Semiconductor Optoelectronics
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Lecture - 44
Semiconductor Photo-Diodes - II: APD

We continue with the next part of the lecture; that is semiconductor photo diodes. In the last class we began with the semiconductor photo diodes, and primarily we have discussed with the pin photo diodes. And in this class we will continue, and discus the second important class of photo diodes, which are the APD'S or avalanche photo diodes.

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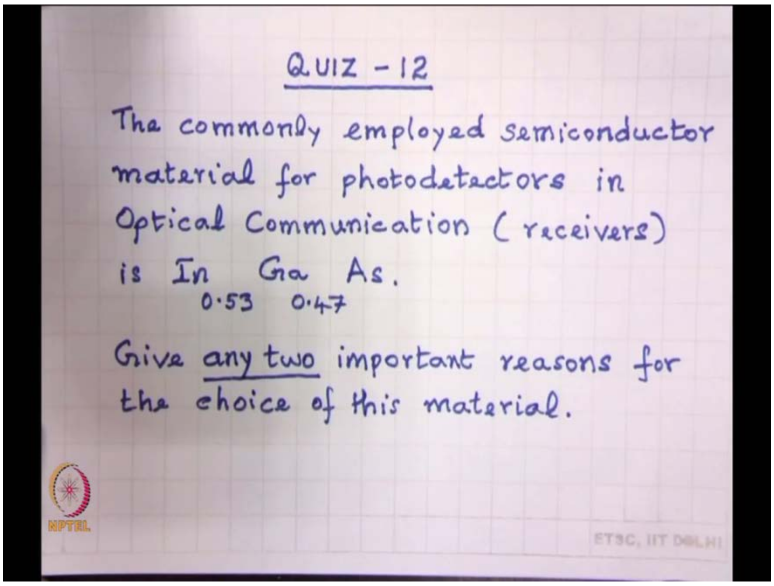

Before I proceed with the lecture, in the last class we had a quiz; there is the last quiz, quiz 12. The commonly employed semiconductor material for photo detectors, in optical communication receivers is indium gallium arsenide. Give any two important reasons for the choice of this material. This was the quiz, and answer is, of course any two.

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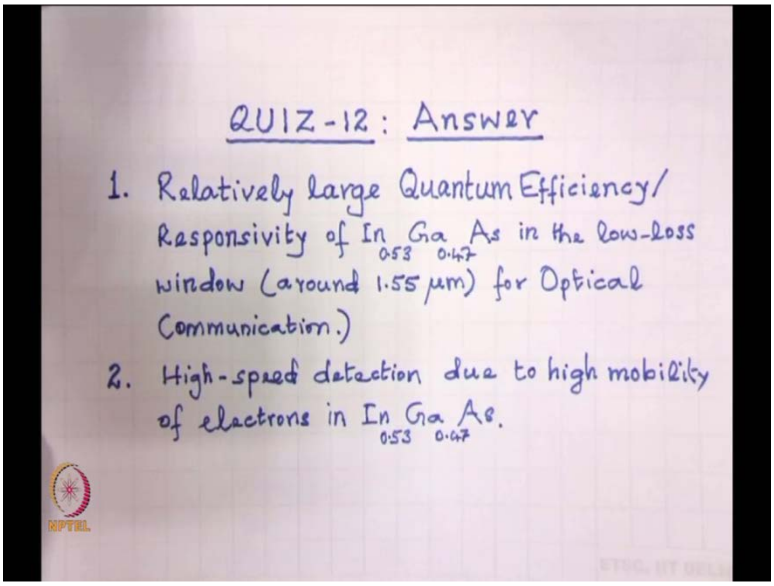

So, you have several advantages and several reasons, why one uses indium gallium arsenide, but the most important reasons are because indium gallium arsenide has a relatively large quantum efficiency or responsivity, in the low loss window; that is around 1.55 micro meter, in the low loss window for optical communication, optical communication. Here we are referring optical fiber communications, and as you know the silica based optical fibers have the lowest loss at 1.55 micro meter. And the window, the low loss window around 1.55 micro meter is where one uses the WDM communication systems or the DWDM communication systems, where a large number of wave lengths and back into the low loss window, centered around the 1.55 micro meter. And therefore, this is detector which is widely used, primarily because of the large quantum efficiency.

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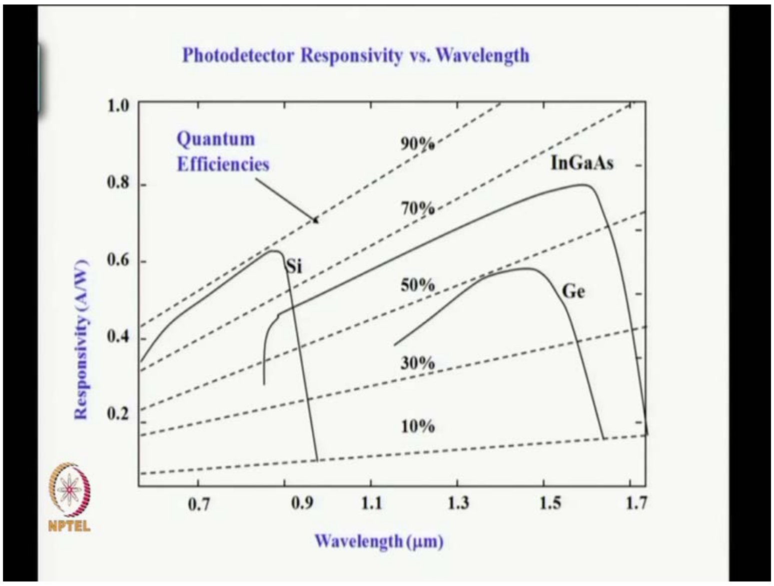

We may recall that we, in last class we have discussed with the quantum efficiency, this graph we had shown, this graph here of quantum efficiency. So, we can see that in silicon has very good quantum efficiency, in the range up to about one micron and less than that here, about 90 percent goes up to 90 percent, where as indium gallium arsenide has large quantum efficiency around 70 percent or so in the range of 0.9 micro meter here, write up to 1.77 micro meter. And as you can see here that at 1.5 and around 1.55 micro, the quantum efficiency for indium gallium arsenide is very high. Although the germanium can also detect, as you can see here, germanium also has responsvity here, but silicon has the indium gallium arsenide, as the largest responsvity, and that is one of the main reasons, why one goes for indium gallium arsenide. The second important reason here, the second reason, is also that for high speed detection, the second reason here, we have listed the second reason, for high speed detection, due to high mobility of electrons in indium gallium arsenide.

In the last class or earlier class we had discussed the mobility of indium gallium arsenide for electron mobility, is all that of 14000 centimeter square per whole seconds, compared to silicon germanium few thousand of mobility of electrons. So, the large mobility implies large saturation velocity, even at relatively smaller electric field, one can get large saturation velocity. And hence the speed of the detector become transient time gets reduced, and the detector becomes high speed, because optical communications, in optical communications we are talking of 10 Gbps and 40 Gbps and so on, you need high sped detectors to detect the incoming pulses. So, these are primary two reasons, why once go for indium gallium arsenide for optical fiber communication. So, today we continue with the talk on semiconductors photo diodes. So, before I proceed with the part two avalanche photo diodes here. A small topic is remaining there.

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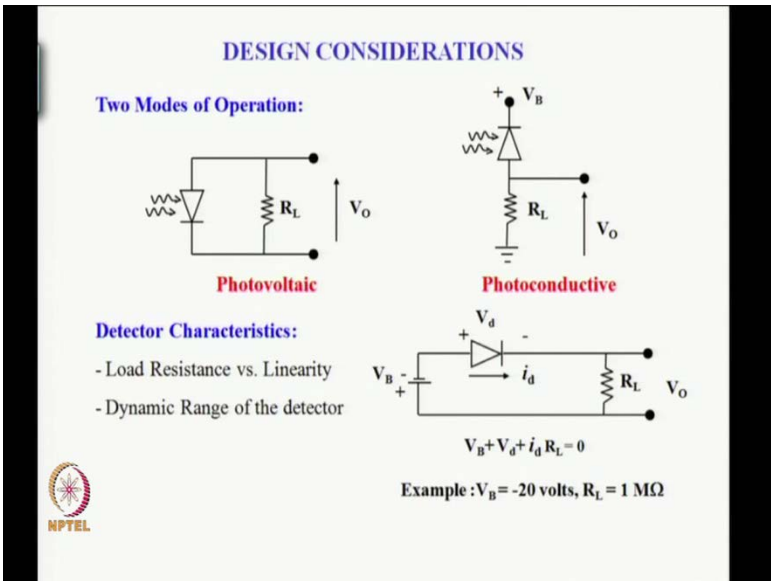

In the last class, we discussed design characteristics of photodiodes, and in particular we discussed that there are two modes of operations; photovoltaic and photoconductive mode of operation. And we have discussed in detail the design characteristics here.

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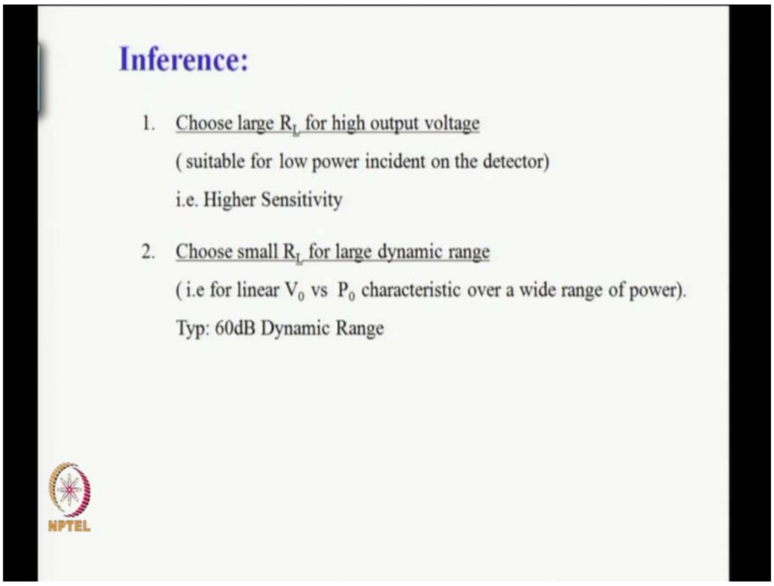

And how to choose the load resistance, here is the summary that we had, that choose large RL; the load resistance for high output voltage, suitable for low power incident on the detector, there is higher sensitivity. However choose small RL for large dynamic range; that is linear output verses optical power input characteristics, over wide range of power, typically 60 to 70 DB dynamic range is possible.

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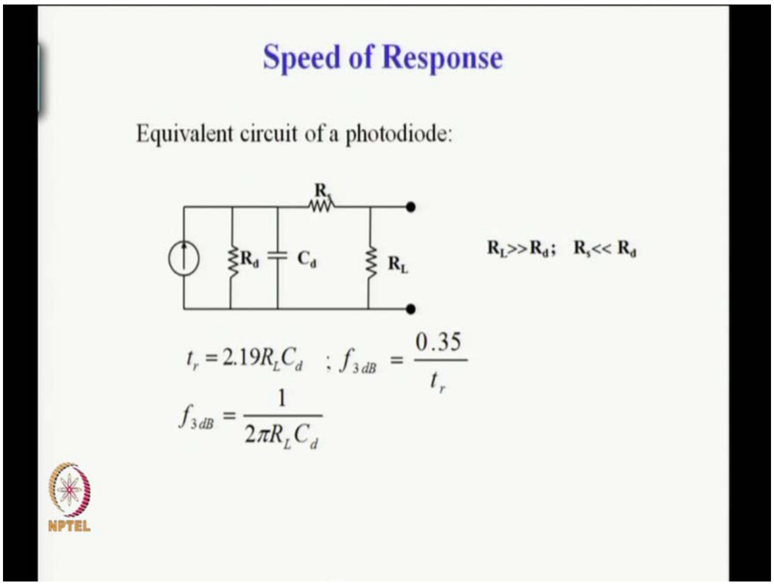

So, a small topic of important is also speed of response of Pin photo diode here, and the equivalent circuit of a typical photo diode here, is shown in the diagram here. This is current source with a resistance across, here the diode resistance, the reverse diode resistance which large resistance, and junction capacity here, the diode capacitance here, which is the junction capacitance c d or c j, and the serious resistance and the load resistance. These make the equivalent circuit of photo diode detector. The load resistance RL is, this is smaller than R d, because the reverse bias under the assumption that, R d is much larger than R S and R L, we can shows that the rise time given by T R is equal to 2.19 R L into C d, and the 3 d B bandwidth of photo detected is 0.35 by rise time, and the frequency, the cut of frequency, or 3 d B frequency, as you know the photo detector respond right from D z. All the semiconductor photo detector respond from d C, and these f 3 dB here refers to higher cut of frequency, and that is given by 1 divided by two pi R l into C d. Rl here the load resistance and C d is the junction capacitance, approximately is given by these formula. The important point to see the three d B cut of frequency, depends on the load resistance R L, and the junction capacitance C d.

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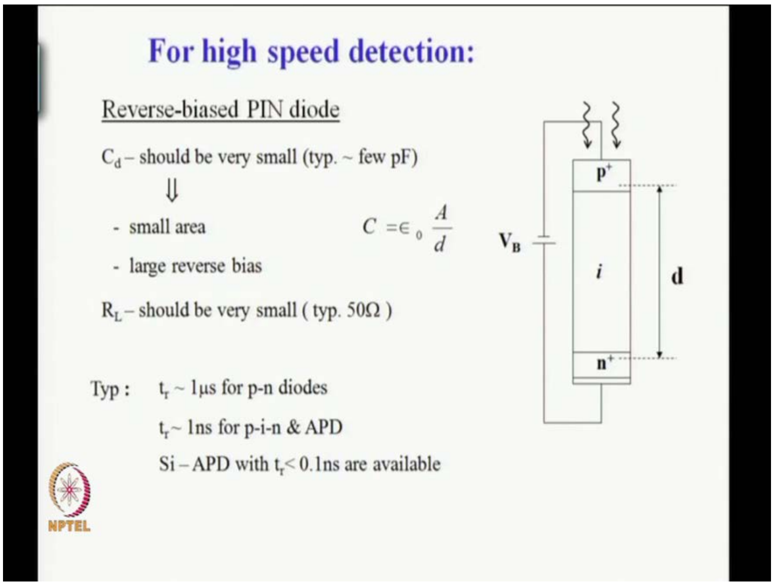

And therefore, for high speed detection, reverse biasing very much help, reverse biased pin diodes are used for high speed photo detector, C d here should be very small, because in the denominator, if you want to large cut of frequency, typically few Pico fared. And C d will be small, if you have a small area, and large reversed bias, large reverse bias leads to small junction capacitance, because the depletion region, width of the depletion region increases. Small area of the photo detector here, as you know the junction capacitance, the capacitance a parallel plate capacitance has a capacitance given by C is equal to epsilon 0 A by d, A is the area, and d is the separation between the capacitor plate. And the large reversed bias leads to a relatively large d. We can look at this diagram here, so it is Pin diodes, which is reverse biased.

The depletion region extends under the reverse bias, relatively large reverse bias, the depletion region extent over the entire interstice region here. The entire the d is extending over the entire region here. So, the d is relatively large, which means C is small, and if you make smaller area detector, then this C will be further reduced. Therefore, to the reduce C when applies large reverse bias and take small area detector. Typical area is 0.1 or 0.01 mille meter square, is the typical area of a small area detectors. Whereas large area detector can be one centimeter square, when the speed is not important, but sensitivity important, one choose large area photo detectors, large area pin detectors. So, R L should be very small, typically 50 ohm, as mentioned in one of the earlier classes. The data sheets typically specified, the rise time at 50 ohm load resistance. If you change the load resistance, then the rise time would also change. So, typically T R is 1 micro seconds, for normal Pin diodes, and T rise time is order of one nanoseconds for pin and APD's. Silicon APD's with rise time less than point one nanoseconds are also available.

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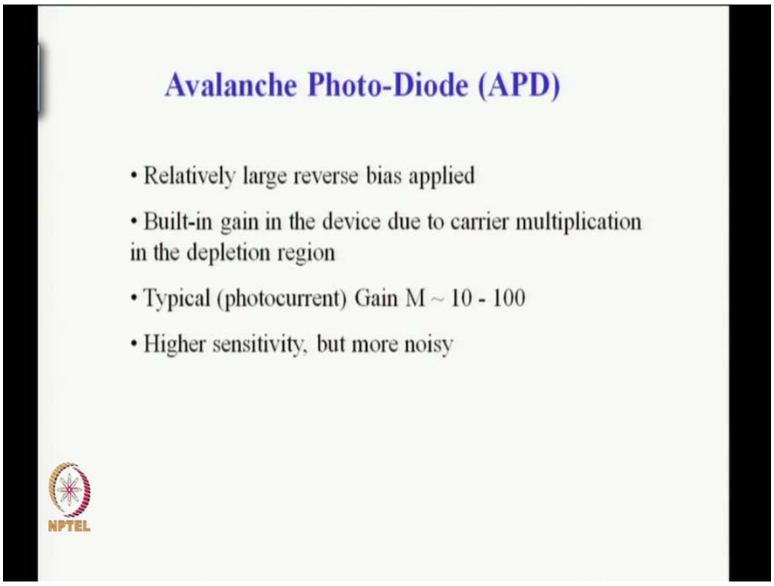

Now, we switch to the next device, which is the avalanche photo diode, is basically pin diode, but with large reverse bias, which provides avalanche gain. So, relatively large reverse bias, avalanche photo diode relatively large, we will see what kind of numbers for the reverse voltage is applied. This depends on the material silicon, germanium, indium gallium arsenide; it depends on the material, what is the reverse bias, what orders of reverse bias are applied. I will give some numbers at the end of the talk. There is a built in gain in the device, due to carrier multiplication in the depletion region by the avalanche process, we will see what is avalanche process. So, built in gain in the device, typical photocurrent gain M, is order of 10 to 100. So, M here is, basically the ratio of primary photocurrent to the current which is generated. So, the photocurrent IP in the external circuit, after the avalanche process to the primary photo current, is M typically 10 to 100, for higher sensitivity, so this gives, because of the current gain, the sensitivity is higher. However, it is little bit more noisy, because avalanche process, by its very nature is a noisy. It is the relatively random process, and therefore, we have relatively noisy output.

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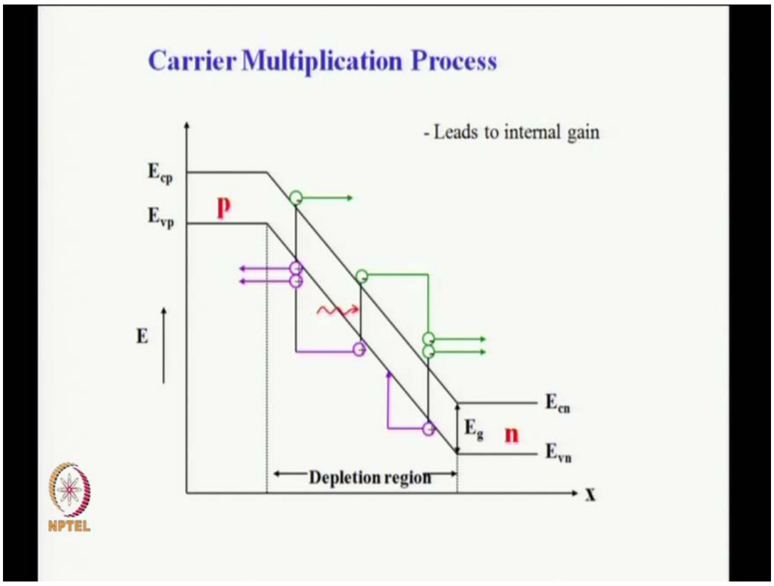

So, here is the energy band diagram of the pin structure here, because of the large reverse bias, we can see that now potential barrier here, or potential energy diagram has large slope here, in the active region, in the depletion region, because of the large reverse bias. So, this is p side, this n side, EVP the valance band energy and conduction band energy. As because of the large potential slope here, potential energy slope. An incident photon that generate an electron and hole pair, a hole and electron, as the because of the large potential energy slope the electron goes down the slope, travels the down the slope, as it travels, it is getting accelerated, because of the potential energy slope here, because of the high electric field; it is DV by DX, so high electric field, which the kinetic energy of the electron, is such that it is knock down another electron, and creates additional electrons by the avalanche process.

It is knock down another electron from bound another bound electron, and creates electron and hole. Similarly the hole which is getting accelerated up here, hole is getting accelerated in this direction. The hole getting accelerated also creates secondary electron hole pairs, hole the electron pair. So, this is primary hole, which has created a secondary pair, which leads to carrier gain; that is increase number of carries by the avalanche process. So, I have shown just a two events; one here at this end, and one here, but actually there are large number of carrier multiplication events take place, as the carrier stairwell up and the down the potential energy slope. So, this clearly illustrates the increase in the carrier, increase the number of carrier due to avalanche process.

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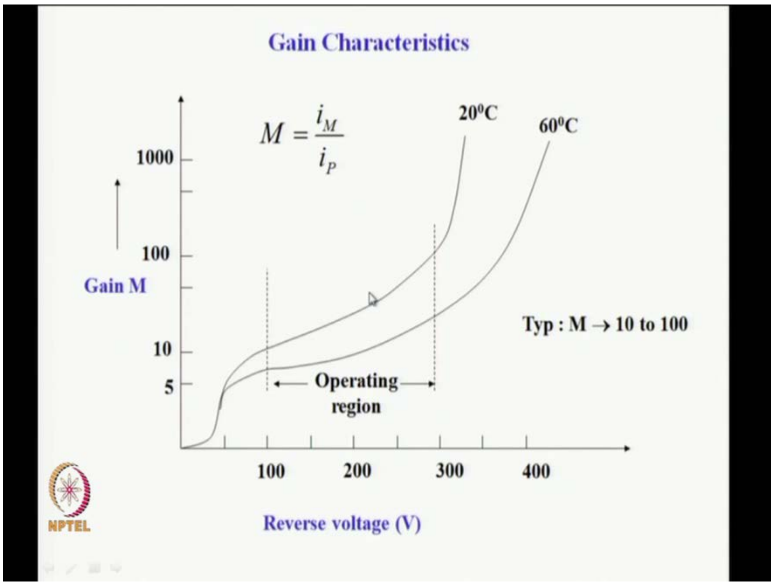

The gain characteristics of typical APD is shown here, reverse voltage, the numbers are here now, typically 100 200 300 volts are applied for, as the reverse bias. And what is the plotted is the gain, the current gain M, M is defined here i M divide by i P, this is the gain after multiplication process, current after the multiplication process, and this the primary photo current due to the incident photons. So, at 20 degree centigrade for example, 20 degree Celsius the current gain increases the initially as the voltage increases, and then it goes over to the relatively slow a region here, the slow rise here, and then finally, it again goes rapidly, and this is where the avalanche process is so rapidly that the device would lead towards breakdown. So, this is not the operation region, the operation region is here, between these two lines, so typically for this example, typically between 100 and 300.

Normally the operating voltage is specified, like 220 to 250 volt dc. So, this characteristic shows the current gain here, for an APD, at a different temperature, say at a higher temperature a characteristics varies, so it is indeed temperature sensitive, and the characteristics change, because at higher temperature, at a higher temperature here we have a more agitations of the atoms in the lattices, and therefore, the electron and holes undergo more collisions; that is the separation between; that is special separations or the average length.

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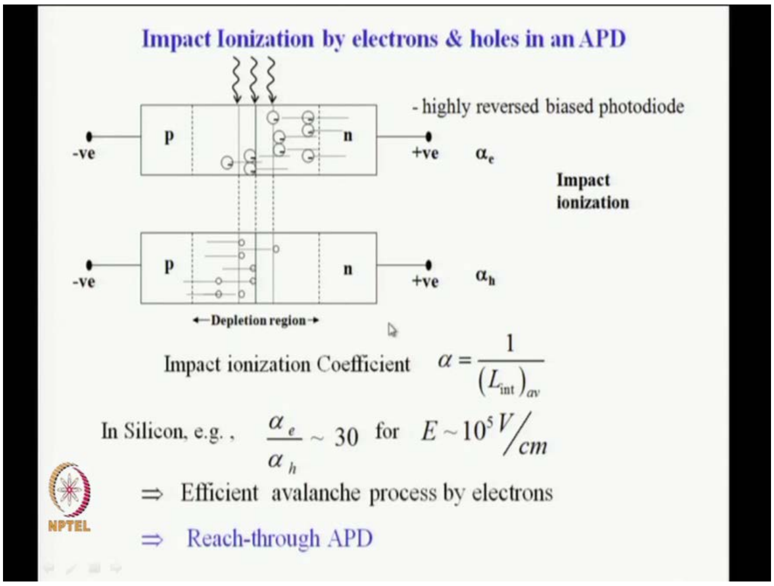

So, let me let me discus in the next slide here, and then come back. We can see that there is parameter is called, impact ionization coefficient alpha, which is defined as 1 divide by l internal average. This here refers to collisions, the distance, the average distance traveled between two successive collisions, so this is l impact. So, the average distance 1 by l impact is called the impact ionization coefficient, this is per unit length. And this depends on l, if you have; for example, if you pi a the temperature higher, then the electrons do not have enough energy, between two collisions, and therefore the number of collisions, which lead to generation of additional carrier pairs decrease, and therefore, the current gain decreases. So, this is just an example show, that it is temperature sensitive and higher the temperature, then lower will be the current gain. In fact most of this detectors are cooled, one can cool these further down, and the curved qualitatively looked like this, it will go up the characteristics will go up, if you cooled the detectors further, and it will be less noisy as well.

So, we come to discussion here impact ionization by electrons and holes in an APD. What you shown here, is the same APD Pin. The incident photons here generate electrons and holes in this region; that is catchment region. Here only electrons are shown. The electrons are swept towers the positive potential here, there is a negative end, which is reverse bias diode, so there is a positive potential at this end, so the electrons are accelerated in the direction. When the electron gain sufficient energy, it leads to generation of the secondary electron and hole pair, which further travel in this direction, and gets the electron travel in the direction, and of course, holes travel in the opposite direction, I have not shown holes in this diagram, holes shown in the next diagram.

First please see only the first diagram, where electron, the secondary electron are also get the accelerated, and creating more and more electrons, as the accelerated towers the positive end. The holes on the other hand are accelerated to other end, as you know electron mobility is higher, and therefore, they gain a higher velocity in the same electric field, in the electric field magnitude in the same, they gain higher velocity, much higher velocity, and therefore, much higher velocity the kinetic energy, and lead to rapid avalanche of further carriers. Holes get accelerated to the other end, and as they proceed whenever the gain sufficient energy. They also generate additional electron hole pairs, and the holes continued to proceed towers the negative end; that is p n. The impact ionization coefficient, this is at a given temperature.

At a given temperature the impact ionization coefficient defined as alpha is equal to 1 divide by average length, and average distance between two successive collisions. In silicon; for example, alpha e; that is the impact ionization coefficient for electrons, is much greater, compare to impact ionization coefficient of holes. Alpha e by alpha h is the order of 30, for a field applied field, in this medium in the order of 10 to the power of 5 volt per centimeter. What it means is, predominantly the ionization is because of electrons. Electron ionization is almost thirty times efficient, more efficient compare to secondary pair generation due to holes. So, efficient avalanche process is by electrons, and to make use of this fact, making use of this fact, a new design APD has been proposed, and this currently widely used design for APD, which is called a reach through APD.

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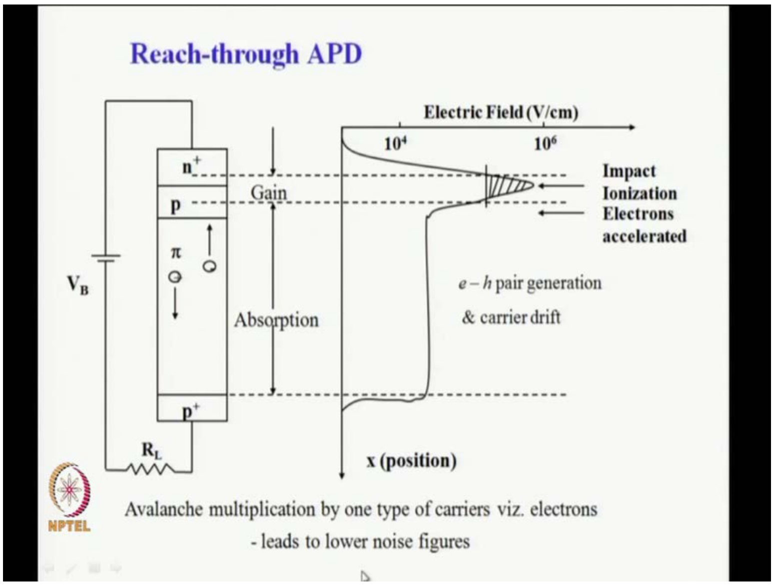

Let us see, what is the reach through APD. Here is the APD structure, a high n plus region, then p region here, and pi that is load hoped, near intrinsic or load hoped region here p, and then this is a p plus, i p. So, because of large n plus, so there is a reverse bias here applied, because of high doping concentration here at this junction, closed to the junction we have large density of immobile positive ions, because of the electrons migrated here, and large density of immobile positive ions. Therefore, if you plot the electric field, the electric field variation in this direction here. This is the direction corresponding to this. The electric field rises rapidly, and is very high around this junction. The electric field is very high you can see here, that it is approaching the peak value approaching 10 to the power of 6 holes per centimeter.

So, this shaded region is a region where the electric field above 10 to the power of 5 volt per centimeter, where the avalanche process take place; that is the kind of field that is required for avalanche process to take place. And field drops down rapidly, because we already discus the field e is nothing but row time d x, row is the chare density here, so carrier charge density. So, it is drop down, because of on the p side, there are negatively charged immobile ions. So, the sum drops down, so electric field drops down further and drops down here, and in the pi region there are both negative and positive charge immobile ions, and therefore, the electric field almost remain constant, in this region, as you integrate row dx. So, the electric field almost remains constant. Actually there is small slope here, there is a small slope which is sloping down like this here, but it’s not shown here, its look almost as if it is flat, there is small slope, but the important point to see is, electric field here e is much lower than 10 to the power of 5 volt per centimeter.

In this region the electric field is higher than 10 to the power of 5 volt per centimeter, in this region the electric field is much lower, because of the electric field is much lower, any carrier which is in this region accelerated either to this side or to the this side, will not be able to have enough kinetic energy to create additional electron hole pairs. Please see in that design, this is primarily the catchment area. The photons are incident in this region photons, photons are absorbed primarily in this region, this is not correct exactly to scale, because the thickness of this region, the thickness of this region, and this region are much smaller compare to this thickness here, much smaller. So, that photon the light which is incident on photo detector, is primary absorbed in this region. There are electrons and holes which are created in this region, so this is why we called it as the catchment area.

And the electron get accelerated in this direction, holes get accelerated in this direction, because of the electric field. However, the electric field in this region; that is in region, is not strong enough to accelerated the electron to energies, where they can generate additional electron hole pairs, or there is no avalanche process taking place in this region. However, the electron accelerating in this region enters this zone here. We note that the electric field is very high in this zone. Therefore, the electron immediately creates very large number of electron hole pairs by impact ionization. The electrons which are the secondary electron, which are generated or further accelerated and collected by the electrode hole here.

The hole which is generated move into the direction, in this direction, but they are moving in a region, where the electric field is much smaller, or electric field it is not strong enough to create additional avalanche process, and therefore, this means that the avalanche process in this design of this structure, is primary due to electrons. So, the avalanche multiplication is primarily by one type of carrier, namely electron. This leads to much lower noise figures. In fact if we look at the pervious diagram here, please see that a carrier pair generated, electron accelerated in this direction, holes get accelerated in this direction, as the electron proceed it creates additional electron hole pairs and hole which proceeding in this direction creates additional electron hole pairs. So, an electron which is created here electron hole pair, electron moving in this direction will keep on creating additional electron hole pairs. Similarly the hole which is generated here, will as it accelerates in this direction, it creates additional electron hole pair.

The process would continue almost unabated even if an incident is, incident light is just a impulse or pulse. It appears as if the process would continuously continue or it is never ending. However, in practices is does crunch after relatively the long time. Whereas if you create in the next design, in the reach through APD design. Since the avalanche process is taking place only this end, the electron the secondary electron created are immediately collected here. The holes which are create or moving in this direction, but they are not creating further avalanche, and therefore, the quenching of the avalanche process; that is stopping of the avalanche process, soon after the light pulse has being switched off or light pulse has, light pulse is absorbed very rapid. So, let me illustrated what I have been saying, so let me just illustrated what it means.

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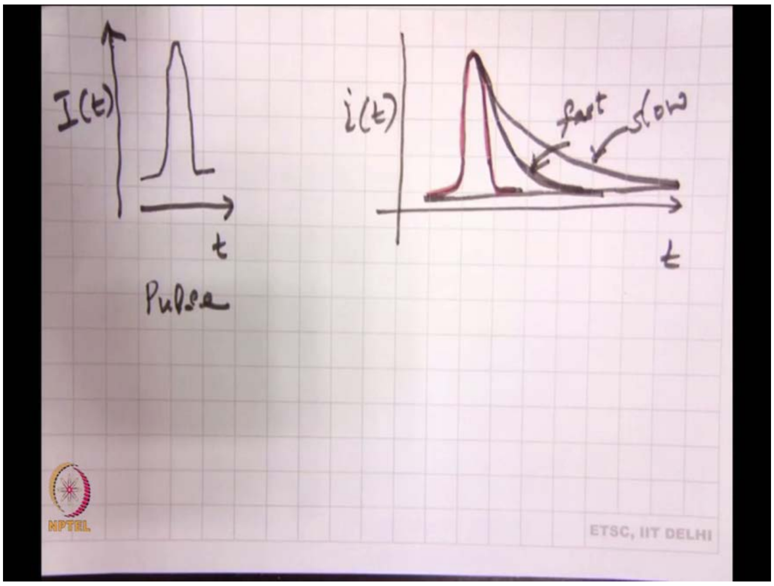

So, if I have, let us say I incident pulse, this is an optical pulse, which is incident on the photo detected, so this is time axis, and this of course, the light energy or intensity I of t. So, this is the incident pulse on the photo detected, the current response of the photo detector, if I take an APD, so because of this pulse. So, this I writing plotting APD current I of t. Ideally when the intensity goes, I should have current going up like this, and when the intensity comes down, the currents should come down. This means if the detector is responding fast enough; that means, the current pulse which is generated is identical to input optical pulse. However, in general there is delay, because even after pulse disappears; that is in time, even after the pulse is absorb or the light pulse is no more there, it takes some time for the carrier to recombine, and the current through come down.

In other words the current pulse, so this is. So, whatever shown here, is the incident optical pulse, and ideally I should get the current pulse like this. However, in practice, what we see is, there is a finite time over which the pulse continues, even after the incident pulse has been absorbed or pulse has pass through. So, this tail here, is because of the carriers which there in the medium, or with reference to the avalanche process, this correspond through this; a rapid, or a drop which is slow here, correspond to how fast the avalanche process quenches. So, this is slow, which means the avalanche process take longer time to quench or to stop, where in this case it is faster, this is fast. So, the reach through APD, ensure the avalanche process is primarily due to electrons, and electron mobility is much higher, and therefore the currents drop downs rapidly, and the device become fasters. So, this is what I was referring to, with this fast and slow detector.

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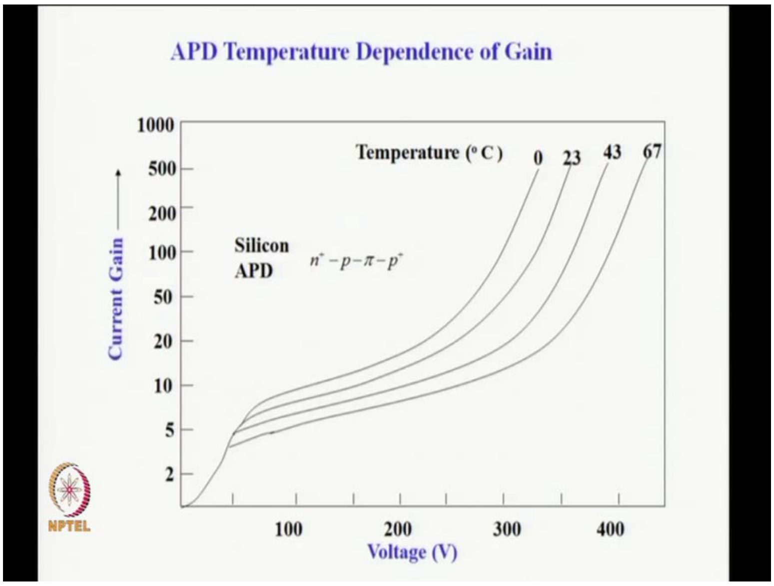

Let me show the current gain characteristics for typical silicon reach through APD, n p pi p plus. So, at 0 degree centigrade, as we have already discussed this, as temperature increases, because of the more number of collisions, the carrier which is undergo more number of collisions with the atoms in the lattice. The distance the average distance between two collisions is much smaller, and therefore do not have sufficient time, they do not have enough time to gain kinetic energy and create additional avalanche processes, and therefore as temperature increases the current gain drop down. However, as voltage increase further, the kinetic energy gain sufficiently large, and then leads to a higher a current gain.

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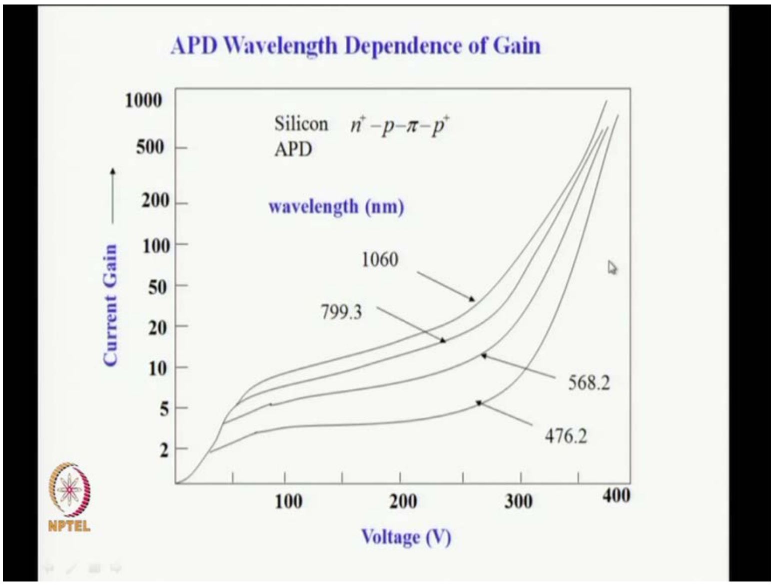

This is a characteristic, shows the wave length depended on current gain, a typical silicon APD the current gain here. And you see that at lower wave length here, at lower wave length the current gain is smaller, and as the wave length is increases up to around a 1 micron, or 1000 nanometer, the current gain increases. This increases this low value of current gain and higher value of current gain here or primarily because of the quantum efficiency. We know that quantum efficiency of a silicon.

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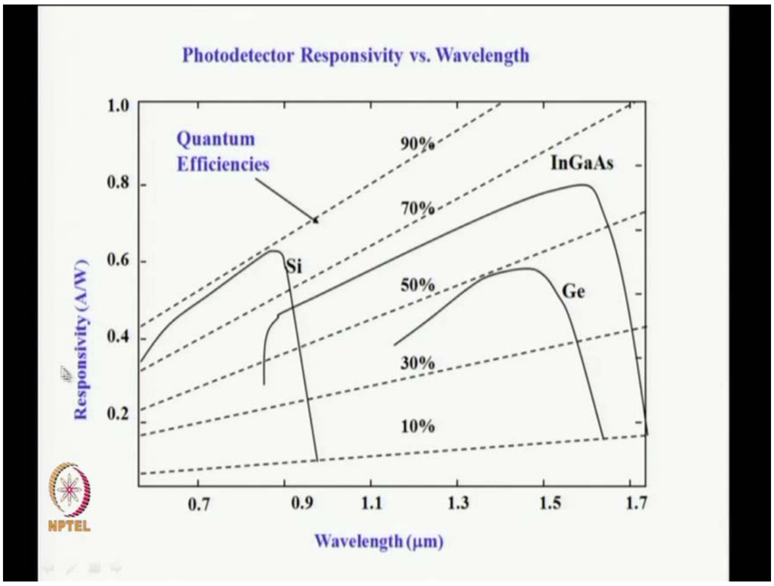

We have already seen this in one of the earlier curves or may be. Let me show write here, we have shown the quantum efficiency. So, silicon here, has a smaller quantum efficiency at lower wave length, and the quantum efficiency here is relatively large. The responsivity is large as the wave length increases. Of course, once as we reach the near the band gap wave length quantum efficiency drop down, and this is the primary reason for the characteristics is that have just shown; that is dependents of current gain on wave length.

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Generic parameters of Si, Ge, and InGaAs *pin* photodiodes

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400-1100	800-1650	1100-1700
Responsivity	R	A/W	0.4-0.6	0.4 – 0.5	0.75 – 0.95
Dark current	I_D	nA	1-10	50-500	0.5-2.0
Rise time	τ_r	ns	0.5-1	0.1-0.5	0.05-0.5
Bandwidth	B	GHz	0.3-0.7	0.5-3	1-2
Bias voltage	V_B	V	5	5-10	5

So, finally, we come to some generic parameter of silicon germanium and indium gallium arsenide pin photo diodes. So, if you take typical data sheets, this is kind of numbers that it would see. Wave length range; that is wave length range over which this is detector is useful, useful operating wave length range, lambda here in nanometer, silicon it is around 400 to 1100, we have discussed this in detail. So, this primarily because of eta or the quantum efficiency of the detectors, where as the germanium can, germanium has a smaller band gap, and therefore, it is useful detectors in this range 800 to 1650, or may be 1700. Whereas indium gallium arsenide primarily is good detector in this wave length range, and that covers the optical fiber communication window, and as we have seen, as have discussed earlier, this is the detector which is widely useful optical fiber communication. The resposivity typical numbers are here, amperes per watt. It is current generated per optical power incident; that is why amperes per watt, so typical number 0.4 to 0.6, 0.4 to 0.5 and 0.75 to 0.95 responsivity is quite high.

Dark current here in nano amperes 1 to 10, 50 to 500 and 0.5 to 2, is dark current typical dark current are detected. Of course, it depends on material, process, and the device structure, but these are some typical generic parameters. The rise time here typically 0.5 to 1 or even 0.1 silicon detectors, and 0.1 to 0.5, and one can have detectors with 0.05 to 0.5 nanoseconds rise time of the photo detectors, bandwidth; that is the detection bandwidth in gigahertz, so this is the primarily inverse of the T R here, of the order. The bandwidth is, detection bandwidth is, of the order of just standard 1 gigahertz, here the order of gigahertz and the order of gigahertz. The bandwidth is almost similar with, as you can see is primarily depending on the inverse of the rise time, how fast a detectors is. A bias voltage; for pin photo diode typical biases are between 5 and 10 volt. Normally they are reverse biased in the 5 to 10 volt.

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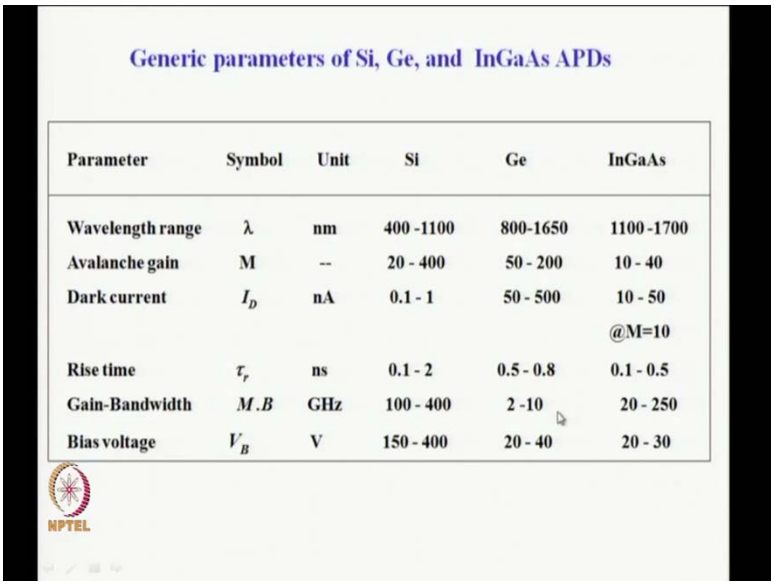

Generic parameters of Si, Ge, and InGaAs APDs

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400 -1100	800-1650	1100 -1700
Avalanche gain	M	--	20 - 400	50 - 200	10 - 40
Dark current	I_D	nA	0.1 - 1	50 - 500	10 - 50 @M=10
Rise time	τ_r	ns	0.1 - 2	0.5 - 0.8	0.1 - 0.5
Gain-Bandwidth	$M.B$	GHz	100 - 400	2 -10	20 - 250
Bias voltage	V_B	V	150 - 400	20 - 40	20 - 30

Generic parameters of silicon germanium and indium gallium arsenide APD's. The wave length range again is the same, as listed the same wave length range. Main differences is the avalanche gain, we have current gain here. Typically 20 to 450 to 210 to 40; of course, it is depends on the operating voltage, but this range of gain typically order of the 100, is the current gain which is employed in practices, and the dark current are again listed here. The dark current in this case you can see are relatively large, because of applied a larger reverse voltage, corresponding to at a gain of M is equal to 10, current gain M is equal to 10. The rise time are typically sub nanoseconds, fraction of nanoseconds here. And the gain bandwidth is again similar numbers hundreds of megahertz to few gigahertz, and one can have detectors with very large bandwidth.

And bias voltages as we can see, earlier we had 5 to 10 volts, but now we have bias voltages of 50 100, typically 10 of volts, or silicon for example can withstands much higher reverse bias and this why we have typical operating voltage of about 250 per silicon, but relatively lower operating voltages for germanium and indium gallium arsenide. We know that they have much smaller band gap, and therefore, you cannot apply very large reverse bias that could lead to breakdown of the device. Think we that we come to the end of this talk on photo detectors, silicon and germanium and indium gallium arsenide photo detectors, widely used in optoelectronics and optical communication. Most of them are pin diodes or APD's if you need gain. When you have gain with the avalanche process, normally there is additional noise. Noise is topic, which are not discussed in detail. In the I will stop this talk at this point, in the next lecture we will discuss about some of the other detectors, other photo detectors, including in the pmt. I briefly mention about pmt which is widely used, we will discuss about pmt and miscellaneous detector in the next class. So, today I will stop at this point.