Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VII
Module-IV
Detection of light (contd.)

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Hello and welcome to this module on photo detectors. So we will continue the discussion from the previous module, here we will look into the structure of a PIN and APD in diodes okay, avalanche photo diodes for photo detection. This is a schematic of PIN photo diode.

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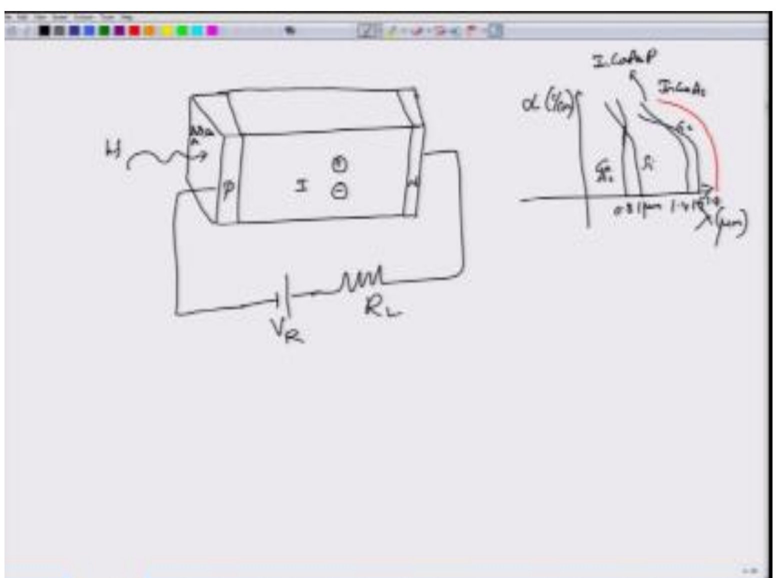

So you see that light is entering from the P side of course, sometimes light can also enter from the end region depending on how you construct whichever is the base material for you or the substrate for you. But the important thing that you have to note down here is that there is a large I section. Now if you just refresh the terminology of semi-conductors P stands for P type semi-conductor which means that it is composed of a pentavalent atoms.

So the intrinsic one is the one where you have equal number of holes and the electrons, therefore there is no net charge out there. Whereas P is the one which has been doped with materials called as acceptor ions right, so they will actually, if silicon is the material to which you have doped, then three of the silicon variants electrons are satisfied right, and then there would be one hole that is remaining or maybe it is actually the five wavelengths electrons which are donated, five which are donated one hole will be remaining.

For the N type material you are actually doping them with what is called as donars. In the donars you will supply them with five wavelengths electrons and one wavelengths electron will be available for each donars right.

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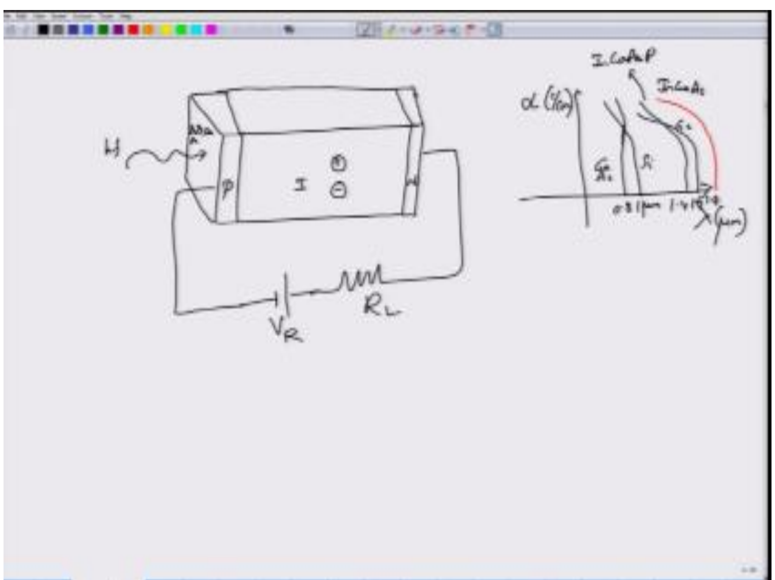

So P region is the one which is positive excess carrier, so these are the holes which it carries. Whereas N carries a largely a negative electrons, because it is contributed by the donar ions which give rise to one wavelengths electron. The intrinsic region is the one which is kind of neutral although in a PIN photo detector that is normally used in the detector designs or photo detector designs, it will be slightly P region okay.

It would be slightly P region okay, this slight PIN comes because of the doping impurities or sometimes it is just internally added in order to manage the electric field okay. If you look at what materials are used for this PIN structure, you can see that there are various materials that are used right, each of these materials by themselves can be used for the photo diode circuit okay.

Each of these materials can be used for the photo diode circuits, what you have to see is that these materials are for the intrinsic region I am talking about okay, intrinsic and the P and N covering regions which I am talking about. What is interesting about these materials if that each of these materials have a large absorption right, so on the Y axis we have plotted the absorption coefficient in one per centimeter.

And here on the X axis is the wavelength axis. So if you look at this absorption coefficient it is actually pretty large for example for silica which I am showing over here, you know you can see my pen movement there, the absorption coefficient is pretty large and then at certain value of the wavelength it is kind of abruptly drops down to zero okay.

At same characteristic you can absorb for any of the material. For example, this Indium Gallium Arsenide if you look at which is shown in the red, there is a large absorption coefficient okay. And then suddenly there is a drop towards zero, the sudden drop is not nicely shown here, but there is actually a almost sudden drop there, okay.

The same characteristic holds for Indium Gallium Arsenide P material, the same thing hold for Gallium Arsenide, the same thing also holds for germanium. Now one sad part of this curve is that, silicon cuts off at one micron. So I cannot really use silicon as a photo detector material for the optical communication systems.

Why, because remember most optical communication systems are operating in the conventional C band and the L band which means they are operating from 1.55 micron right so they are operating in this region where you can either use germanium but it is not very efficient or you can combine this indium gallium arsenide and indium phosphate in order to form a hetero structure or you can straight up use an indium gallium arsenide or an indium gallium arsenide and P material okay.

So in gas P photodiodes are in gas photodiodes or the combination of in gas and in P photodiodes right the sad part is that I cannot use silicon and as we know silicon is the one which is found in VLSI as lot of this fabrication nice properties for fabrication unfortunately they cannot be used for optical communication photo detectors how ever there is recent trend of trained silicon photonics not for detectors but for other materials people are working on that.

So hopefully we will be able to harness all of the VLSL technology in order to come up the silicon materials for optical detection as well in future any way.

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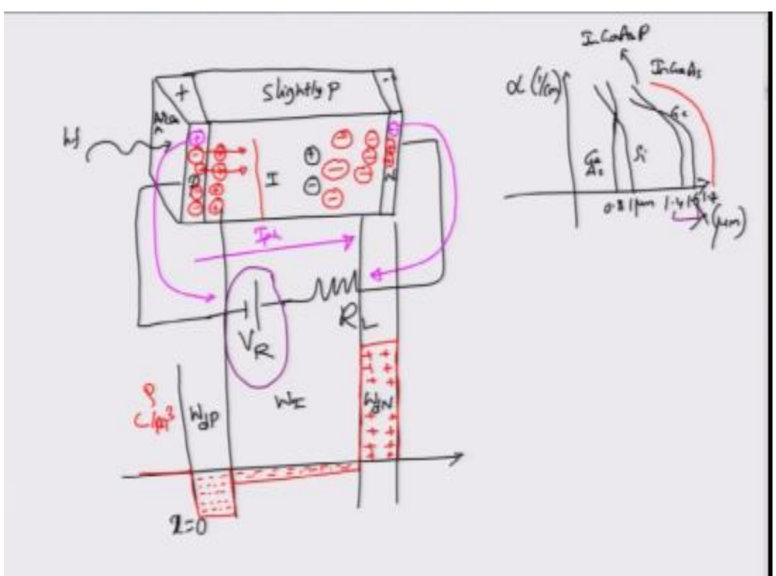

So far now what we are looking at is a structure called PIN structure right when light is you know incident on this one this is one way of incident in light right there can also be a top level incident so you put light from the top so that it directly reaches the inherence region what is the characteristic of this PIN diode that I have drawn here look at where the biasing is if you look at the bias the bias is in such a way that there is a depletion layer in the intrinsic region.

The amount of depiction layer actually starts to increase as you increase the reveres bias voltage correct so as the reverse bias voltage the amount of depletion region also increase what happens during depletion is that due to this negative polarity the wholes which are present here which are carrying positive charges these holes would be attracted and then go to the so this whole actually get attracted and then flows through the battery terminal okay similar the elections in the n region will also be absorbed and will flow through the battery terminal giving rise to a convectional current from this direction.

This would be the photo current that I am obtaining okay in the correction of this one right so but while this wholes and electrons move in this particular way what happens is that they leave behind opposite charge carriers okay these opposite charge carriers are immobile they start extending into the region okay because they are now looking at this side so they start extending into region where in they will create opposite charges in this way so there will be immobile irons layers which are created to balance out them there will be positive charges over the intrinsic region right in fact you can see that this will be this extends if you dope the B side with a very large dope and concentration.

Then this region actually extends into the I region the amount of charges required in order to naturalize the immobile irons on the P side will be much larger on the intrinsic region a same thing will happen on this side as well so there would be this positive charges right which are left behind after all the elections have moved out in order to balance them out you will need a negative charges and it so happens that if you choose the doping profiles in a way that normally is chosen you actually end up having a net number of charges in the I region to be much larger than the plus regions okay.

So if you look at the charge density you know let me draw the charge density for you this we can consider it to be some x=0 and this would be some x= something the depletion layer width from the P side let us call this as WDP the depiction layer from the n side let us call this as WDM P stands for P type, N stands for N-type right, in between let us call this as WI, WI is the intrinsic clear right the charge concentration if you where to draw you will see that the P side region is characterized by heavy negative charges, okay. This is characterized by negative charges because all the electrons that are there sorry all the holes that are there they have flown through.

Only the electrons are left behind, similarly for the n type region you will actually see a positive charges, okay. So you will typically see this is the doping profile n is much more doped compared to the P side region therefore the amount of charges which the n layer occur you know covers will be much larger than this one, okay. So this would be the charge concentration here in-between there is a small negative channel kind of a thing, right.

Is not exactly a channel but it has negative charges, okay. So this is essentially the charge density ρ in measured in per column meter you can say so this is a charge density as a function of the cross section of the length along the photo detector, now while this is charged density how about the electric field?

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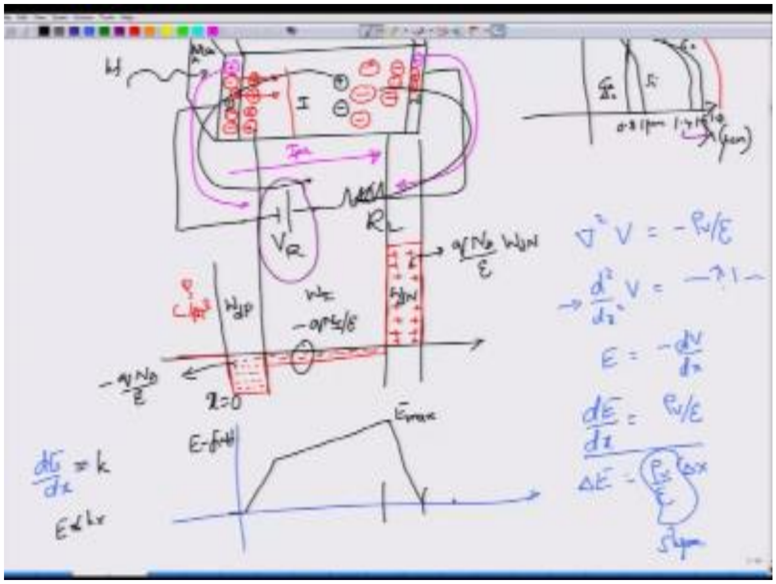

How can you find the electric field from the charge density, well you can use those poisons and Laplace's equations here it is the poisons equation that you are using you know that ∇^2 v = - ρv/ ε, ε being the material permittivity of the semi conductor whatever that we have used and ∇^2 in this case really reduces to d^2/dx^2 because variation is only in one axis, okay. We also know that thi9s is the same thing.

So we also know that electric field is given by –dv/dx in this particular case, why? Because this is gradient of v right but gradient minus gradient of v but gradient in this particular cases this is the one dimensional function, so this is simply –dv/dx right, this is the electric field in appropriate direction there, so you can use this equation dE/dx substituting over here intro this equation.

The electric field equation you can see that dE/dx is given by ρv/ ε incidentally this is one dimensional gausses law as well, okay you can use these equations what it tells you is that, the electric field is basically the charge density divided by ε times Δx so change in the electric field is Δx times this, so this is essentially the slope in a sense, right. So you multiply this slope by Δx you are going to get the electric field.

Let us not do all those calculations because I am not going to carry those calculations for you what is interesting is to actually look at what would be the electric field, there in order to have charge density constant the electric field has to rise linearly right, so dE/dx is some constant k right, is this some constant k then integrating this one will give you E= kx sorry is $E \propto kx$ so electric field has to change linearly whereas the charge density in that particular region is constant.

And we had assumed that charge density which is constant, so what you see is that the electric field rises, okay within this regions so let us try to follow the boundaries which we have already drawn so this is the boundary for the electric field so the electric field will rise to a very peak value this let us call this as E_{max} the amount of this one that it had raised is given by what is a charge density here?

The charge density is qN_d this is the donar charged density, right. So qN_d we will divide this one by ε you are going to get the slope so multiply this one by the appropriate number WDN you are going to get the electric field right, so this would be the electric field that you are going to get at the peak value then the electric field actually slightly reduces while it traverses through the depletion layer. Because here the charge density is negative, right. We can give that charge density as $-qN_i/\varepsilon$ okay.

So because of this negative the electric field reduces a slightly and then the electric field actually drops of to 0 when it enters into the p type material here the charge density is $-qN_A/\varepsilon$ so you multiply this one by wd.p that would be the charge density but which eventually reaches down to 0, okay.

So this is the electric field profile that you can see for a simple PIN structure, okay so any electrons which are generated here or the photons which are the generated they will be moving in the opposite direction, right so you can see from the figure on the top if there is a positive electron whole pair that is generated here then this positive charge will be attracted towards this side, right so they would be attracted towards a negative terminal and it would take this particular direction. Whereas electrons will be going in the opposite direction, okay so this is what you see for the electric field, right.

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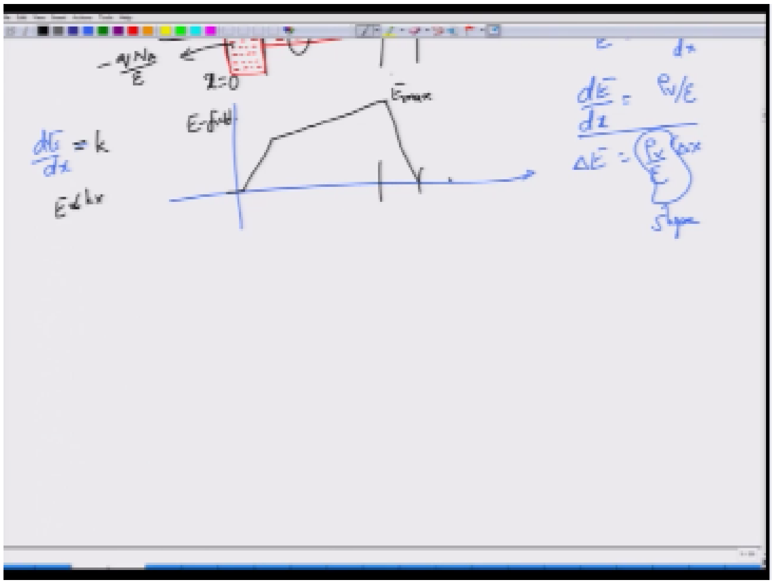

And what is interesting is that you can control the amount of maximum electric field by appropriately adjusting the doping profiles, okay. So you have to adjust the doping profiles and then you can control the amount of the interethnic layer width the depletion layer width by adjusting the bios voltage. It is for this reason that you will also see what is the maximum useable voltage, what is the maximum reverse bios that you can apply to a photo diode, because if you apply more than the internal enteric field will become very large.

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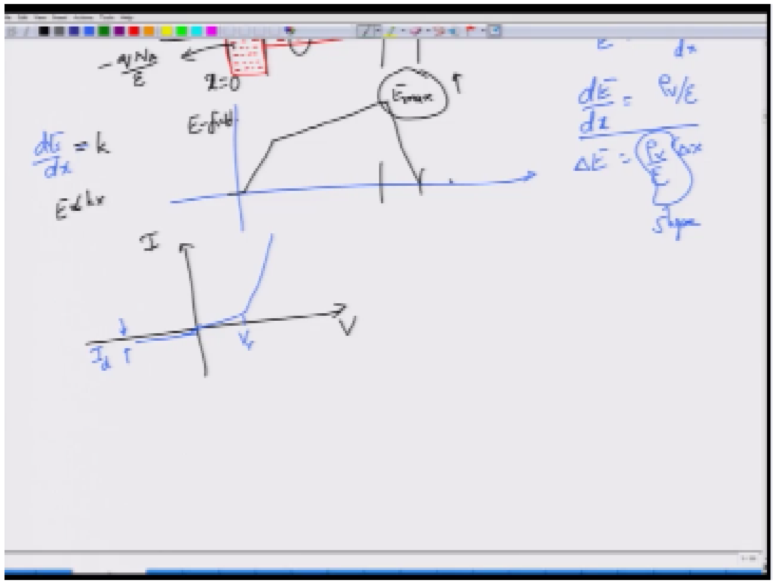

And it might lead to break down of the photo diode itself, okay. Now this is for the electric field all this terms but what you are probably interested if you are designing a photo diode circuit is what would be the current and the voltage characteristic, right what would be the current and the voltage characteristic so if you go back to a simple PN junction diode you already know what the current and voltage characteristic will be right. So you start typically with some very small dark current sorry, very small negative current and then the current will be and then it will start slowly to raise and then eventually it will raise of, right.

There is this cut in voltage on the positive voltage access, if you forward biasing you are going to get this. This is for the case when there is no elimination, there is no elimination therefore this current can be thought of as the dark current, what is dark current, what is dark about it. It is simply that there has been no optical input here. But what would happen to this curve when you actually reverse bios and apply certain amount of optical signal, so consider what happens at v=0. We have short circuited the PIN junction, right so by short circuited in the external side we have not kept any potential difference between that.

But there is a depletion layer inside because there is an in build depletion layer and I will supply some optical energy which will create electron whole pairs, and this electron whole pairs because of the in build electric field which is already there they will move in the opposite directions causing a certain amount of current. So even with v=0 external voltage applied to 0 you still end up having some amount of current, okay.

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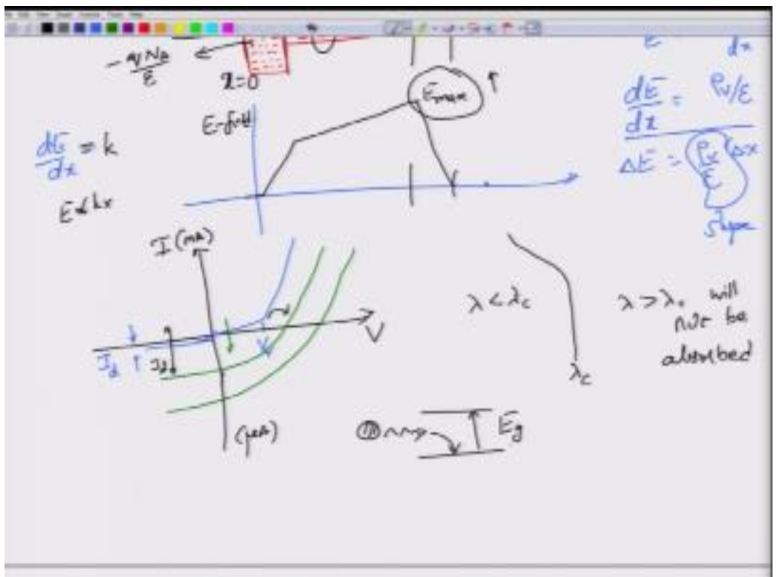

So that is why the graph simply moves vertically downwards, so what you see is this type of a graph, okay this is of course slightly exaggerated not slightly it is been exaggerated pretty badly, so what you can see is that the vγ the cutting voltage that you would have seen for the photo diode without any elimination would actually become larger and larger at the same time the reverse current will also keep increasing, okay. this is the IV characteristic of a photo diode, okay.

Of course you have to understand that this scale here on the positive is in milli ampere hours whereas the scale here is in the microampere case, okay. One last point about the materials before we move on, we said that if you take a typical material semi-conductor material which we are looking for the absorption of light you see that there is a drastic cut off right at some cut of wave length δ c any δ that is photons of wave length δ > δ c will not absorbed this is important to would not be observed only those δ within which have δ<δ c will be absorbed why is this well it terms of that if you go to quantum mechanics of the material that are there what exactly is this happening is you coming with the certain photon okay.

A photon comes in falls on to the photo diode then it gets absorb by the atoms in the ground state okay, there by promoting a electron or a particular atom on to the upper state okay. This can happen only when you consider light energy which is greater than the energy band gape available okay so if it is less than you would not be able to absorb so it would not absorbed it would simply be transmitted.

Then we say that this particular material is transparent when it cannot be absorbed right so you want your hc /δ which is the energy c/δ is f so hc / δ is the energy.

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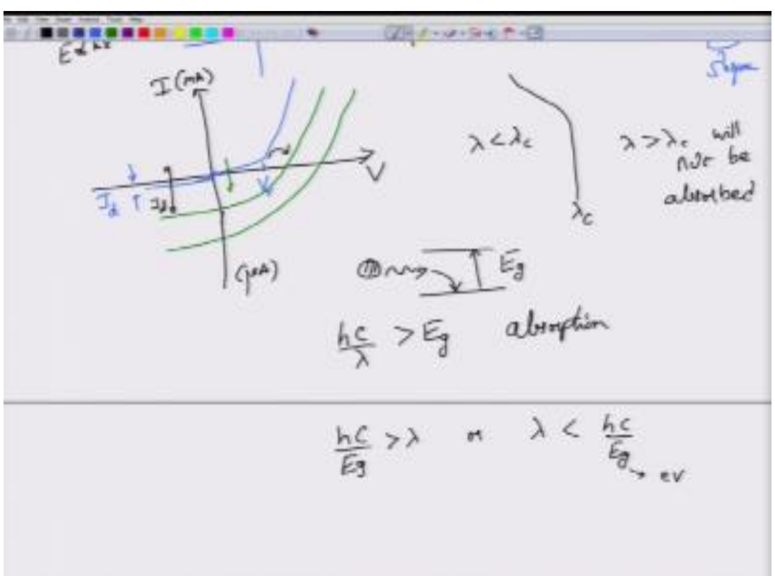

This energy should be greater than Eg for absorption right absorption so it has to be greater than Eg it turn around this equation you can see that hc/Eg must be greater than δ or δ has to be greater than δ. So what would happen here hc/Eg x δ > δ or δ < hc/ Eg correct, so you can put in the typical value of h which is that 6.6 x 10^{-34} and c value you can put in and express Eg in terms of electron volt.

So how do I express energy in terms of electron volt divide that one by 1.6 x 10-19 that would be the volt of an electron right so if it is moves through one volt that would be the energy that the electron would gain so if you express this quantities then a nice way of remembering.

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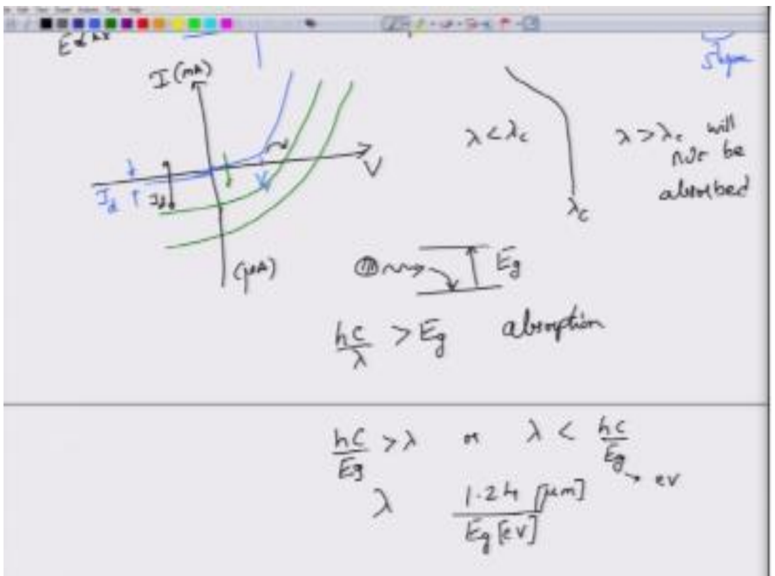

This cut of condition is that δ has to be 1.24 micron did we get this correctly we want hc/δ > Eg so you need to have okay alright so we have obtain this one so δ < 1.24 micron divided by Eg when you express this one in electron volt. Oaky so this is what differentiate between absorption and no absorption okay so we now have looked at the PIN junction diode a small change in to the PIN will give you APD diode okay.

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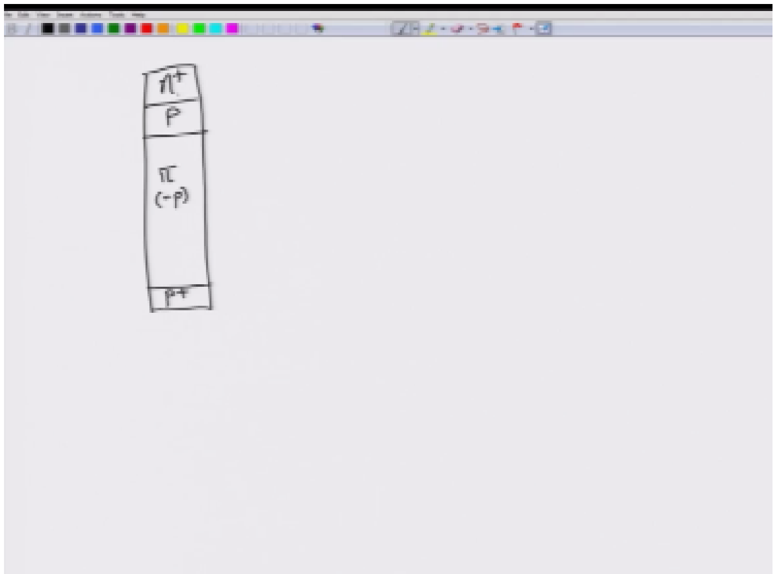

APD is structure let me first draw the I would not draw the structure as such I will simply indicate the layers over here so it is starts off by having the thin p+ region a large π region okay this is the intersect region but this is mostly and very small amount of p material doped okay so this π layer is mostly small amount of p layer doped there would be one more p region and this is important there is a n + region okay.

N+ region is a heavily doped electron you know heavily doped with donors which give you electrons so there is a large number of electrons over here and this is heavily doped. And this is also typically + doped or at least very highly doped so you will actually see that here is a large electric field gradient over here because once this is reversed by us this will leave behind a lot of positive charge carriers over here the ions there and p will be negative.

So there is a large gradient of the electric field okay so if you sketch the electric field itself you will see that a large electric field, you know you going to get over here, and then there is a drop of the electric field, because this region becomes negative right? This was the simple PIN type of structure, of course it's not N here, but it's just PNI type, and here what will happen is because of this P+ region, okay so there would also be this holes which will become, sorry this will make this fellow negative by a large amount and the electric field will go down to 0, okay.

If you dope it slightly or if you reverse bias voltage is not very high then this electric field gradient will not be very large, okay, so it would looks something like this, so this would be the case for low bias situation, unfortunately for this situation you want really get the effect of the multiplication layer, because you need a certain amount of E minimum in order to for the impact ionization to occur, Because electric field carries certain amount of energy ½ epsilon e $^{2\,i}$ is the energy that is carries typically.

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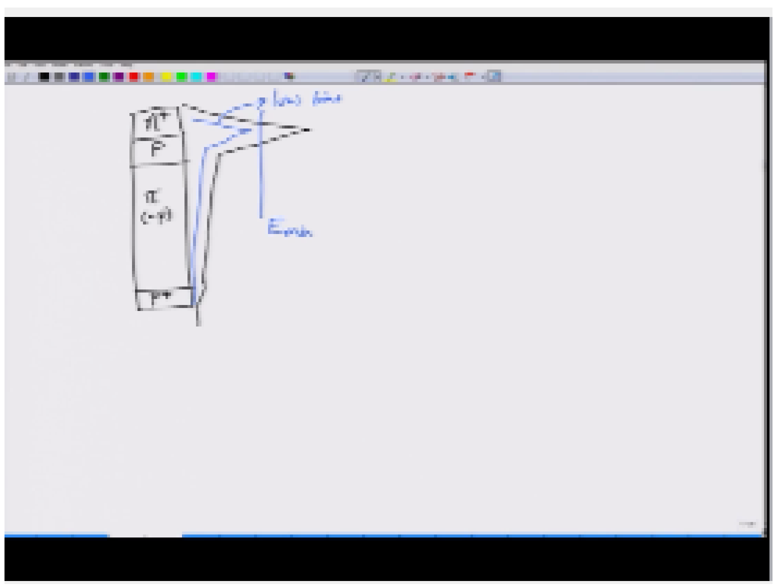

So unless that energy will be greater than the lattice constant of the material it won't be able to kick that lattices which are in the absorption as in the multiplication region, in order to release the secondary HP's, okay to release the secondary EHP's impact ionization you have to kick them very hard, and that can happen only when the electric field is of sufficient value such that there is enough amount of energy to kick them and then generate the secondary EHP's.

Because this generates secondary EHP the responsibility of an APD is multiplied by a factor called M, M is the multiplication factor, it turns out that this multiplication factor is the statistical parameter, you cannot say that M=10, OR M=20, or know with the predicated value M can be measured, okay its mostly measured and power fit in curve fitted to find the value of M for a given structure.

But you can’t in general say that this is the value of M, a you know with any nice precision, so this is slightly statistical parameter infect this shows up in the EPD noise as well, which we will see in the next module we will see that because of this multiplication factor even the noise kind of becomes large in the EPD structure compare to PIN structures.

Advantage larger current gain also turns out this can be made to work very fast, okay but large current gain is the primary advantage of APD’S, disadvantage is that the signal to noise ratio suffers a little bit, okay. But they are very useful for measuring extremely low optical powers, okay.

The responsibility for the APD is m times, the responsibility of the PIN diodes so whatever the quantity that you get as a straight factor of 1, for the APD it becomes factor of m multiplication, okay one interesting thing about this one is that typically light enters for an APD in this way, so it's actually enters from the n+ region, light is incident from this region then, and this n+ region is made sufficiently thin so that most of the light is actually coming through the P region, again this P region will also be made in such a way that light does not really get absorbed much there. Now how can we ensure that it does not happen, I mean what can we do about that?

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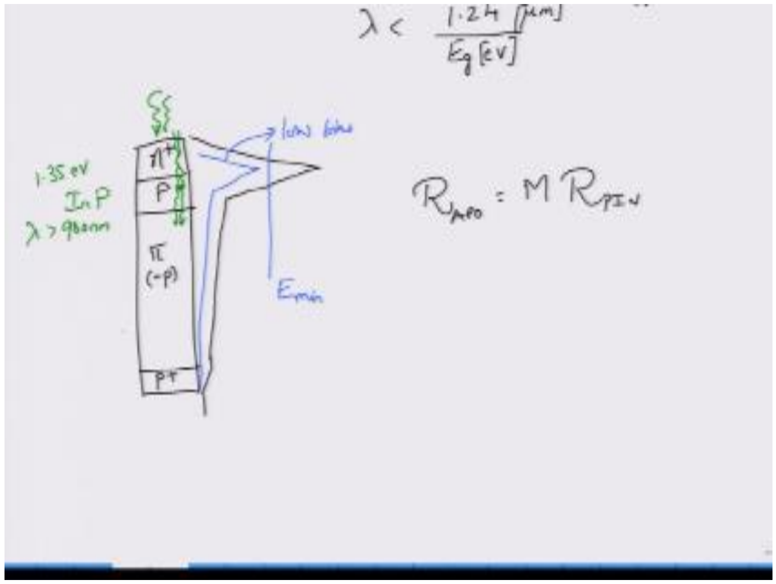

Turns out that if I use indium phosphate over here, these InP material have a band gap of around 1.35 electron bolt, which means that for λ that is greater than around 916 nano meters, this won't be sufficient energy here, so that whatever the photons that are incident will not be absorbed here. This P layer and N+ layer, if you dope them with InP material or make them with InP material, they will become transparent to the light in the optical second and third windows.

So light simply goes through the intrinsic region reaches the л region or intrinsic layer, where it gets absorbed. How can we ensure that, well you operate this one with in gas diode, I mean with in gas material, we know that in gas material has a cut off at 1.6 microns or 1.7 microns. So this will absorb all the photons, however the photon carriers that are generated, the photo carriers that are generated, they will be corrected in this region, they will b end to this region, so that they will experience very large electric field and this electric field will then cause them to generate the secondary age space.

So this is how this particular material is performed, of course P+ region here is also made up of InP material, so if you look at it, you're looking at a sandwich structure where the material, the intrinsic layer is essentially a in gas material and the layers on the top and bottom are with the different materials, so this is how a typical Sam APD works, sometimes you also find separation created absorption multiplication regions. SO instead of making this abrupt, kind of do some grating of the layer in order to, you know obtain even better current gain profiles and to change the noise properties.

So well this was all about the structure of APD and structure for Pin diode with , we will then look into the next module about the response time of the photo diode which has essentially determined by the bandwidth of the photo diode and we will look at what associated noises are there in the photo diodes and then we will talk about simple optical receiver, we will go back to the communication system which we talked about in the first or second modules and then we will talk about that simple direct detection, on off key detection.

And then see what kind of optical receiver tradeoffs one has to perform in order to detect optical signals and to make an optical receiver function. Thank you very much.

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