Transducers For Instrumentation
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Lecture - 18
Optical Sensors: APD Photodiodes and LED Sources

Hello, welcome to the course Transducers for Instrumentation. Last lecture we discussed some optical detectors mainly the photodiodes or PIN diode and we saw that the structure of this photo detector is P type intrinsic and N type there are three regions and the intrinsic region is ah has very high electric field because we bias this photo diode in always in reverse bias. So, intrinsic region has very high electric field and a photon comes in and it generates electron hole pair and that electron hole pair gives rise to the electrical ah voltage or the current which we sense across a load resistor as a electrical output. So, this we saw and then we discussed some of the equations which ah govern how many photons will be absorbed in a particular distance when when we shine a light on a material because not all the photons are absorbed on surface itself they actually penetrate the material they go well inside and there is a kind of exponential relation of absorption with the distance. So, this we discussed last lecture today we are going to discuss the avalanche photo diode which is we call APD. Unlike PIN diode where the electrical output is kind of say equal to or the ah kind of corresponding to number of photons received by the device because one electron one photon give rise to one electron hole pair and that give rise to one unit of ah charge outside. Unlike PIN in avalanche photo diode if a one ah photon comes in then we have a very high electric field in the intrinsic region. So, that the the generated electron hole pair they acquire energy from this very high electric field and they acquire so much of energy that they that the same electron can itself knock down one more electron hole pair. So, this is kind of a chain reaction one electron hole pair give rise to two electron hole pair and these two electron hole pair give rise to four electron hole pair. So, this is a chain reaction and suddenly within ah ah fraction of ah seconds we get so many electron hole pair that a reasonable amount of current flows in the outside load.

So, a single photon give rise to significant current. So, we have some sort of a gain in the avalanche photo diode. So, we are going to discuss today avalanche photo diode. So, this is avalanche photo diode or we call it APD in short and the structure and electric field profile of this APD is something like this. We have the similar region for example, we have this N plus here and then we have a P region here and this is intrinsic region and this side we have P plus region and all these photo detectors are always biased in the reverse bias mode. So, we have a external voltage which is connected in reverse bias means the positive terminal is connected to N plus and the negative terminal is connected to P plus through a load resistance across which we will measure the output voltage. So, this is our

R load this is my electrical output. So, this is the structure of APD or avalanche photo diode and we have intrinsic region which is connected to P type this side and which is further connected to N plus. If we plot the electric field profile of the same structure this looks something like this. So, we have a very high electric field building in this vicinity where N plus and P are joined together because this is a very heavily doped region.

So, the electric field will be very high in this is electric field with respect to x which is the distance across this device and the electric field profile look something like this. We have a peak at this point and then there is a constant field profile because intrinsic region the potential will be dropped linearly and then we have like this. So, this is the electric field profile if we apply a certain voltage across this APD and we see here there is a peaking of electric field happening at this interface N plus and P and we call it avalanche region and this is our depletion region. And the physics of working of this device is exactly same where we have intrinsic region where photon will strike and it will knock down electron hole pair. Now this electron hole pair will move towards the terminal where this charge carrier see a avalanche region. Avalanche region is a short region where the electric field is very high as we can see in this field profile because of this very high electric field these charge carriers will start gaining energy when they are moving through this region. So, they will acquire enough energy so that this electron or hole they can knock down one more electron hole pair by releasing that energy to to the lattice. This generated electron hole pair will further move according to the electric field and start gaining energy from electric field and knock down again one more electron hole pair. So, this is a chain reaction one photon give rise to one EH pair or electron hole pair. This one EH pair give rise to two EH pair two gives four and four gives eighteen and this is like a geometrical series.

So, we get at the end a very high current in the output load which is the R load. So, one single photon gives rise to a significant current in the output load. So, we can say that there is a gain in the device where this gain is multiplied to the number of photon received we get let us say hundred photons, but that hundred photon give rise to one million kind of electron hole pair. So, this is a gain in the in terms of the signal. So, this is the structure of APD. Now, let us write down few important points. So, the APD has an internal gain M which is obtained by having a electric field in fact, high electric field that energizes photo generated electrons. The second point is these electrons. Ionize the other bound electrons in the valence band upon colliding with them which is known as impact ionization. Then these newly generated electrons and holes are also accelerated by the high electric field and gain energy to cause further impact ionization.

This phenomena is actually called the avalanche effect and hence the name of this device which is avalanche photo diode. This phenomena is called avalanche effect. So, we see that this avalanche photo diode generates multiple electron hole pair even with a strike of a single photon. It means there is a gain which we can say M times it depends on the device geometry and it depends on how much reverse bias we applied, how much is the electric field profile. So, depends on all those things this gain actually depends on those profiles, but this APD has a internal gain and one photon gives rise to M number of electron hole pair and accordingly the current which is proportional to the number of charge gain. So, this is the avalanche photo diode which is second type of photo diode which we use for these optical detection. Let us see some of the numerical problems what for the equations we just discussed last lecture. Let us have some of the examples based on that. So, we have example here. So, we need to find out the maximum value of the energy band gap energy gap or we call it band gap which a semiconductor used as a photo detector can have if we want to make for yellow light for example when we have yellow light it means we are we know the lambda for yellow light which is 600 nanometer. So, this is the example. So, let us see what is the solution. So, here we want to make a photo detector which is sensitive to yellow light it means it should detect when the yellow light is coming and for the yellow light it is universal value that yellow light has a lambda of 600 nanometer. So, when yellow light will come the photons the yellow light carries they have a certain energy which is equal to which is equivalent to the 600 nanometer wavelength. So, we need to find out that much energy what is the energy of those photons and if the energy of these photons are more than the band gap of the material more than or equal to the band gap of the material then the material can absorb these photons and generate equivalent amount of electrical signal.

So, we need to find out how much is the energy of this photon and our band gap of the material should be equal to or equal to or lower than this the energy of these photons. So, for the limiting case we take band gap as equal to the energy of photons. So, to calculate energy of photons we know E the energy of photon is equal to h c upon lambda where h is this plane constant c is the velocity of light and lambda is the wavelength of light. So, we can put the values here h is 6.626 into 10 to power minus 34 multiplied by c which is 3 into 10 to power minus 34 and divide by lambda which is 600 nanometer. So, we need to convert it into meter 10 to power minus 9 and the value comes out as 3.3 into 10 to power minus 19 joule or you can express it in electron volt which is more relevant for the band gap calculation it comes out 2.07 electron volt. So, here we see that if we use a material which has a band gap of 2.07 electron volt it means it can absorb the photon of yellow light and it can produce a electrical signal. So, this material which has band gap 2.07 electron volt it can act as a good photo detector for yellow light. So, this is how we calculate the band gap of material which material should be used for which kind of light. Let us take the second example this is one. So, a photo detector whose area is given let us say 5 into 10 to power minus 2 centimeter per centimeter square is irradiated with yellow light whose intensity is 2 milli watt per centimeter square.

So, now we assume that each photo each photon generates 1 electron hole pair. In short we can write electron hole pair as PHP then we need to calculate the number of electron hole pairs generated per second. So, here is example we have a photo detector whose area is given 5 into 10 to power minus 2 centimeter square and we irradiated this area using yellow light for which we already know the energy of the photon and intensity of this light is 2 milli watt per centimeter square. So, when we shine this area with this much of intensity of yellow light how many electron hole pairs are being generated per second. So, this is what we need to find out. So, here the assumption is that each photon generated gives rise to 1 electron hole pair means the efficiency or the quantum efficiency of these photons are 100 percent all the photon give rise to a electron hole pair. Here the assumption is efficiency or the quantum efficiency is 100 percent. So, this is the assumption we are making then we can calculate the number of electron hole pair generated per second is equal to the number of incident photon per second. So, the number of number of incident photons per second is equal to I the photo current divided by the charge of electron which is equal to the p node the incident power of photons divided by h nu or h c by lambda which is the energy of a single photon. So, these two quantities are equal because we are assuming that the quantum efficiency is 100 percent.

Now, we can put these values together where I p h over e is number of electrons per second. So, we can calculate from this equation that p node upon h nu is equal to 2 into 10 to power minus 3 multiplied by 5 into 10 to power minus 2 what divide by h into nu which we have calculated in the earlier example this value which is 3.3 into 10 to power minus 19 and the value comes in 3.02 into 10 to power 14 per second. So, in this example we see if we irradiate this photo detector with intensity of 2 milliwatt per centimeter square with yellow light then how many number of electron hole pairs will be generated assuming that each photon is giving rise to giving rise to electron hole pair. So, 3 into 10 to power 14 electron hole pairs will be generated in the material or in the photo detector and this will come out as a electrical signal across the load resistance. So, these are some of the examples which we can try based on the equations we discussed for photo diodes. So, we discussed two photo photo detectors one is p i n photo diode and the avalanche photo diode. Next we are going to discuss the source the optical source which can generate the optical signal or the optical photons from the electrical signal we apply electrical on the device and it generates the optical photons which we can coupled to the optical fiber and optical fiber carries these photons to the long distance. So, let us discuss the photo source. So, photo source or optical source is nothing but a light emitting diode. So, we have LED we call it in short. So, this is a diode which is forward biased and it gives rise to the optical photons and we call it the light emitting diode and the structure is also very similar to a normal LED. So, we discussed LED the light emitting diode. A light emitting diode or we call LED in short is a device which converts optical energy to light energy or to optical energy and these devices are quite inexpensive robust and have long life.

These devices can be easily modulated that means switch on and off at high speeds. The third is this can couple enough output power over a small area to couple to fibers. So, we have this LED or the light emitting diodes which is a device which converts electrical energy into the optical photons the optical energy and these LEDs has certain properties. First is these are very inexpensive in nowadays with the progress of microelectronics these LED devices are very inexpensive. These are quite robust because these are solid state devices. So, they are quite robust in harsh environment as well and have very long life because there is no moving part. They can be easily modulated because the size of these LEDs are very small and junction capacitance is also very less. So, we can modulate or we can turn them on and off at very high speeds which is desirable to send these optical signals and we can couple enough output power from these LEDs because the area where the light is being emitted that region is very small. So, we can easily couple that to optical fiber efficiently. So, that all the photons which are generated by LED they couple to the fiber and they go inside the fiber. So, these are some characteristic of LED as a optical source. Then we have two types of phenomena's one is called photoluminescence and one is the electroluminescence. So, these are two different phenomena's occur to generate these photons. Let us discuss them as well. So, the first one is the photoluminescence in this the electron hole pairs these excess electron hole pairs are created by photon absorption.

The photon is emitted by the combination. So, this process is called photoluminescence. And the other phenomena is electroluminescence. Where this excitation of these excess carriers is a result of an electric current caused by an applied electric field. And this happens for example in LEDs. So, we see here two phenomena's one is photoluminescence. In photoluminescence a electron hole pair combines and they get annihilated give and releasing the extra the amount of energy. This energy is released in terms of a photon. So, photon get generated by annihilation of electron hole pair. So, this is photoluminescence. In electroluminescence a current is passing in the device and this current gives rise to the this the energy is actually released by the from this current because the current is the flow of electrons. These electrons acquire energy from the applied electric field and this extra energy is released in terms of photon. So, the photon generated by in this process is called electroluminescence. So, these are the two phenomena's and electroluminescence actually happens in LEDs or the light emitting diode. So, let us see how this happens in terms of the energy band diagram.

When a junction is made of p-type and n-type material the Fermi levels on both the sides are not aligned. Because, the Fermi level for a system equilibrium should be uniform the band bending takes place. So, now we have two material one is p-type and one is n-type. And remember these material this material is not silicon material this is a direct band gap material because as we discussed last lecture for optical full photon generation it we need a direct band gap material. So, this is a direct band gap material for example, gallium arsenide or so. So, now we have p-type material and n-type material when we join them together in equilibrium the Fermi level should be uniform. So, but for individual material the Fermi level is not aligned. So, when we join them together the band bending takes place and we can draw the band diagram for this structure. We have this first side where we have band something like this and on the other side we have like this. Let us say this is p-type where this Fermi level is close to the valence band. So, this is our E b and this is E c the conduction band energy and this is our Fermi level and our intrinsic Fermi level lies somewhere in the middle this is our E i the intrinsic Fermi level. Now when we join them together these Fermi levels actually in the in equilibrium this Fermi level should be flat. So, the band bending takes place which looks something like this and here like this. So, we have the band bending and this region is formed as a intrinsic region which is depleted of charge carriers and sometimes we call it the depletion region as well because this region is depleted of charge carriers. And in now in this we have certain holes which are majority in p-type and we have some electrons let us say this one they are in majority in n-type region and the energy band gap is let us say E g which is uniform in both the sides E g is the band gap between this level and this level this is E c this is E b.

So, now we have drawn the energy band diagram of LED in equilibrium where we are not applying any bias to this device when we are not applying any bias it means the Fermi energy the Fermi level remains flat and because in p in the p-side Fermi level is close to the valence band and in the n-type Fermi level is close to the conduction band. If these level need to be aligned it means the band bending will take place that is as shown here and when we join them together there is a depletion region formed this region is kind of depleted of mobile carrier just like our normal diode this is what happens in our diode the depletion region forms the same thing happening here the depletion region is formed and the band bending whole of the band bending is taking place in the depletion region. When the band bending is taking place it means we have a certain electric field available in this region. So, depletion region is the region where all the electric whatever voltage is applied that whole voltage will appear across the depletion region where the band bending is taking place if there is no there are the bands are flat it means there is no potential applied in that particular region. So, when we apply a voltage bias across this device this band bending will be further high and that causes a high electric field this electric field give rise gives the energy to the moving charge carriers.

So, this is what happens when we apply the electric field. So, the LED works in the forward biased case. The carriers diffuse to the other side of the junction where they can combine quickly. So, we can draw the same energy band diagram in when we apply a voltage. This is EC this is EV the valance band and now we apply a voltage across this device this is a forward bias voltage. So, when we apply a forward bias voltage these electrons these electrons will start moving towards P type and these holes which are on the P side they will start moving towards an N type this is the intense equation for the depletion region. So, now we have this device and we apply a forward biased across this device. Now, electron and hole will see a field which is pushing them towards the other side. Now, when this electron from N side where this is in the access or the majority carrier when it moves to the P side where this is a minority carrier and it can recombine there because there are so many holes available. So, when this electron and holes will recombine they will release the extra amount of energy in terms of a photon and this photon will come out as a optical photon and this works as a LED or the light emitting diode. So, this device now these electrons can recombine and give rise to a photon all these recombination will give rise to a photon. So, this is how this LED works the recombination of electrons and holes also takes place non radial non radiatively. So, we see here that these electron and holes are recombining and emitting the extra amount of energy as a photon, but sometime this release of the energy is non radiatively it means this does not lead to a photon, but it is given as a kind of phonon to the lattice and the device actually heats up instead of emitting a photon. So, this phenomena actually reduces the output of LEDs. Hence there is no 100 percent output and some of the energy is actually wasted in terms of heat in the device.

So, let us consider some equations for all these devices. The fraction of electrons that are injected into the depletion layer which results in photons getting produced is called the internal quantum efficiency or eta of LED. So, if n is the number of electrons injected into the depletion layer every second the power output of device is given by P is equal to eta which is the internal quantum efficiency multiplied by the number of electron injected into the depletion layer and multiplied by the energy of single photon which is h nu. So, this is the power of power output of this device or we can also write it some like eta I into h nu upon E, E is the electronic charge. Now if the energy of photon is measured in electron volt the current in milli amp the above expression becomes E the power in milli watt is equal to eta E gamma into I. So, these are the formulas to calculate the output power of a device when the number of electrons which are going into the depletion layer is known eta is known the quantum internal quantum efficiency and the energy of a single photon is known. So, let us have one example based on this. A gallium arsenide LED radiates at 900 nanometer. If the forward current in LED is 20 milli amp calculate the output power of the circuit. Assuming the power output assuming a quantum efficiency of 2 percent. So, in this example is given that we have a gallium arsenide based LED and this LED radiates at 900 nanometer. So, 900 nanometer is the wavelength of photon it means we can calculate the energy of a single photon how much is the energy it of a single photon it radiates. If the forward current in LED is 20 milli amp it means 20 milli amp current is flowing by this flow we can calculate how many electrons are actually injected into depletion layer per unit time per unit per second. So, if the current is given 20 milli amp we know number of electrons going there and the quantum internal quantum efficiency is given as 2 percent which is a reasonable number for this internal quantum efficiencies it is in the range of this only. So, now let us find out the power of this device. The energy of the photon first we calculate in electron volt is h c upon e into lambda this we can put down the numbers for blanks constant which is 6.62 into 10 to power 34 into 3 into 10 to power 8 divide by 1.6 into 10 to power minus 19 multiply by 9 into 10 to power minus 7 which is the wavelength of this photon. This number comes out to be around 1.38 electron volt. So, this is the energy of a single photon.

Now we can calculate the power output P is equal to 0.02 which is the efficiency internal quantum efficiency multiply by the energy of a single photon which is 1.38 multiply by the current which is 20 milli amp here. So, the power output of the device comes out to be 0.55 milli watt. So, this is the power of this gallium arsenide LED. So, this is how we calculate the power of any LED which is in terms of energy of single photon and how much current it is flowing. So, today we saw one optical detector which is avalanche photo diode then we discussed optical source which is LED and we saw the band diagram how a LED generates the photo photons and these are the some examples to calculate how many photons or how many how much the power of this LEDs.

So, this is all for today.

Thank you.