why you know just I am trying to give you the justification for what is known as this anti reflective layer. So, we want it to have less reflection.

So that is why we can design that there is some technique we can, you will study some other time. So, you have the anti-reflecting layer. And then below that you make the structure of you know, let us say N + P + and then some other regions in between. Now, we have introduced another P region here, the reason we do that is, if you have an N + region and a P region, you are going to have a large electric field.

We design the structure and doping in such a way that we have large enough electric field. So, the electric field, if you plot it in the vertical direction, it turns out that you know, in the end you do not have much then there is a sharp electric field because of n + p junction and then there is some normal amount of electric field and then finally it comes down here in the P type.

So, it will be designed in such a way that the electric field is in excess of the field necessary for impact ionization. Remember what is impact ionization? We said that if you have a semiconductor and you make electrons you know, if the electrons are moving in a field they get kinetic energy. When they get kinetic energy they will hit another electron or it can actually create one more electron hole pair.

So, the electron can actually hit electron which is part of the covalent bond and actually make it free. So, thereby generating one more electron-hole pair and that process can repeat. So, first, if you have one single energetic electron that can produce to 2. 2 electrons can produce 4 electrons and so on, 8 electrons and so on. So, this kind of multiplication factor, we can actually calculate and I mean there is a lot of careful design that we have to do.

And if you study a purely opto-electronic devices course, you will actually go through all that. But you know, for us what is important is, we want to have a large multiplication factor. What do I mean by this? Well, it just means that in the previous cases for every photon there is no, we would like to have one electron produced. But now, for every photon, 1 photon is now going to produce M into M electrons or rather M electrons hole pairs.

Which is a multiplication factor. So, by just creating this large field region and quickly increasing the number of electrons, thereby I mean increasing the, the current. So, basically, that is it. So well, I mean, I am just giving you a very, very qualitative description. But I hope that you know, it makes you appreciate the concepts that we learned.

Those concepts are actually useful for design. You know you can actually do a design of efficient photo detectors. You will have technology tools which are which computational tools which will help you design all these structures and we can do very accurate calculations. And that is one of the directions that is interesting for us. So, these are again you know, PIN diodes and avalanche photodiodes are another interesting class of photo detectors.

And nowadays, you know we even have photo detectors which you can actually detect at the single photon level. So, we are built and we call them as SPADs, Single Photon Avalanche

Photo detector. SPAD. So, these are photo detectors which are designed very, very carefully to actually detect single photons. And this can be very, very costly.

For example, a single SPAD you know we have in our lab and that costs about 20,000 dollars on the higher end. So, even though these concepts are simple enough for us to understand to actually make it is actually quite challenging. And it is very, very interesting part of technology. It is very unfortunate that we do not have people who are making those in India.

But I hope that you know, with sufficient amount of technical high level technical knowledge, we can do that. So, I will stop this part of the discussion here. So, finally I will record one more video where I talk about the metrics of photo detector. And with that I will close the description. So, thank you very much for your attention. I will see you in the next video. Bye.