Photonic Integrated Circuit
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Lecture 44
Semiconductor Photodetector

Hello, everyone. Welcome to another edition of Integrated Photonic Circuit lecture, and in this particular lecture we are going to look at photodetectors. So, photodetectors as the name suggests detects photons. So, the fundamental process is converting a photon to charge carriers. This is something that you must have already very familiar with. So, let us look at how this fundamental process happens and how we could do this in a semiconductor and integrate this in a, in a circuit fashion. So, let us look at that.

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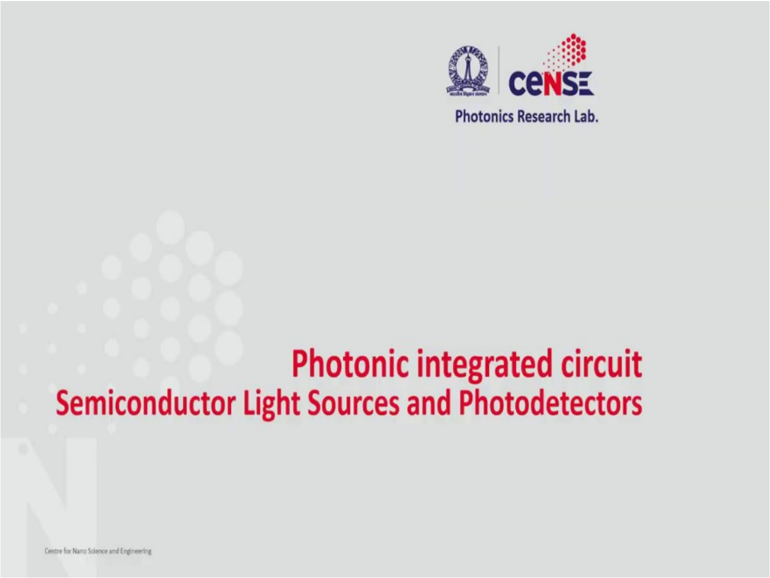
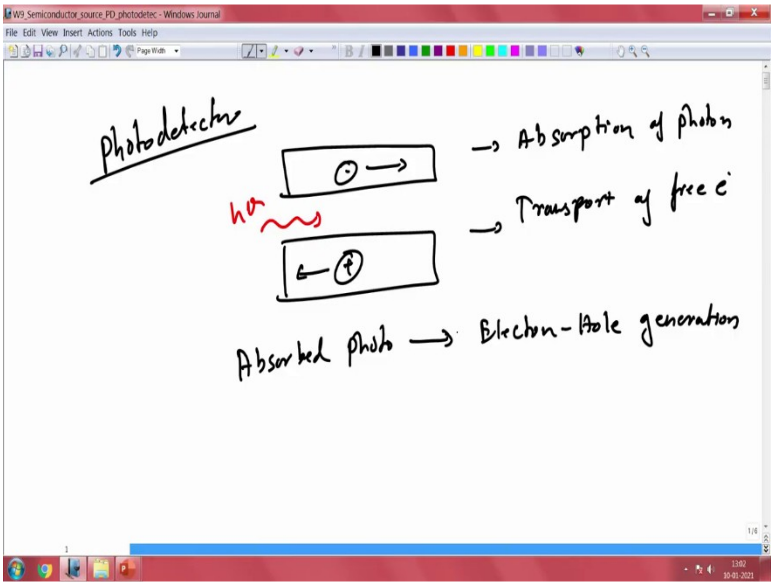


Photonics Research Lab.

Photonic integrated circuit

Semiconductor Light Sources and Photodetectors

Centre for Nano Science and Engineering



A simple process of photodetection is governed by the internal photoelectric effect. So, the photodetector is primarily trying to do is to put a, create a charge pairs here, when there is an input field, and then you want to take out the charges out. So, the first thing is absorption of photon and next process is transport of free electrons. So, this is essentially what we are trying to do.

So, when the photon is absorbed, absorbed photon should result in electron-hole generation. So, this is the essential, necessary condition in order to create a photodetection using quantum detector. So, there are other forms of photodetection as well, so there is thermal as well. But in this particular course we are primarily interested in light detection in semiconductors. In semiconductors the, the fundamental process here is to generate charge carriers and these charge carriers should be able to be transported to create a current flow.

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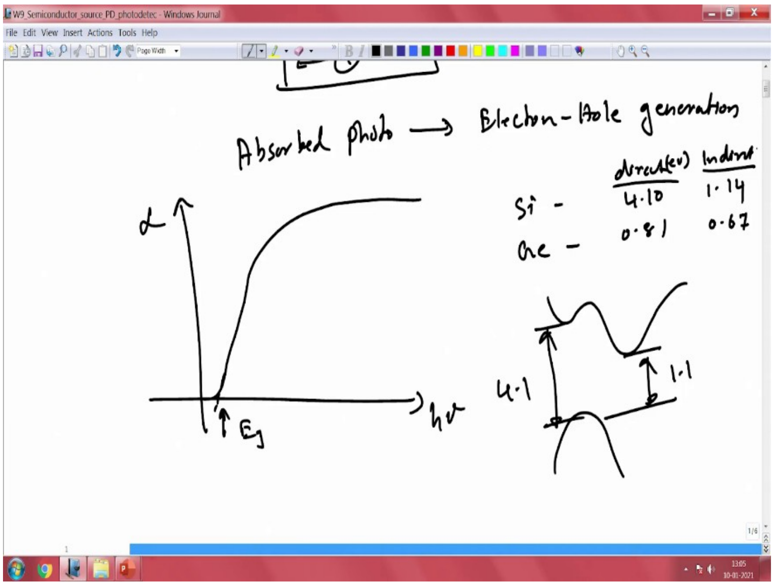
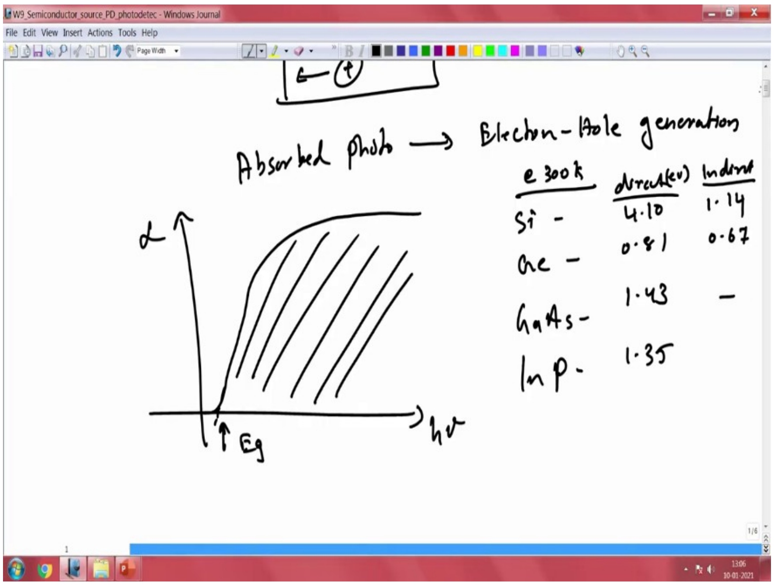


Absorbed Photo → Electron-Hole generation

	direct(eV)	indirect
Si -	4.10	1.14
Ge -	0.81	0.67



Absorbed Photo → Electron-Hole generation

@ 300K	direct(eV)	indirect
Si -	4.10	1.14
Ge -	0.81	0.67
GaAs -	1.43	-
InP -	1.35	

And this absorption is an important characteristic, so that, that depends on the material system and if this is our energy that we have and this is absorption coefficient let us say, so different material got their own band gap, it is band gap driven system. So, what you would see is something like this, where you have very low or no absorption below the band gap. So, this is your band gap that you have and then once you are going into the band then there is a complete, very high absorption.

So, when there is low absorption outside the band, once you again to the band you have very high absorption. And this band gap depends on the material as I mentioned for silicon the direct band gap is 4.10 and for germanium it is 0.81. And there is indirect band gap for this as well that is 1.14 and 0.67. So, we normally look at this (direct) indirect band gap only when we discuss silicon or germanium, but if you look at the the band diagram the E-k diagram you also have a direct band transition as well which is much much higher, so that is why the indirect band gap wins here.

So just for, for you to remember so you will have something like this, so for silicon or even for germanium in this case. So, the direct band gap here is 4.1, but the indirect band gap here is 1.1. So, this, this these two band gaps are there for both this material. So, just keep that in mind why there is a direct band gap for silicon or germanium, it is there but then it is larger than your indirect band gap and that is the reason why the indirect gap dominates because it is lower energy, any transition happens within that.

And for III-V materials, it is all direct only. So, 1.43 for Gallium arsenide, for Indium phosphide it is 1.35 and so on. So that is giving the band edge here. So, this is all at 300 Kelvin room temperature. So, what is the implication of having high absorption? So, we are interested in this region, so you want very high absorption.

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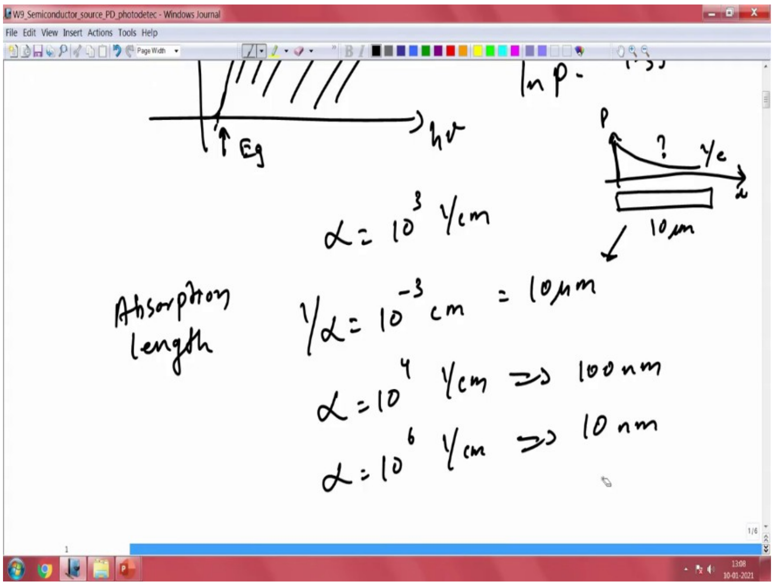

$\alpha = 10^3$ 1/cm

$1/\alpha = 10^{-3}$ cm $= 10 \mu m$

$\alpha = 10^4$ 1/cm $\Rightarrow$ 100 nm

$\alpha = 10^6$ 1/cm $\Rightarrow$ 10 nm

So, just for example, if you have an absorption coefficient of 10^3 per centimeter let us say the power required to reach $\frac{1}{e}$ so that is $\frac{1}{\alpha}$ is equal to 10^{-3}centimeter, so that is about 10 micrometers. So, the absorption length, the absorption length when α is 10^3 per centimeter would result in 10 micrometer long device. So that means in a 10 micrometer long device the power decays to $\frac{1}{e}$. So, this is our power, and this is as a function of length.

So, what is this length requirement? And, and that is what this particular length is all about. So let us say when it is 10^4 per centimeter, so then your absorption length will be 100 nanometers and if α is 10^6 per centimeter this would result in 10 nanometers. So, this is optical power absorption, so $\frac{1}{e}$ optical power absorption length. So, as you can see when the

the absorption increases the, the length that the photon should travel also tremendously reduces at the same order.

So, this is very important because that is the first function that we want, we want to absorb the photons inside the medium. So, you want to have very high absorption make sure to (su) select a suitable material that has high absorption. So, the absorption as I mentioned could be in would be between two bands, one is direct and another one is indirect band gap absorption, but normally indirect band gap has a lower energy, so that the transitions are primarily in that lower energy.

So, one interesting fact that should be noted here is the photodetectors itself. So, we have photodetectors from different materials. For example, the photodetectors that you have in your cellphone camera and that cellphone camera has silicon, as the material in it. So, most of the charge coupled device, the CCD cameras, they use silicon as, as the material. But silicon is an indirect band gap material.

The question here is whether we can use indirect band gap material as photodetectors? Because in our all-earlier discussion for the light emission, we only wanted direct band gap material. So now we are saying that we, we, whether we can exploit indirect band gap characteristics, the reason for that is these two important characteristics that absorption should be there and even more importantly we should generate carriers that we can transport, so the carrier generation is important.

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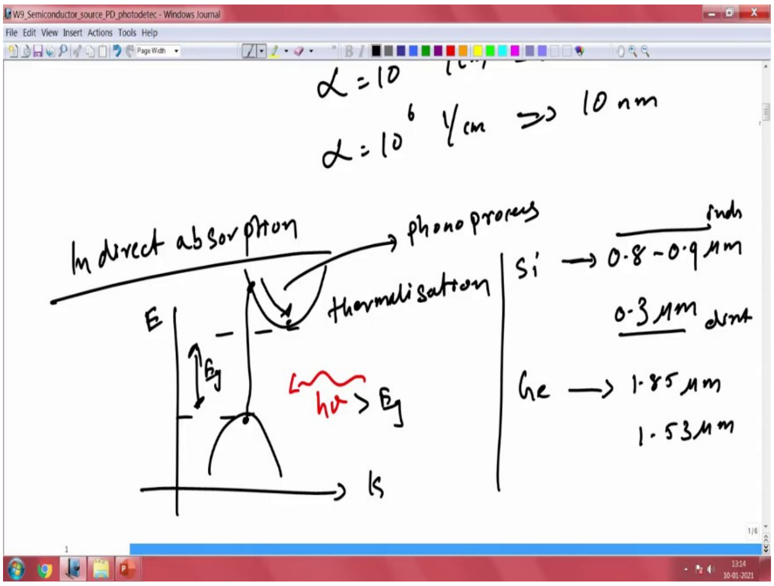

So, let us look at silicon as an example which is an indirect band gap material to see whether we can use it as a photodetector. So, silicon and germanium got both direct and indirect band gaps, so that is what we, we saw. So, the indirect band gap requires the assistance of phonons, so that your, your momentum is (con) momentum and energy are conserved. This is required for emission process but for detection process we do not need.

Let us look at the reason there, so this is E, and this is sorry this is k, and this is E. So now we have these two bands, let us say. So now when I put in a photon inside the system, so you will have electrons sitting here. We have electrons sitting here, so if this energy of this photon is greater than the band gap, so that we have in this case indirect band gap that we have, then you could actually take this absorption here by absorbing this, and you will generate the carrier here but then it could thermalize.

So, this, this thermalization could happen, the thermalization would happen and this is a, this thermalization will make the charge come into the valley point here. So, the indirect band gap material you could use this for light detection, but then it is going to be slightly inefficient compared to direct band gap material because of this transition. And this transition is assisted phonon process, so you have leakage or thermal, thermalization where you are giving energy into the phonon. So that means that energy is essentially lost into the material itself, you are not using it for charge transport.

However, your charge is now in the conduction band, so that is what you are interested in, you are you want to create that charge that could be conducted through the, through the material system. So, let us, this is the process through which you can make an indirect band gap material detect a photon. So, for silicon we have two bands. So, we have a band that is between 0.8 and 0.9 micrometer, then we have a cut-off and a direct band gap that is happening at 4 eV that is at 0.3 micrometer.

So, this 0.8 to [0.9] 9 is our indirect, and this is our direct detection. So, this particular detection 0.8 to 0.9 that we have is primarily coming from the, the band absorption that we have. Similarly, for germanium we have the, the indirect absorption that is happening with a threshold of 1.85 micron and then we have direct absorption that is happening at 1.3 micrometer.

So, this is the two bands that your germanium will, will start (detec) acting as a, as a photodetector. So, silicon is a very popular material, we are using it for multiple application, popular application including cameras and so on, is, is dictated by this wavelength range. So, how do we choose the material? So how do we choose the right material for this?

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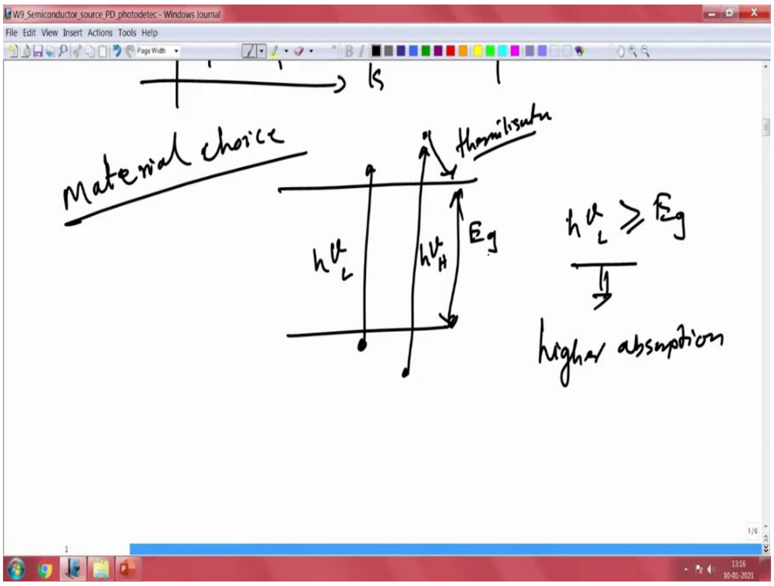

It is rather straightforward. So, you want to detect a photon and make sure [instead of this], make sure that your energy band is slightly lesser than the photon energy that you need. So that means you have a transition like this, and then you could have a transition like this. So, this is our lower level, and this will be your higher level. So, by using the right photon energy bands, we should be able to generate this. So that means your photon lower-level energy should be greater than or equal to E_g.

So, this is where it starts to start creating or absorbing the photons. So, once you have this, this higher the energy level the better the absorption. So, all you want is higher absorption. And what happens if your, if it is too high? So there the problem is thermalization, when you are going to very high energy level it is going to thermalize. So thermalization could result in a lot of heat, and this will also create thermally generated carriers as well and which is also dark current in this case.

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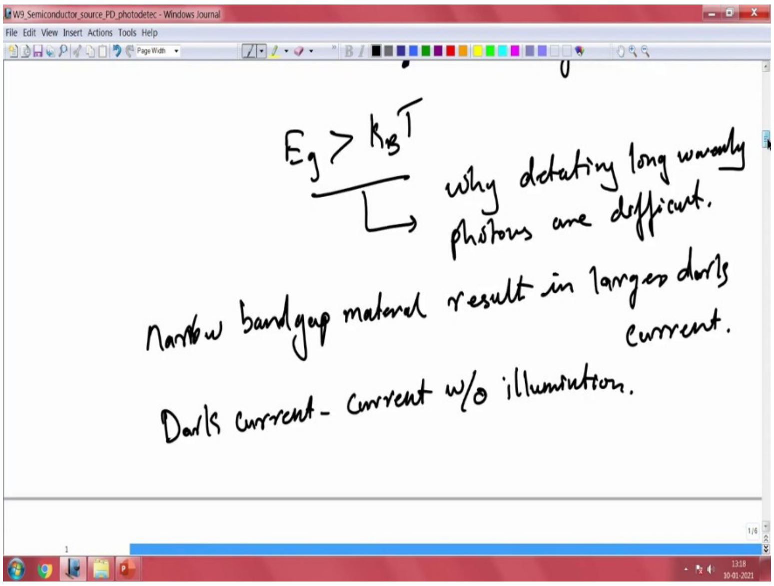

$E_g > k_BT$

↳ why detecting long wavelength photons are difficult.

Narrow bandgap material result in larger dark current.

Dark current - current w/o illumination.

So, the that thermalization is, is energy loss but at the same time your energy gap should also be greater than your, your k_BT limit, and this is one of the reasons why detecting long wavelength photons are difficult. So, when you are using quantum detectors like what we are discussing now, when you, when you have a very small energy or the longer wavelength energies let us say 0.1 eV, let us say then your band gap should be also 0.1 eV or even below that.

But that strongly depends on your k_BT because you do not want your temperature to create thermal, thermally generated carriers. If the thermally generated carriers are high, then you will have dark current. So, you do not want that to happen. So narrow band gap material would results in larger dark current. What is dark current? That is a current flow without illumination. What is dark current? Current without illumination.

So, when you have a semiconductor and because of the heat, you will start conducting, so the charges are already starting to flow and that is what dark current is all about, so you want, do not want that dark current and by choosing material with larger band gap should help you in achieving this.

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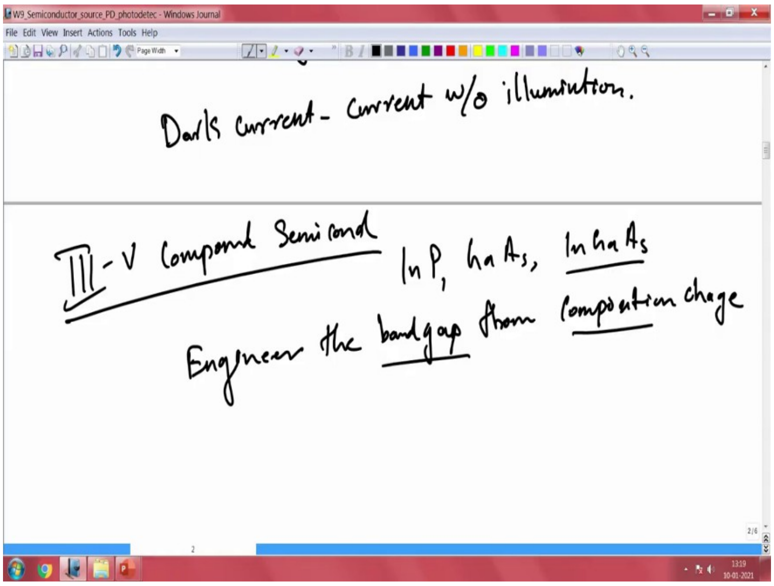

Dark current - Current w/o illumination.

III-V Compound Semicond InP, GaAs, InGaAs

Engineer the bandgap from composition change

So, you can also use III-V semiconductors for this, so this is all for silicon, let us say. So, you can also, silicon and germanium, you can also use III-V compound semiconductors. So here you can use a combination of, of material here, so you can have Indium phosphide, Gallium arsenide, Indium Gallium arsenide, phosphide and so on, Indium Gallium arsenide in this case.

So, the, the whole idea of using this is, is ability to change the band, the band gap. So, you can change the or what you call engineer, the band gap through composition change. So, by changing the composition of material that you have here we should be able to create different band gaps and that means you can detect photons of different energies.

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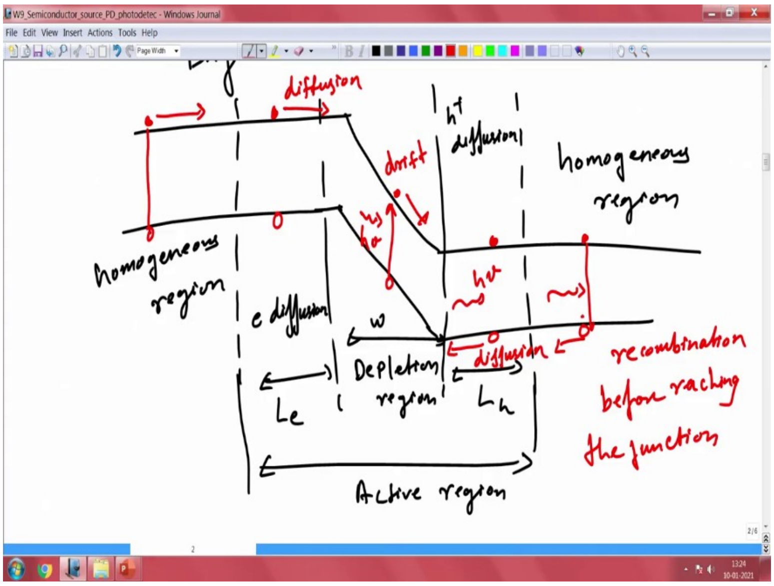

So, let us look at a very simple p-n diode that can be used as a photodetector. So, this is the band diagram of a very simple p-n junction. So, when you have this particular region is called our, let me draw it properly, this is called depletion region of certain width w and then you will have some diffusion regions as well, so this region that are very close is called diffusion region. So, this is hole diffusion, and this is electron diffusion and L_e then L_h.

And this whole, the distance between these two is called the active region which is nothing but $w+L_e+L_h$. So why do we have this diffusion region? Because of the field that you have. So, when you create a p-n junction you have a built-in potential here. So, you will have this field that has an influence on the region neighbor by region where you could get the charges into the field. After this region where you have homogeneous region and here again, where you, you can generate carriers, but they will not have any influence on the field that you have.

So, let us understand how the, the absorption process happens. So, in the depletion region you will, you can generate carriers when you have a photon impinge, and this will be drifted. So, this drift happens because of the built-in potential that you have. Similarly, you could have photon that is in this diffusion region that could create, what you call the diffusion current here. So, there is a diffusion process here.

Similarly, we could have an electron diffused through this system, so this is diffusion. And here again we have diffusion that happens but then you could also generate carriers outside this region. So, you could, you could generate this outside this region but the problem here is, there is no fields with which the carriers could get drifted or diffused. So here the resultant will be recombination before reaching the junction.

So, it cannot reach the junction where it could, we could separate the carriers. So, they, they are unable to reach the, the junction here. Similarly, the, the electrons that are generated here they are unable to reach the, the junction here. So, this is how the process in the various absorption regions happens in a p-n junction diode. So, we need to understand that light can be absorbed in any region.

So, in whole of the semiconductor, we can induce charges but then the important thing is, again I will go back to our fundamental idea, transport of this free electrons are important. How do we transport that? This transport depends on where the, the drift and diffusion fields are, so unless you can, the carriers are in the diffusion or in the drift region you would not be able to collect those carriers.

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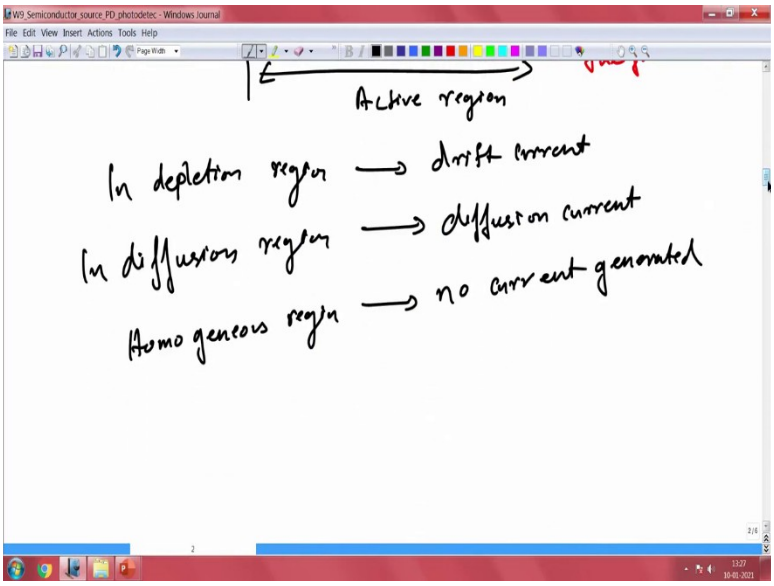
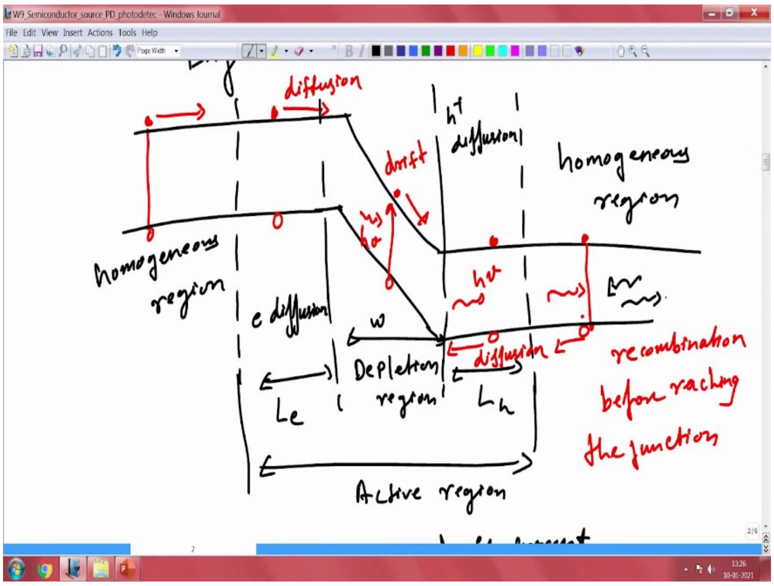


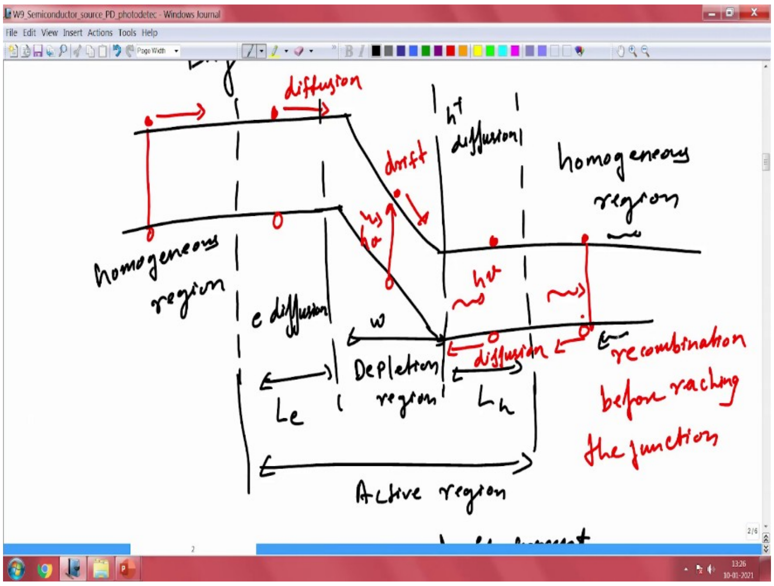
Active region

In depletion region → drift current

In diffusion region → diffusion current

Homogeneous region → no current generated





So, let us look at the currents that these guys are going to generate. So, in the depletion region, so you create a drift current because of the, the voltage, the built-in potential that you have or the reverse potential, the reverse potential that you have. So, in this case you could have drift because of the built-in potential but we can also do a reverse biasing.

So, the p could be connected to n and the n will be connected to a anode in order to make this reverse bias. So, you will have a, a drift current happening here. And then you could have diffusion in the diffusion region, you will have diffusion current. So, in homogeneous region you will not have any current firms, there is no current generated because you do not have any influence of the field from the depletion region.

So, you are unable to diffuse, there might be some diffusion happening here, the charges could diffuse a little bit left and right here, but then they would not be able to reach it, because the lifetime of this carriers are short enough that before they reach the diffusion region and then or the, the depletion region they will be recombined. So, the recombination lifetime is much shorter than this. So, when you are illuminating this with a light source, so how the junction currents are going to be generated between these different regions, so let us look at that.

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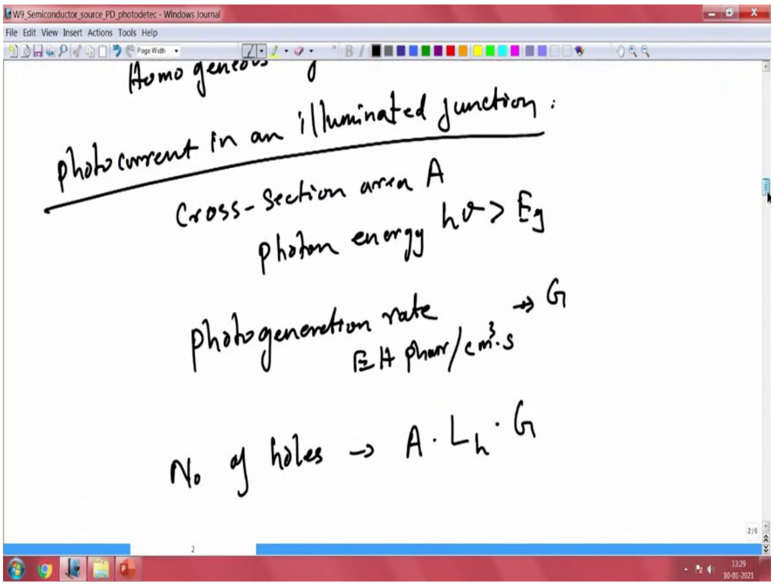


Homogeneous

photocurrent in an illuminated junction:

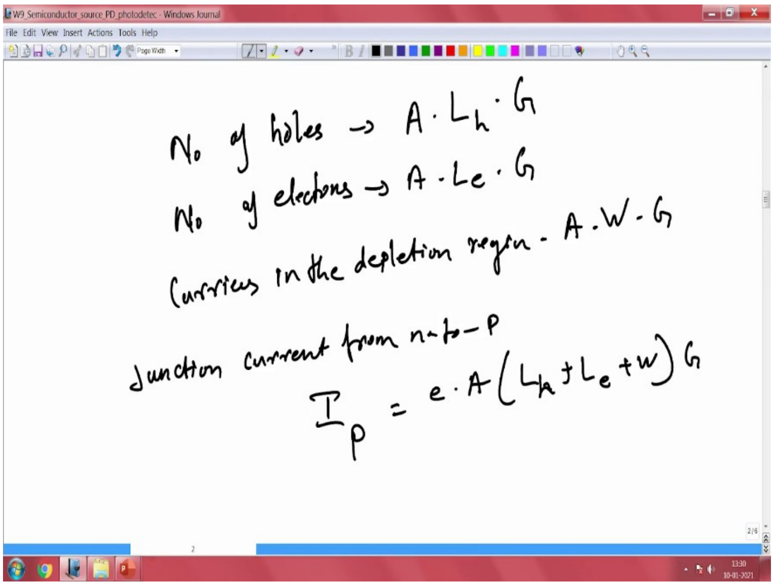
Cross-Section area A

photon energy $h\nu > E_g$

Photogeneration rate $\rightarrow G$

EH Pair/$cm^3 \cdot s$

No of holes $\rightarrow A \cdot L_h \cdot G$



No of holes $\rightarrow A \cdot L_h \cdot G$

No of electrons $\rightarrow A \cdot L_e \cdot G$

Carriers in the depletion region - $A \cdot W \cdot G$

Junction current from n-to-p

$$I_p = e \cdot A (L_h + L_e + w) G$$

So, the photocurrent in an illuminated junction. So let us have a cross section area A, that is the area A, and we have a certain energy hν. So, photon energy hν, which is obviously greater than E_g. So now the photo generation rate, the photo generation rate it nothing but electron hole pair per centimeter cube per second that is G, so that is our G.

And this gives rise to a photon current, there is a holes that are generated and there are electrons that generated, so the number of holes is given by the area times the hole times the generation rate. So L_h is the hole generation here, look at this and then L_e is the length of the diffusion region there. So now number of electrons are A L_e times G, p side and the n side.

And now the total carriers, the carrier generated within the carriers in the depletion region is given by A W times G. So, W is the width here see so A W G. So now what is the junction current? So, the total current here. So, so junction current from n to p is given by I_p which is nothing but $e\,A(L_h + L_e + W)G$. So, this is our total current that is going through.

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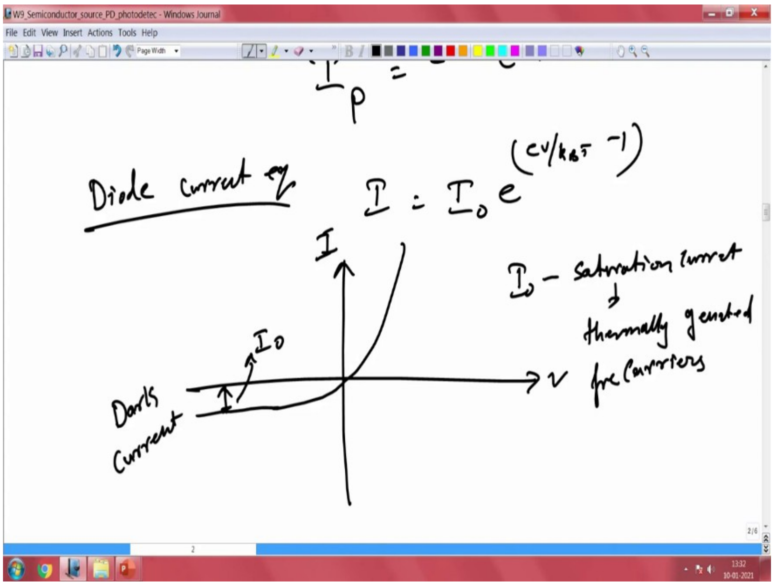

And let us look at a very simple diode configuration that gives us how this current is going to change. So, the, the basic diode current equation and that is something we all know $e^{\frac{eV}{k_B T}-1}$ and we also know how it looks. So, this is what we call the dark current when there is a reverse voltage, there is, there should not be any current flowing through but then there will be a leakage current which, which is due to the saturation current, since I_0 is nothing but saturation current or in other words thermally generated free carriers, due to thermally generated carriers, free carriers, so which results in dark current.

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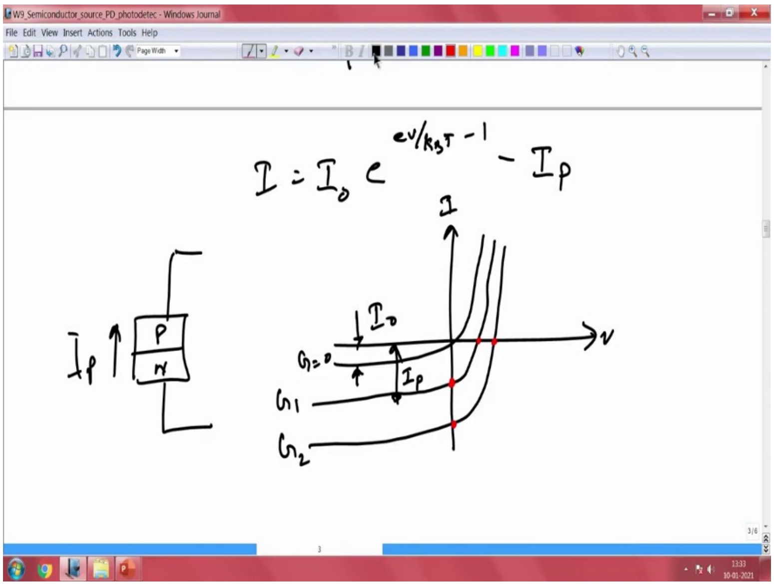

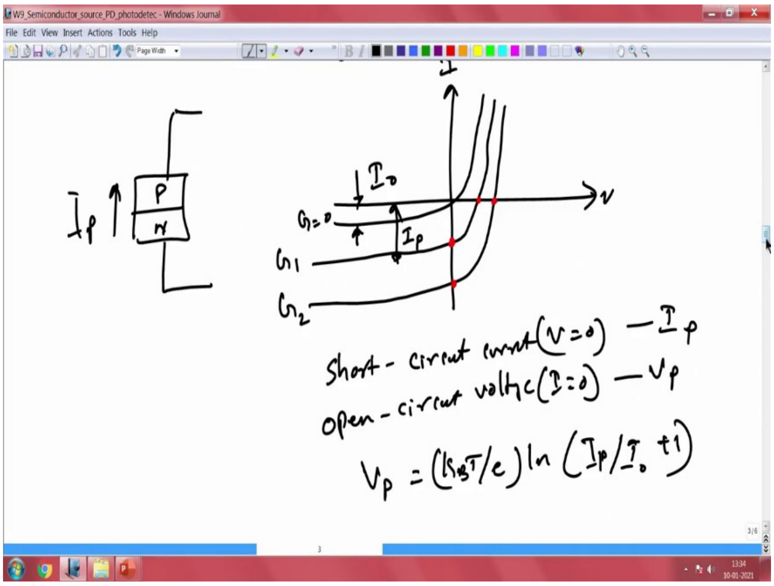

Short-circuit current (V=0) — I_p
open-circuit voltage (I=0) — V_p
$V_p = (k_BT/e)\ln(I_p/I_0+1)$

So now when you illuminate it, so upon illumination so this equation is going to change a bit. So, you are going to add a reverse current here, there is an additional current that is going through this and this I_p, we have already, already seen what this nature of this I_p is going to be. And, and you take a, a simple p-n diode and the current will go through this and so this is our I_0. So, where G is 0, G is equal to G let us say instead of G1, G2 is our new generation and this is actually our I_p, so the current that we are generating.

And there is interesting points here as you all know, here what we call the potential across. So, the the short circuit current and the open circuit voltage is something that we all know from our simple diode understanding. So, the short circuit current when V is equal to 0 is I_p and open circuit voltage that is I equals to 0 which is V_p. So now your open circuit voltage is $\frac{k_BT}{e} ln\left(\frac{I_p}{I_0}+1\right)$. So, we can find what is the potential drop across this diode based on the illumination or the based on the current that we have.

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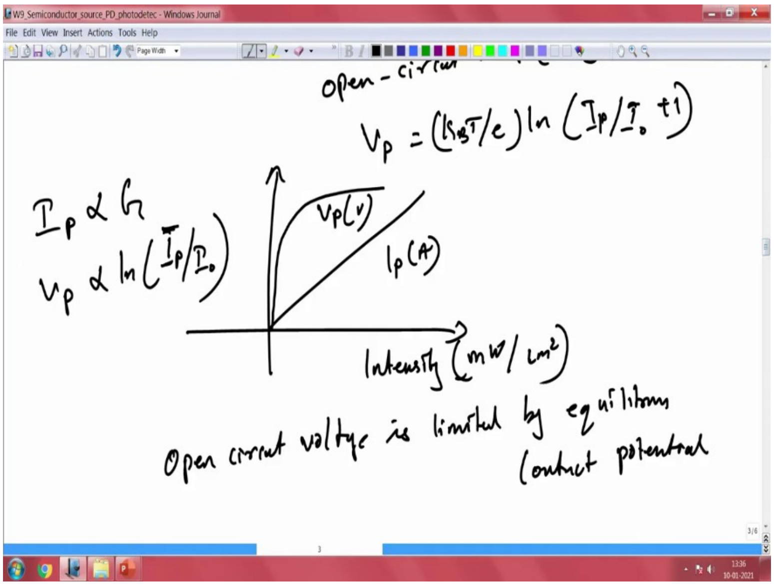

open-circuit
$V_p = (k_BT/e)\ln(I_p/I_0+1)$

$I_p \propto G$
$V_p \propto \ln(I_p/I_0)$

Open circuit voltage is limited by equilibrium (contact potential)

So, another important thing to, to notice here compared to the other basic diode electrical understanding is what happens to your current and voltage with respect to intensity? So, when you have an intensity of certain Watts here, the current as a linear trend, so your current will actually linearly increase with the intensity. However, your voltage will saturate in volts. So, voltage will saturate, while your current will linearly increase. So, your I_p is proportional to the generation rate here.

However, your voltage is proportional to your current that is generated here. So, the limit to this one that V_p, it saturates to that. So, this is limited by the, open circuit voltage is limited by, by the contact potential. So, equilibrium contact potential, so it is not internal to this, so you, the contact potential gives you the limit to which you can have your open circuit voltage here. So, you can operate this, the diode in two different regimes.

One is photoconductive regime, the other one is photovoltaic regime, when you have an illumination, you generate a current change, that is photoconduction based on the illumination the current changes or in, in photovoltaic you generate a potential drop across, so there is a change in the potential that you have. So, it is basically whether you are in third quadrant or whether you are in fourth quadrant.

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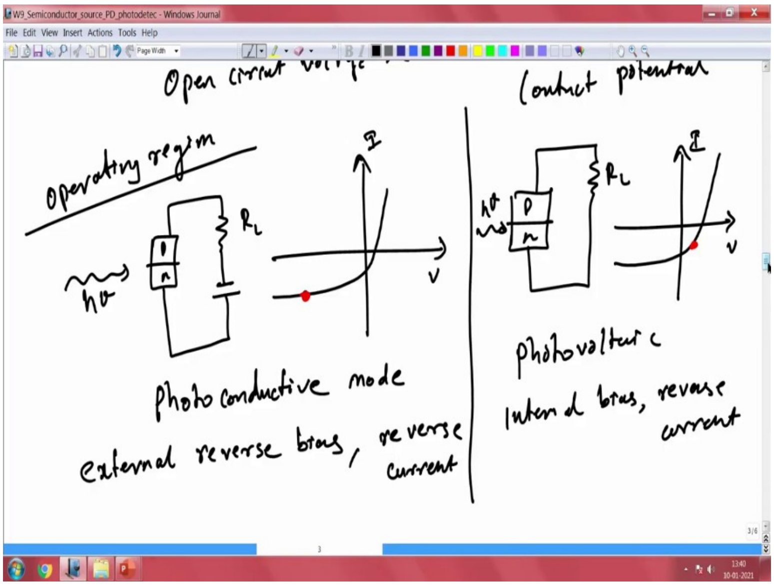

Let us say the operating regime, so you could take a p-n junction and connect a load resistor and do this and when there is a incoming photon you will, you will generate a current like, this and this is where you want to operate, this is called photoconductive mode. So, the circuit, the positive power is, or the power is directly delivered to the external circuit through this load here, so this is something that you can do once you connect it through a reverse bias.

So, you can see here this is reverse potential, so you, you have to connect it through a reverse potential you should be able to operate it in this. So, there is an external reverse bias which results in reverse current. So, we primarily operate the photodetectors in this photoconductive regime, so photoconductive operation working in the third [quadrant].

So, the other mode is photovoltaic where you do not connect any power source into this and when there is a photon impinging. So, what you get is this and you are operating through this. So, it, it works with where the principle is called photovoltaic, where the power is delivered to the load by the device, this is the solar cell thing.

So, there is an internal bias and a reverse current. So, this is how your two different regimes of diode operation we could use one or the other but for, for integrated circuits we and also detectors, the high-speed detectors we use the photoconductive mode where we deliver the positive power to the external load that you have here.

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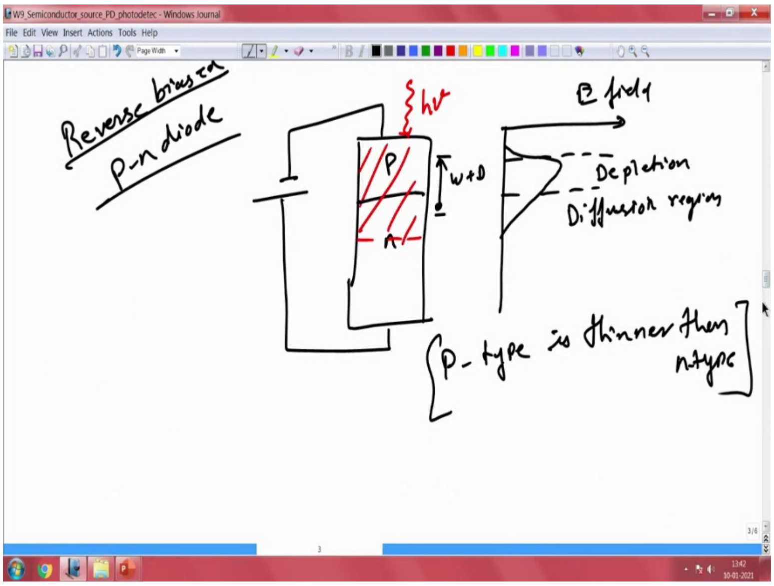

So, let us look at how this reverse bias is going to help us in this in achieving this. So reverse biased p-n diode. So, we can take a very simple diode here this p type and n type and connect this to negative first you do this and when you connect this it creates a certain width here. So, you have depletion width plus diffusion width, and the electric field will start this and then high in the depletion region and then it dies down.

So, we have depletion region and then we have diffusion, diffusion region, and the light is getting absorbed in this whole region. So, we do not have to worry too much, so the light is getting absorbed in this whole region if you are illuminating it from top. So, you can see here the light is traveling through p type material, through our junction and into n type. So that is the reason why you make p type thinner than the n type. So, you have larger n type compared to the p type.

So, p type is, p type material, p type is thinner than the n type. So, the idea here is to make this absorption happen in this depletion region so that you can efficiently collect the charges from this, because that is where your depletion region is present. So, you want this depletion region to be very large so that you can efficiently absorb light. So instead of having a simple p-n diode, we can increase this whole depletion region and the absorption region by going to a p-i-n configuration.

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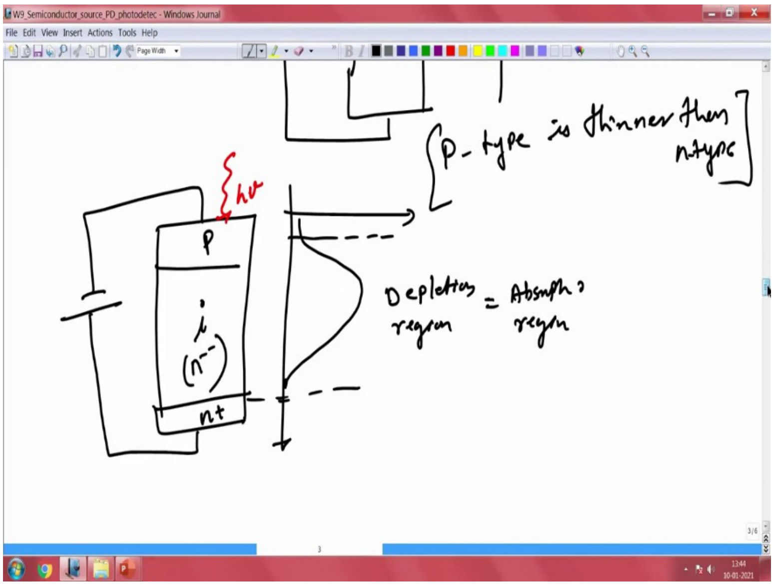

So, we can take configuration where we have p type, where we have n type and then we have intrinsic in between and here again it is reverse biased. So, in this case the field would look very large, you have a very large field distribution and then it will end before the n type starts. So, this is the, the depletion region, which is equal to absorption region. So now we have very large absorption region and that is overlapping with the, the depletion region. So, you have effective collection of charges that you are absorbing.

Another important thing to notice here is the n type material that you have on the lower side, you wanted this, this to be highly doped so that you reduce your resistance. So, all the (absorb) absorption takes place in the depletion region and the intrinsic region can be and this can be an n type material for all practical purpose and then makes a low resistance contact to this n^+.

So, this n material, the intrinsic material could be slightly n doped. So, the intrinsic should be or n^{--} let us say, so one could have such a configuration where you could efficiently collect the charges through this system. So, by doing this you can efficiently collect the charges these are different configurations that you have.

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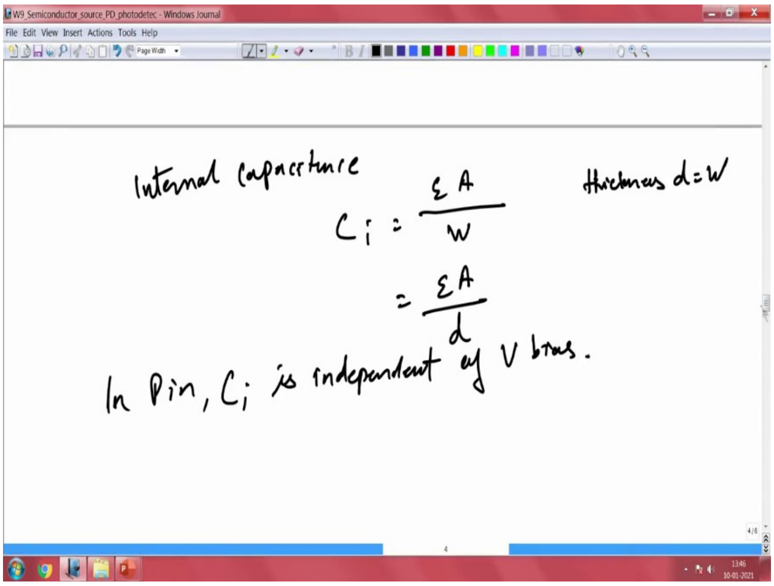

Internal capacitance

thickness $d = W$

$$C_i = \frac{\varepsilon A}{W} = \frac{\varepsilon A}{d}$$

In Pin, C_i is independent of V bias.

And the other important thing is the problem with the capacitance once you make these diodes p-i-n, the capacitance starts to crop in. So, the internal capacitance C_i is given by ε A over width. So, as you can see here, when you make this really large, really wide your capacitance will have an effect on this.

So, if d is the thickness of what you have, let us say if is equal to W then is essentially, the different thicknesses that you have in the medium, you can just use it as d because you can look at both the depletion and also you have the diffusion capacitance there. So, it is a combination of diffusion and depletion capacitance could be taken here.

So, the capacitance is independent of the bias voltage in this particular case, and it should remain constant throughout the operation. So that is something that that is, that is p-i-n offers. So in, in p-i-n, the important thing is capacitance, C_i is independent of the voltage that you have in this case bias, V_{bias}. But, but in, in in p-n junction, your junction capacitance here is a function of voltage but in this case your, your junction is pretty large and whatever change that you may have because of the DC is negligible. So, you can neglect that.

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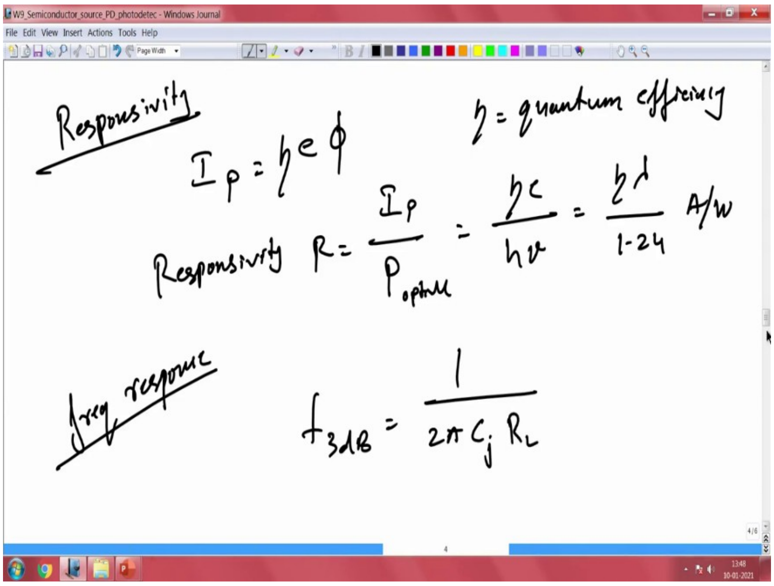


Responsivity

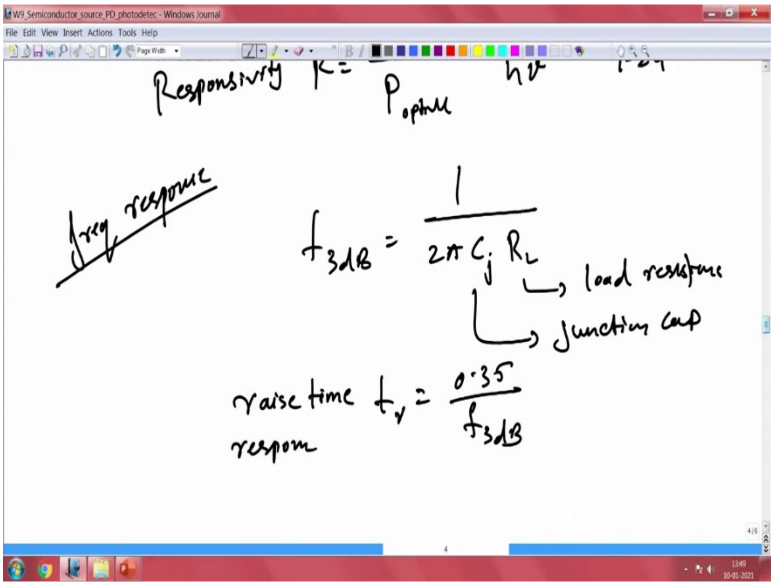
$I_p = \eta e \phi$

η = quantum efficiency

Responsivity $R = \frac{I_p}{P_{optical}} = \frac{\eta e}{h\nu} = \frac{\eta \lambda}{1.24}$ A/W

freq response

$f_{3dB} = \frac{1}{2\pi C_j R_L}$



Responsivity $R = \quad P_{optical} \quad h\nu \quad 1.24$

freq response

$f_{3dB} = \frac{1}{2\pi C_j R_L}$

$R_L \rightarrow$ load resistance

$C_j \rightarrow$ junction cap

raise time response $t_r = \frac{0.35}{f_{3dB}}$

And your, the responsivity of or the current that you could generate out of this system is the next important parameter, it depends on the, the current. So, the current generated is the, the quantum efficiency, the charges that you get in and your flux that you have. So here η is your quantum efficiency and responsivity R is nothing but the current to the power that you apply. So, this is power optical and that is the current that you get. So, this is given by $\frac{\eta e}{h\nu}$ or in other words $\frac{\eta\lambda}{1.24} A/W$.

So, the. the responsivity for LEDs on the other hand is Watt per amps. So how much Watt of power is generated for the current that you give in, but in this case, it is how much of current is generated per Watt of input power. Now the, the response of this diodes let us say the frequency response or bandwidth. So, frequency response is another property that is determined by the, the capacitance and the junction capacitance we have and your load resistance.

So, the junction capacitance that we have, the internal junction capacitance will play a role and also the load resistance that we connect here R_L. So R_L is load resistance and this is your junction capacitance. And similarly, we could calculate this with our quick thumb rule given by this, so it depends on our raise time, so this is our raise time response.

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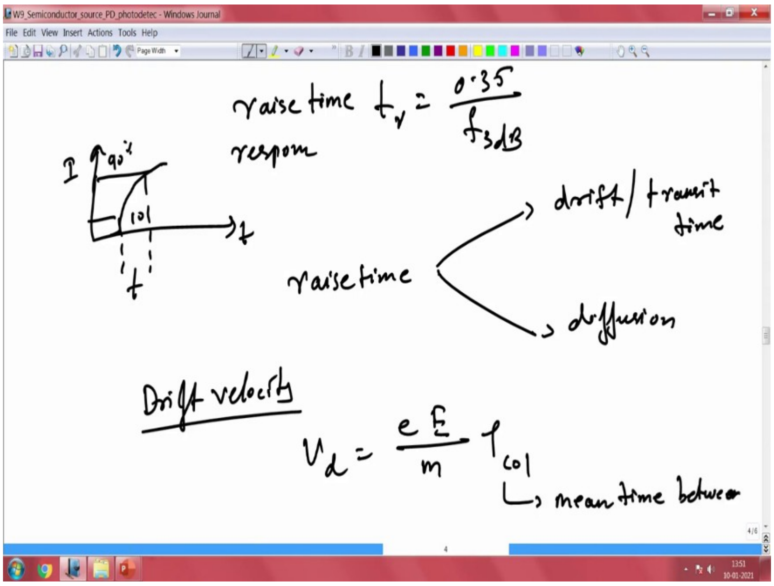


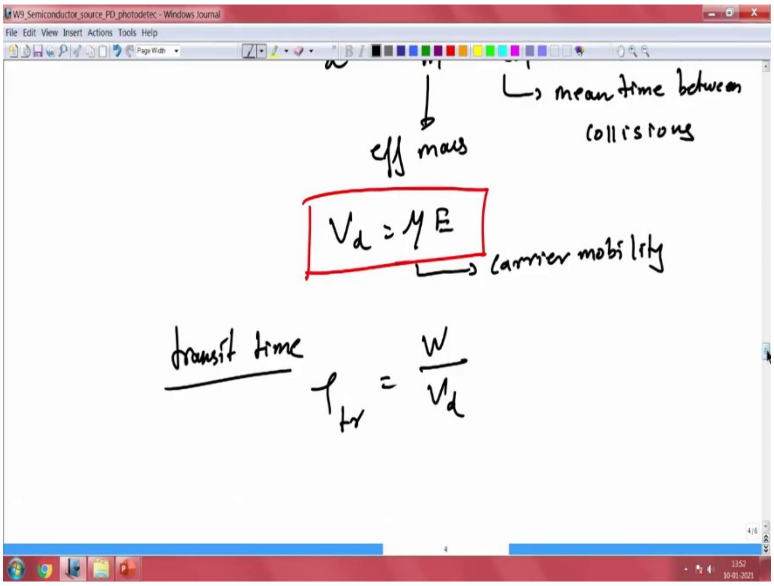
raise time $t_r = \frac{0.35}{f_{3dB}}$
respom

raise time → drift / transit time
raise time → diffusion

Drift velocity

$v_d = \frac{eE}{m}\tau_{col}$

↳ mean time between



$$\boxed{V_d = \mu E}$$

$$\tau_{tr} = \frac{W}{V_d}$$

So that is nothing but as a function of time we have a pulse raising from 10% to 90% what is that time required and based on this we could calculate, this is the current, calculate what is the bandwidth that we have here. So based on this time difference, the raise time, we could find how fast this particular diode is, but this, the time that is, that is taken depends on two things, the raise time depends on two different things, one is drift and other one is diffusion.

The drift time is what we call transit time. So how much time it takes for the charges to drift and reach the electrode, and that, that is, that strongly depends on your mobility. So, drift velocity is given by $\frac{eE}{m}\tau_{collision}$, let us say. So mean time between collision, so mean time between collision is this and e is the charge m is the effective mass, effective mass of electron that you have.

So, this could be written as simply μE. So, μ is our mobility. So, this is the reason why if you want a a fast detector which, which, where the charges could be collected fast, find a material that has high carrier mobility. So, the frequency response depends on your mobility this case, so you can get a material with higher mobility that will result in a very low transit time, that means the diffusion drift current can be much faster.

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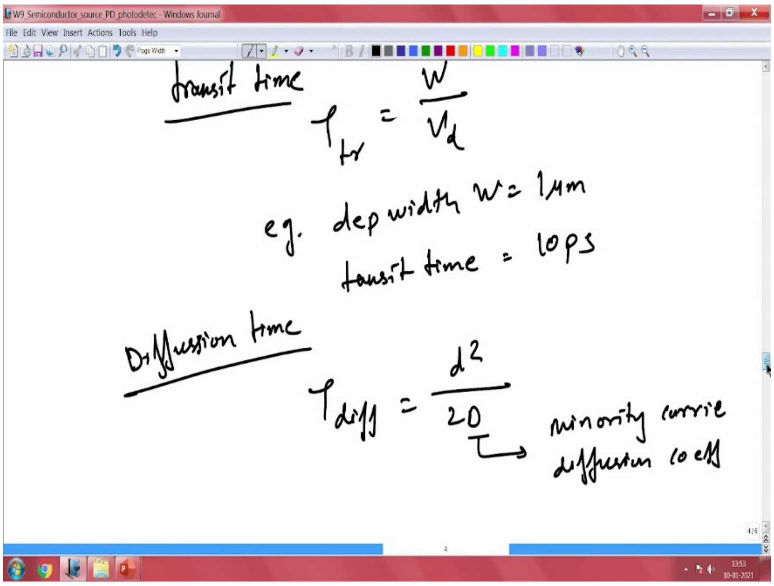

transit time

$$\tau_{tr} = \frac{W}{v_d}$$

e.g. dep width W = 1 μm

transit time = 10 ps

Diffussion time

$$\tau_{diff} = \frac{d^2}{2D} \quad \underset{}{\rightarrow} \text{ minority carrie diffusion coeff}$$

So, also this transit time that we are talking about also depends on the size, your τ_{tr} the transit time depends on how large your width is, so the transit time depends on the velocity and the distance it has to travel. So, make sure we, we cannot make depletion widths very large for example if you have a depletion width W which is 1 micrometer, then the transit time will be approximately for silicon at least transit time will be about 10 picoseconds. So, you can have a smaller depletion width in order to reduce this transit time.

So, next thing is the diffusion time. So, so the diffusion time that is $\tau_{diffusion}$ depends on the minority charge carriers. So, so d is nothing but minority carrier diffusion coefficient, so based on, on this that again d is your size, your diffusion distance here so the d that we already saw earlier, where is it, so W+d here. So, d is the diffusion, so based on the diffusion width, diffusion layer width, we should be able to calculate this particular diffusion time.

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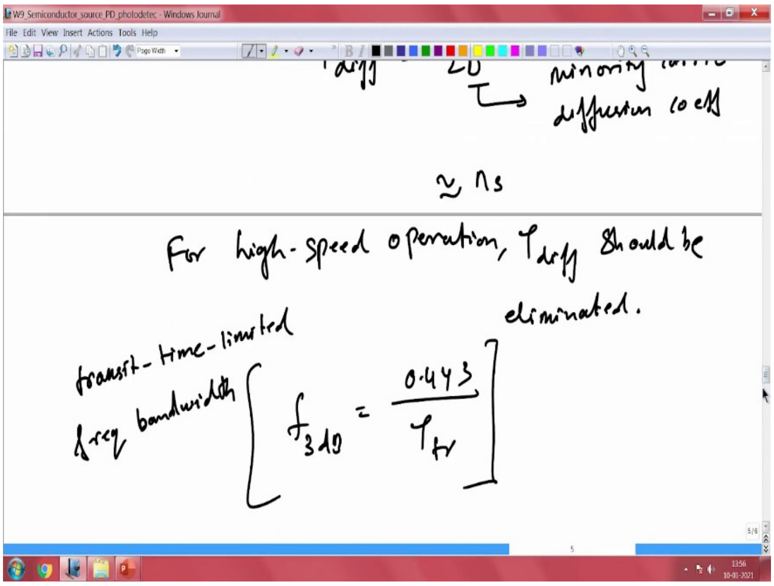

diffusion coeff

≈ ns

For high-speed operation, τ_{diff} should be eliminated.

transit-time-limited freq bandwidth

$$\left[f_{3dB} = \frac{0.443}{\tau_{tr}} \right]$$

So, it is important for high speed that this diffusion mechanism should be completely eliminated. For high-speed operation τ_{diff} should be eliminated, so we do not want this to be there. So whatever carriers out, generated outside the, the depletion region you do not want them to come in. So, you do not, you want to avoid that diffusion, so that you can have only the drift component which are much much faster.

So, the diffusion compounds are much much longer in this case they are in in nanoseconds, in nanoseconds. So, you do not want this to, to affect your speed of operation, so you want to reduce this by controlling your diffusion lifetime here. So, based on this, one could calculate what is the total time required in order to get the maximum speed that is achievable using a particular diode configuration.

So, let us look at the transit time, a limit as well here when it comes to 3 dB limit, the frequency of operation is given by the transit time limited. So, this is our transit time limited frequency bandwidth. It only depends on the transit time, and this is, this can be given by this. So, based on this one can work out how to compensate for the capacitance that we have between the p-i-n junction and p-n junction configuration, and we can look at various integration strategies in order to get this.

In the later part we will look at how to integrate this into the into a guided wave system as a demonstrator, and then see how you can have a a guided wave and then integrate a photodetector on top or photodetectors on the side in order to detect or extract this photons into charge carriers, but in order to analyze those data we need to understand the basics of how fast it can operate, what are all the limitations of those speeds and also, we need to look at the responsivity.

So how much absorption length is required in order to achieve a certain responsivity and so on. So, with this we have covered how to understand a photodetector in a semiconductor and later in the course we will see how we are exploiting this understanding to demonstrate a photodetector that is integrated with a waveguide. Thank you very much for listening.