Introduction to Photonics
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Semiconductor Detectors 1

So welcome back today we will switch tracks little bit we have been talking about semiconductors lights sources during the past few lectures and what we will talk about today is semiconductor light detectors.

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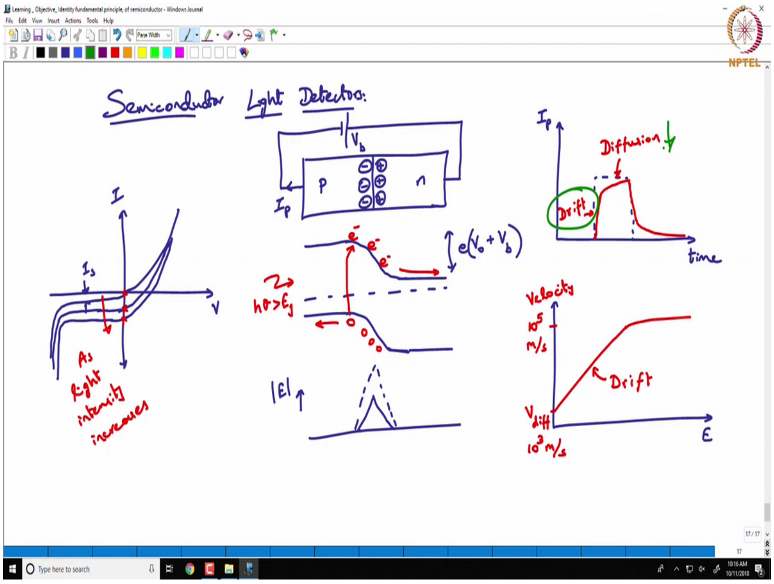

And once again we are going to rely on the familiar PN junctions right so as we saw before when we consider PN junction diode, so what we have here is the excess holes are going to the N side from the P side and that is leaving behind some fixed charges, negative charges on the side and positive charge on this side right and the corresponding energy level diagram will be such that on this side you have the conduction band here on this side you have the balance band here, so you have a conduction band from this side going like this right.

Now what we are talking about is the light detector, so what we are saying is if you have h nu such that h nu is greater than Eg the band gap energy then what you will have is light will be absorb by this material and absorption is such that it takes an electron from the valence band to the conduction band leaving behind a hole in the valence band, so you are essentially generating an electron hole pairs and of course the electron is going to go this way and similarly the holes are going to go in this way and that generates the photo current in the external circuit.

Now as we saw before the presence of fixed charges at the junction that creates an electric field right, so you have… Looking at the magnitude of the electric field at the junction you have something like this right and that electric field also is represented over here as e times v naught right that is basically a barrier that is a built-in there which prevents just diffusion of electron hole pairs without any external elimination right without any external elimination it is all equilibrium, so there is no transfer of charges across that barrier right but in the presence of light, light actually falls on this photo (())(4:02) generates electron hole pairs and then those electron hole pairs the inbuilt electric field actually ends up pushing those electrons to the right side and holes to the left side okay.

Now interesting things happens once again when you have bias when you give an external bias to this, so but this time unlike the case of light sources we are giving you reverse bias over here and when you give the reverse bias what happens is let us say reverse bias VB we said this potential is going to be modified the barrier is going to be modified such that in this case now because it is reversible bias you have enhancement of the barrier.

The forward by s case we were saying that the barrier height gets reduced but here we are saying it results in enhancement of the barrier so the corresponding electric field gets enhanced you know in the presence of this external bias okay, so one obvious effect of that is, so you have much larger barrier height so the electrons actually flow faster across the junction, electrons flowing towards the right side and holes flowing towards the left side.

The mobility is increased because of this external field and in such that when we talk about mobility we talk about the velocity of these charges when we look at that as a function of the electric field okay what happens is, normally without any electric field you have the fusion process happening, so the charges just diffuse and of course they cannot diffuse beyond that built-in potential but with the influence of electric field it actually increases and then it saturates okay.

So this is actually what is called the drift…so the drift back as happens under the influence of electric field so larger the electric field larger it attracting the velocity of these charge particle moments and we are basically saying that under the influence of electric field the velocity increases and it achieves saturation velocity which is in the order of 10 power 5 metres per second this diffusion velocities in the order of 10 power 3 metres per second okay, so clearly we can say that these charges get swept out faster due to this process.

Now what is the effect of that on this response for photo diode, effect is in terms we can look at that effect in terms of time, the temporal response, so let us say this is actually the photo current, so IP let us say it is a photo current generated because of light falling on this photo diode. If you have an incident pulse that is like a square pulse, incident optical pulse that is square in shape, how is the photo diode going to respond to this? Well what you are going to see is typically this is going to respond fast and then it is going to slow down right and similarly when you turn off the light input there is going to be a fast DK and then there is going to be a very slow DK. Okay so how do you explain this?

Now clearly we say that any charge under the influence of the electric field is going to have a high velocity, so those are the charges that you are going to see come out of that… contribute to external photo current right, so in this region we have drift and then the slope response actually corresponds to diffusion right. So you can say that diffusion is going to be a process that limits the response of your photo diode which is based on just PN junction diode, you understand this?

Right so it is not a question of whether you can get a photo current or not a right that we already know let us see the other day we were talking about the IV characteristic of your photo diode so let us say this is I and this is V and we were talking about how it behaves in the, forward by us it is going to have an exponential dependence on the forward bias voltage and in the reverse bias it is going to come out like this, so there is going to be a certain current which we were previously calling as IS right we were calling as IS, so there is going to be a certain photo current that is going across at reverse bias.

Point here is we are trying to use it as a photo diode, so what happens when you increase the amount of light that falls on the photo diode. You essentially have a shifting of this curve, so as you increase this level is going to increase right, so according to, so what we are saying is as light intensity increases, as the light intensity increases initially you have no light falling on the photo diode there is no photo current but as you increase this light intensity the corresponding current increases and this is actually very important point to note a lot of people tend to get confused about the role of the reverse bias okay.

They tend to think that as you go to higher reverse by as you get more photo current out of the photo diode okay that is a common misconception. You do not need any bias just to generate of the current itself right. Photo current is generated just by this simple principle that if your light energy is greater than the band gap energy it is going to generate electron hole pairs and those electron hole pairs are going to diffuse across and find their way to the external circuit, so even without bias as you increase your light intensity you are still going to get a photo current, so then what is the role of that external bias if you do the reverse bias what does it improve?

It improves the velocity with which these carriers move, so it improves the response time basically, right? So without any external bias the response time would have been all due to diffusion except for those carriers that are generated in the depletion region itself right everything else would have been under the influence of diffusion, it would have been a very slow response right. So you are increasing your external bias primarily to improve the response time but nevertheless coming back to this picture here if you want to have a high-speed response you need to essentially encourage drift and you want to discourage diffusion right, so how do you do that?

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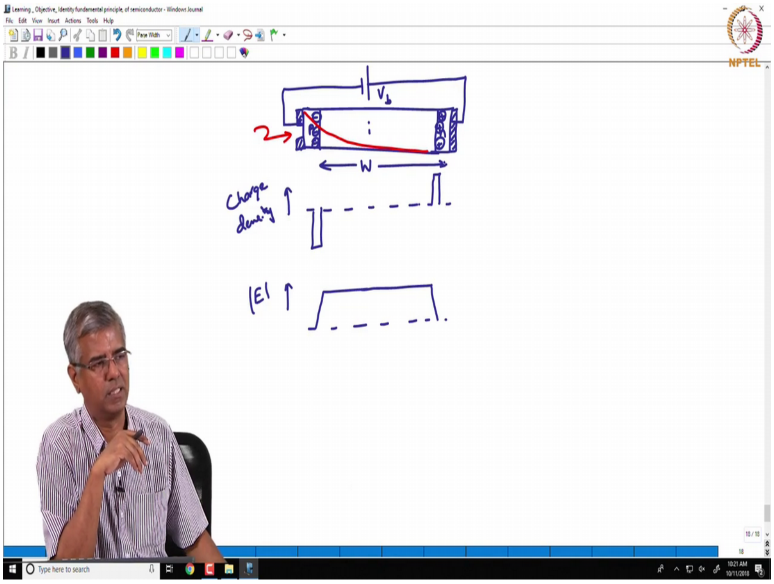

It turns out there is a very neat way of accomplishing this, so you just go for what is called a PIN structure, so what do you have in a PIN structure? You have your PN regions and then you have I region, what is I correspond to? Intrinsic semiconductors, so it does not have the electron and whole concentrate are the same essentially in the intrinsic semiconductor and the firmy energy is right in the middle of that the band gap right.

So in this case when you look at the charges that are present, the charge density is going to be such that you are going to have negative fix charges over here positive charges over here okay and so in terms of charge density if you were to look at, what is happening this is actually this is charge density right and you have positive charge density over here but key is what do you see when you are looking at that magnitude of that electric field okay when you look at the… The electric field you can find by applying gauss law across this entire structure and if you look at the magnitude of the electric field that is going to increase like this and then in the intrinsic region there is no potential drop there is no work done right.

So you would essentially maintain that electric field and then comes down when it goes through n region right. So what if you manage to do is distribute your if you do and external bias now distribute that bias across the entire I region and if you make your PN N region relatively much smaller then you can say that across the entire structure you have an electric field. If you have an electric field what happens? You are encouraging the drift process, so as very negligible diffusion that is happening, so intrinsically this sort of structure is going to give you a very fast response time okay.

So that is one of the major advantages of going to PIN photo diode and thing is that the I region can be extended to whatever width you want, why is that important? Because the typical way of illuminating this is your going to have your electrons define like this and you are going to illuminate from here right because if you think about the structure it is actually grown, so it is grown from N, I, P and so on right, so it is just easy to illuminate from here and if you do that illumination that light is going to get absorbed as it propagates through this material and how is that absorption going to happen?

What is the profile of that absorption or the power as it goes through? That is going to go down exponentially, so you are going to basically have an exponential profile for the light that this propagating through the structure and so the width of that I region, let us call that W right so that the width of the I region can be extended so that you can absorb all the power that is incident on the structure right, so it is give you a sort of free-sort of design parameter, so by changing the value of W or rather increasing the value of W you can absorb all the light that is falling on the photo diode.

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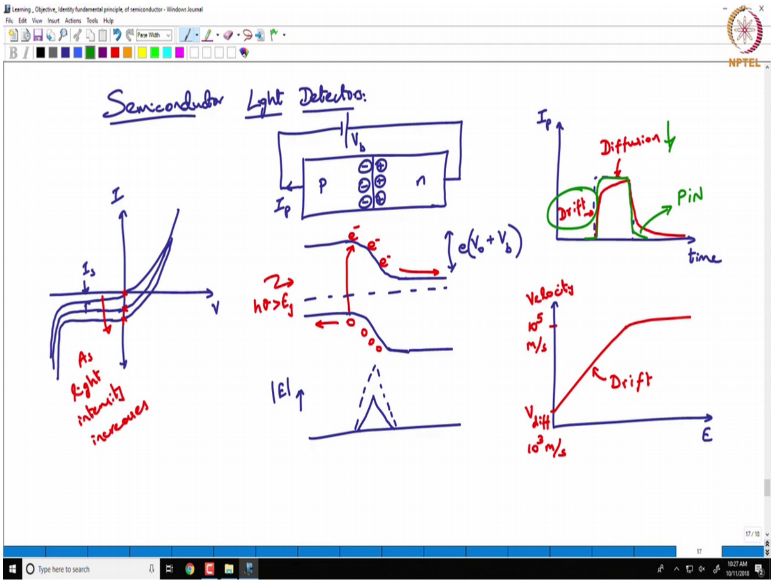

So the electrons and holes are generated all across right and if the electron hole pairs are generated in the depletion region then they are under the influence of the electric field so they get pushed out faster but if the electron hole pairs are generated anywhere else they are under the process of diffusion, so when we look at this graph closely there is a slight difference between the current that you have at 0 bias and the current that you have at you know some finite value of bias.

Basically that will account for the electrons that you would lose in this process or holes that you will lose in the other side as well, they are not actually seeing the external circuit, so they do not contribute to that photo current right, so there will be slightly lower current generated at 0 bias compared to some higher value of the bias. Yes, so the question is can be just reviewed this IP versus time, so what you are saying is that illumination is given by this dotted line over here that corresponds to the power as a function of time are right.

So you would want ideal photo diode to have the photo current follow that same daughter line but because of the fact that only the carriers generated in the depletion region are going to be under the influence of this drift process, the high velocity thing those are the ones that will come out all the photo diode first, so those will contribute to the initial photo current and then you have the slower sort of charges coming out of this photodiode right, so the once that are going through the diffusion so then they would have a slower time constant they will come later essentially right and what we have fixed with the PIN structure is that now you can get a response something like this, so this will be the response of PIN structure right.

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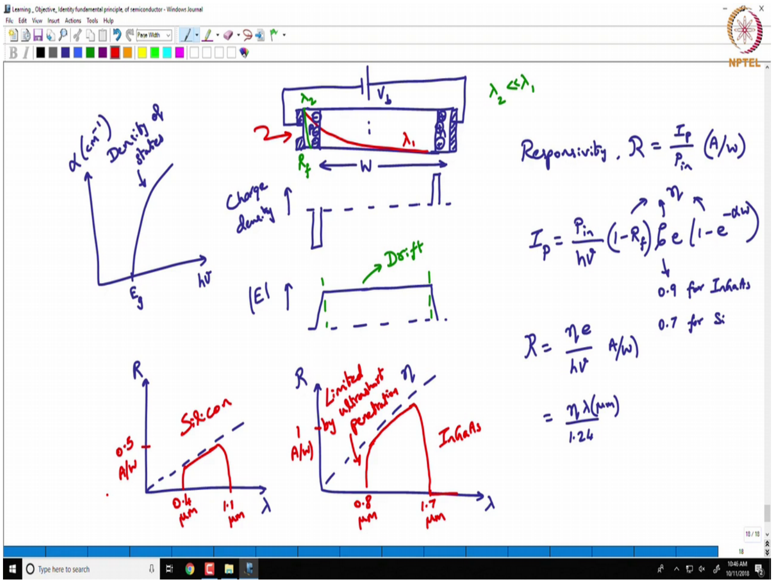

So that is what we are talking about and then of course we are also saying is that by changing the width of I you can actually show how the power is getting absorbed across that structure, so maybe we can… So just to emphasis this point all this region cross this entire region you have the drift process dominating, so that gives a better response from the photo diode. So let us now track the characteristics of photo diode let us start with responsivity of the photo tired right, so responsivity which is denoted by R is essentially given by the photo current generated say IP for certain level of power that is incident on the photodiode, so this is in units of ampere per what?

So let us now try to find an expression for IP so what exactly is happening when light falls on this photo diode. Now light falls on this photodiode at certain rate, that rate is given by…the flux is given by power over photon energy right. So PN over HU is the rated which the photon are incident on this and when they are incident on the material, the material is the high index material right so you are coming from air into a high index material, so you are going to have certain losses due to reflection at the surface right let us say RF is the reflectivity at the facet so RF correspond to the reflectivity at this facet over here.

Okay so 1 minus RF is what is coming in and those photons are going to generate electron hole pairs and that is actually sort of a quantum phenomena, so it is not like every photon generates an electron hole pairs there is a certain efficiency with which that conversion happens that efficiency we will be naught as Zeta, so that is actually the photon to electron hole pairs conversion efficiency.

To give you an idea Zeta will be fairly high in the order of 0.9 for in gas which is a direct band gap semiconductor whereas it is around 0.7 for silicon which is indirect band gap semiconductor light and then of course you are generating charges so you can represent the electronic charge E and then what is the amount of light that is absorbed within this medium that is going to be given by a factor 1 minus e power minus Alpha multiplied by W right if W is the width of your structure right. e power minus alpha times W is a fraction of power that you have and the end of the device, so the power absorbed will be 1 minus E power minus alpha W okay.

So based on this expression you can write the responsivity as some factor Eta right multiplied by e over h nu right where E is the electronic charge h nu corresponds to the photon energy and Eta is essentially a product of these 3. Those 3 terms determine value Eta and that is going to be amps per watt and of course h is a constant, e is a constant so if you worked that out what you will find is this is going to be given by some factor of 1.24, so nu you can write it as c over lambda right, so h, C and E are all constant so you are going to have 1.24 or rather eta lambda divided by the factor of 1.24 where lambda is expressed in microns, so that is actually selectively easier thing to compute, so eta now your RF can be reduced, how do you reduce RF?

Reflectivity at the facet you could do an anti-reflection coating their right, so that can reduce RF. In Zeta where you are stuck with whatever material that you are given, so if it is a direct band gap then it is 0.9 or it could be even 0.95 materials purity is very good and 1 minus E power minus alpha W is your design parameter, so for a given material you know what is alpha, what is alpha depend upon, you can basically say that alpha if you are tracking as function of h nu, what is the alpha for h nu?

Less than EG there is no absorption light will just go straight through right there is no absorption happening but beyond EG you start having absorption and your alpha increases and the rate at which it increases is primarily driven by the density of states right? As you go to higher values of h nu you are accessing deeper regions of your valance band and your conduction band and in those deeper regions you have higher density of states right, so that will pretty much determine what your alpha is.

So alpha which is typically express in terms of inverse centimetre, so that actually you know gives us some thought, what it tells you is that this profile that I have drawn over here, the profile at the rate at which the power is absorbed within the material that is actually for a particular wavelength or particular frequency. If the incident frequency changes right, so incident frequency changes, the frequency is much higher than the frequency for which I have drawn this red line.

So let us say the Red Line is at frequency nu 1 let us say corresponding to wavelength lambda 1 then if you have lambda 2 which is much smaller or corresponding frequency is much higher, the energy is much higher if you have that then all your absorption is going to happen over here, so this is for lambda 2, lambda 2 is smaller than lambda 1 or much smaller than lambda 1, you understand this?

So if you are going to a much shorter wavelength which corresponds to much higher frequency and higher energy then you have a high value of Alpha because your density of states is very high in this corresponding regions right and so it will get absorbed within a very thin layer near the facet itself okay and that will if it all gets absorbed over there here is only under the influence of diffusion and not most of those charges will get lost I mean they will just recombine among themselves and they will lose that energy, so it will not make it to the external circuit.

So you will have good responsivity for certain wavelengths, so the 3 domains that we are talking about one domain is if you have a wavelength which corresponds to the band gap energy right that is where you start observing any wavelength it is greater than you know which has a corresponding energy which is less and the band gap energy is not going to get absorbed let me just draw that. I know there is a question back there but I will just come back that in a minute. So this is responsivity as a function of wavelength okay, so let us say your eta line is like this so that is going to be guiding your responsivity.

So in terms of the responsivity what we will find is, there is a part of wavelength right corresponding to the band gap energy any wavelength greater than that cut off wavelength is not going to get absorbed because the energy is less than the band gap energy, so there is no responsivity beyond this, 0 responsivity beyond this. But within this it is going to increase and then it is going to be guided by the value of eta and then it is going to drop off right it is going to drop off abruptly because of the fact that at this point it is unlimited by ultra-short penetration because as you go smaller and smaller and wavelength that corresponds to higher and higher energy and it is such that all your absorption happens near the facet itself, so it does not generate a photo current in the external circuit okay so then that will be the limitation. There is question back there, yes.

Student: (())(36:01)

Prof: Sorry 1 minus E power minus alpha W, yes.

Student: (())(36:09)

Prof: So yeah that gets transmitted so you typically have a contact layer that this fairly thin but it also absorbs that light, it is a metallic layer so it absorbs light and there could be a residual light that is coming out of that structure as well.

Student: (())(36:34)

Prof: Part of it could be right, so part of it could be…

Student: (())(36:41)

Prof: Yes we are just looking at the 1st level thing but if you leave light over there some of those photons can come back but you typically design your photo diode for the longest wavelength of population, so at the longest wavelength it should be absorbed completely.

Student: (())(37:04)

Prof: Yes so then you basically try to maximise the term, so you try to maximise that to one, so E power minus alpha W that fraction is going to be very close to 0. Yes there is one more question.

Student: (())(37:21)

Prof: Photo diode as a broad range of wavelengths that is responsive…

Student: (())(37:29).

Prof: So yes this thing typically for some let us look at the case of Indium gallium arsenide so this is that 1.7 microns and this fence around 0.8 microns, so it is actually fairly broad okay, so that is for Indium gallium arsenide and if you draw the same graph for silicon. Silicon is indirect (())(38:13) of semiconductor it is harder to achieve very high value of eta, so eta is somewhere around 0.5 typically and the corresponding…the bandage corresponds to 1.1 micron, so anything greater than 1.1 microns wavelength will go straight through the silicon right, so it will not absorb any of that light and within that it is going to go like this and then it is going to fall off typically about 0.4 microns.

Now you have something called UV enhanced silicon photo diodes in the market and the extend the absorption to even like 0.2 microns and what they exactly do is you would have a much smaller structure to start with right much thinner structure to start with W will be very small, so it allows you to even for the shortest wavelength it still allows you to extract the photo current if you make it very short okay, so this is for silicon. Do you understand this picture? Yes very high penetration depth is let us say the width, the depth over which the power drops by 1 over E right that is typically the definition for the penetration gap and that depth will be very short if you have very high value of Alpha that is what it is saying.

Okay so then the question is that is my responsivity and it could be the values could be in the order of 1 ampere watt in silicon it is typically about 0.5 ampere per watt right. The question is can I get more photo current for the same power that is incident on the photodiode, how can I get that? How can I improve my responsivity? Okay, so let us look at that.

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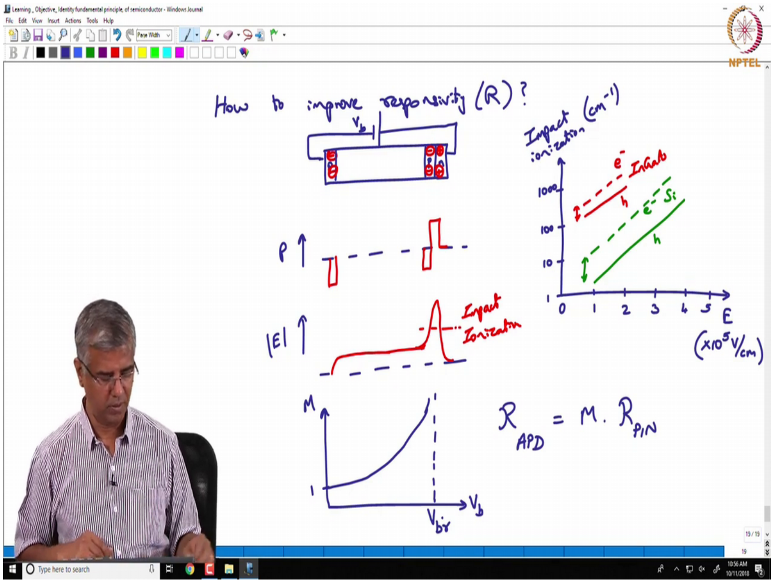

How to improve responsivity okay? So that is actually done by a very clever manipulation of these layers, so you typically have a P and N layer right, now what type you have another thin layer of P right next to the N layer right, so what happens if you have something like this now in terms of the fixed charges be can say that these are going to leave behind negative charges here, negative charges here and positive charges over here right and so the corresponding charge density you can say is going to be like this and over here it is like this and then like that right because there are some negative charges and then immediately some positive charges.

So now if you look at the electric field across the structure, so this is basically the charge row but if you are looking at the electric field across the structure of magnitude of the electric field that is going to go like this and in this region it is suddenly going to spike up because you have negative charge particles there… Negative fix charges there on the P side and then as you go the field response time then there are some more negative charges, so the field increases over there and then the positive charges sort of utilise this entire thing so the field comes down. So you have a very high electric field that is within a very all region. You have a very large voltage drop within a very small region, so what is the effect of that?

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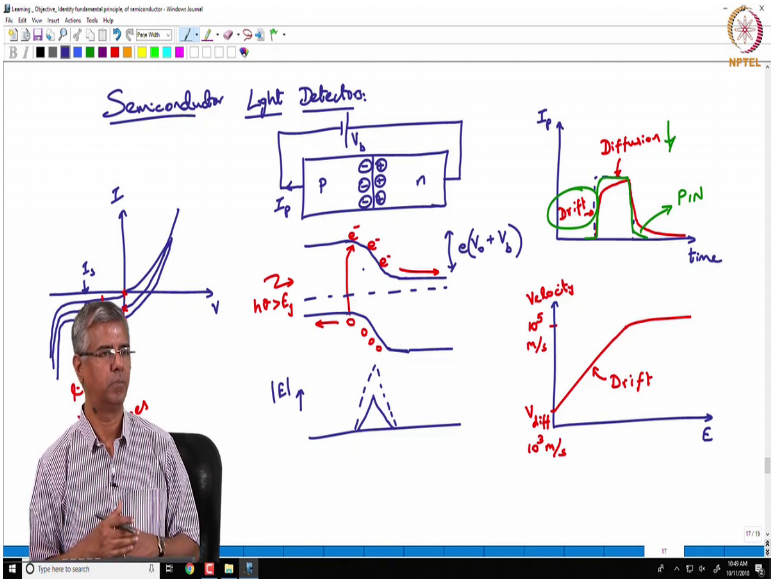

You can say that when you look at the band gap around this particular point by going to a very large voltage what you are essentially doing is we are increasing the slope at that junction, the slope over which the energy drops-down right, so when that slope increases with external bias you are essentially having a larger acceleration provided to the charges in that region, so specifically in this region you are under the influence of very high drift velocity, so almost to the level of the saturation drift velocity you know 10 power 5 metres per second.

Under those conditions you have a process that is called impact ionisation, basically these charges are so much momentum that travelling at so high velocity that way so much momentum that if they collide with any other nearby atom they are going to…just heat it and they are going to ionise that atom, so they are going to immediately have an electron pop off from that location and you generate an electron hole pairs and those electron hole pairs still carry a lot of this momentum, so those can go and create an impact ionisation on the neighbouring atoms and so on.

So this entire process can multiply and if you look at the impact ionisation as a function of the electric field we are tracking electric field in the order of 10 power 5 volt per centimetre very close to the breakdown strength of the material okay. 0, 1, 2, 3, 4, 5 in this impact ionisation coefficient is inverse centimetre and it is 1, 10, 100, 1000 and so on. If you look at the impact ionisation coefficient for Indium gallium arsenide for the electrons it will be something like this and for the holes it will be something like this right.

So holes have a smaller impact ionisation coefficient typically because the mobility of the holes is actually slower compared to the electrons in the materials like Indium gallium arsenide , so this is for Indium gallium arsenide whereas for silicon it is like this, so this is once again electrons and this is holes and that is the thing you have for silicon, so what it essentially says is that the impact ionisation process in silicon happens at a much higher electric field or higher voltage, applied voltage compared to what you have for Indium gallium arsenide but one thing that matters is actually the width between the impact ionisation for electrons with respect to the holes.

So in silicon that width is larger meaning electrons you can get impact ionisation happening at a much smaller voltage compared to…when the holes actually go through impact ionisation. So we will come back to that will come back and see the difference between these 2 but nevertheless what we have now because of this process of impact ionisation which happens beyond this threshold here is your effective responsivity of this structure which is called avalanche photo diode right that avalanche photo diode is going to have M times the responsibility of a PIN photo diode.

So that the process of impact ionisation creates an avalanche of carriers and so that is why it is called avalanche photo diode and if you plot M as a function of that external bias, now you still are giving an external bias like this Vb, if you plot M as a function of Vb, M equal to 1 over here and with sort of increases exponentially as we go to higher Vb and it will be limited by your breakdown voltage, so beyond a certain voltage that junction itself will punch through and it will break down and then you will not be able to use that device anymore but almost until then you can get gain right and gains of 10 or 100 are possible through this process and this is what you are going to try to do this week you will actually look at PI and photodiode and APD photodiodes you will look at the characteristics of those photo diodes and you will try to quantify those okay.

So we are out of times let us stop at this point and we will continue the other part of this is the response time which I can tell you in general depends on the time it takes for carriers to go across the structure right so the response time is going to be limited by the width of that structure, so higher the width lesser will be the response time right so in that case the response time and the responsivity there is a trade-off to get higher responsivity you want larger width so you can absorb all your radiation but then your response time decreases okay, so let me stop at this point we will continue this in the next lecture.