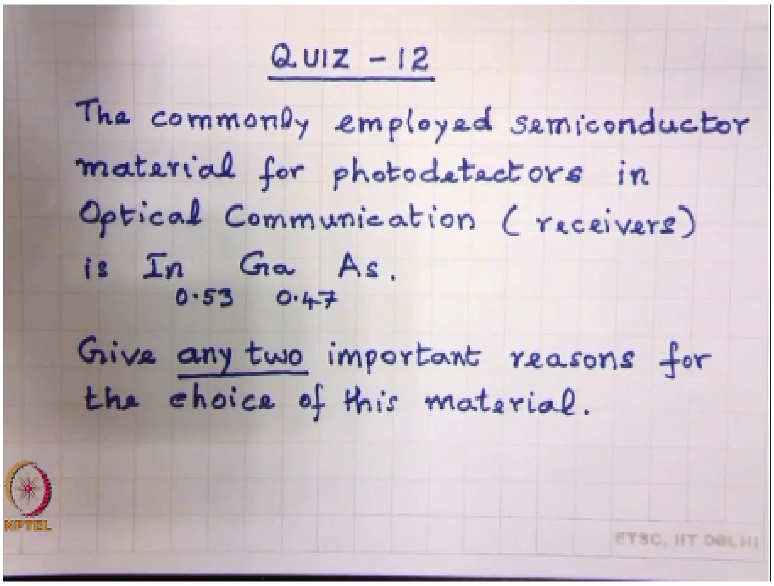
Semiconductor Optoelectronics
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology – Delhi

Lecture - 43
Semiconductor Photodiodes-II APD

We continue with the next part of the lecture. This 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 discuss the second important class of photo-diodes which the APDs or avalanche photo diodes. Before I proceed with the lecture.

(Refer Slide Time: 00:56)



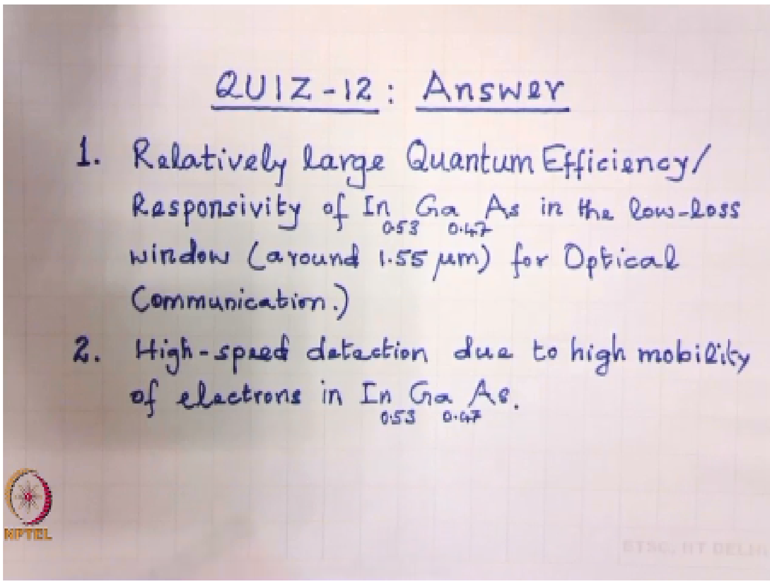
QUIZ - 12

The commonly employed semiconductor material for photodetectors in Optical Communication (receivers) is $In_{0.53}Ga_{0.47}As$.

Give any two important reasons for the choice of this material.

In the last class we had a Quiz that is a last Quiz 12. The commonly employed semiconductor material for photo detectors in optical communication receivers is Indium gallium arsenide. Give any 2 important reasons for the choice of this material. This was the quiz and answer is of course any 2 so you have several advantages and several reasons why one uses Indium gallium arsenide.

(Refer Slide Time: 01:37)



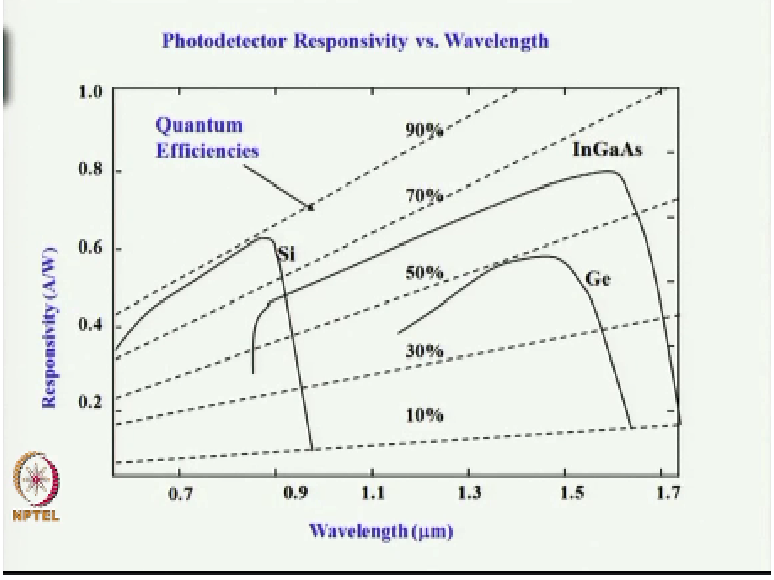
QUIZ-12: Answer

1. Relatively large Quantum Efficiency/ Responsivity of $In_{0.53}Ga_{0.47}As$ in the low-loss window (around 1.55 μm) for Optical Communication.)
2. High-speed detection due to high mobility of electrons in $In_{0.53}Ga_{0.47}As$.

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 micrometer in the low loss window for optical communication. Here we are referring to optical fiber communication and as you know the silica-based optical fibers have the lowest loss at 1.55 micrometer and the window the low-loss window around 1.55 micrometer is where one uses the WDM communication systems or the DWDM communication systems.

Where a large number of wavelengths are packed into the low-loss window centered around 1.55 micrometer and therefore this is the detector which is widely used primarily because of the large quantum efficiency. We may recall that in the last class we have discussed the quantum efficiency.

(Refer Slide Time: 02:45)



This graph we had shown this graph here of quantum efficiencies so we can see that the silicon has a very good quantum efficiency in the range up to about 1 micron or less than that here about 90% goes up to 90% whereas Indium gallium arsenide has a large quantum efficiency around 70% or so in the range of about 0.9 micrometer here right up to 1.77 micrometer.

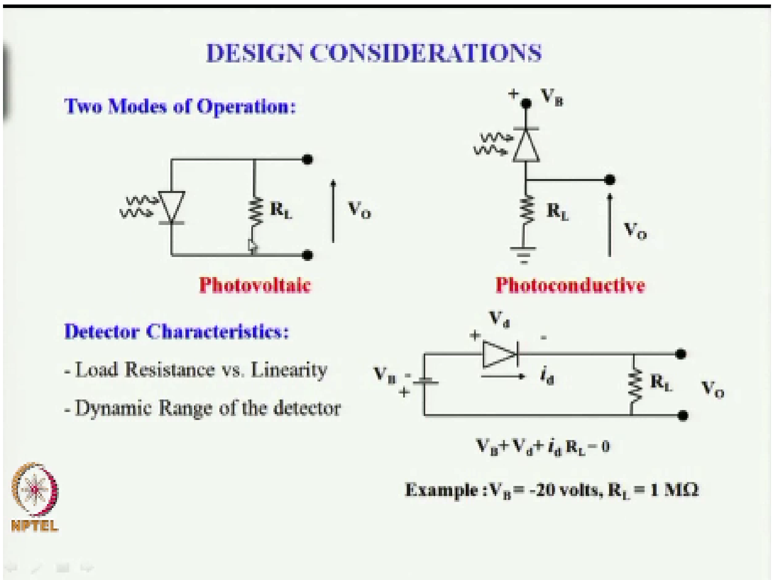
And as you can see here that at 1.55 the quantum efficiency for Indium gallium arsenide is very high. Although germanium can also detect as you can see here germanium also has responsivity here, but silicon has Indium gallium arsenide as the largest responsivity and that is one of the main reasons why 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 second reason for high speed detection due to high mobility of electrons in Indium gallium arsenide. In the last class or in an earlier class we had discussed that the mobility of Indium gallium arsenide for electron mobility is of the order of 14,000 centimeter square per volt second.

Compared to silicon germanium which have few thousands of mobility of electrons. So a large mobility implies a large saturation velocity even at relatively smaller electric fields one can get a large saturation velocity and hence the speed of the detector become the transit time gets reduced and the detector becomes a high speed because optical communication in optical communication we are talking of 10 Gbps 40 Gbps and so on.

You need high speed detectors to detect the incoming pulses. So these are the primary 2 reasons why one goes for indium gallium arsenide for optical fiber communication. So today we continue with the talk on semiconductor photo-diodes. So before I proceed with the part 2 that is Avalanche photo diodes here. A small topic remaining there in the last class we discussed the design characteristics of photo-diodes.

(Refer Slide Time: 05:40)



DESIGN CONSIDERATIONS

Two Modes of Operation:

Detector Characteristics:

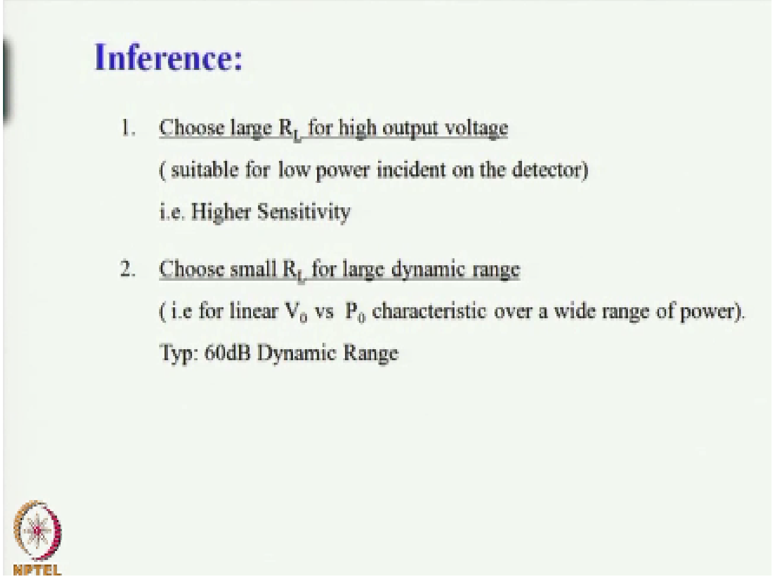
- Load Resistance vs. Linearity
- Dynamic Range of the detector

$V_B + V_d + i_d R_L = 0$

Example : V_B = -20 volts, R_L = 1 MΩ

In particular, we discussed that there are 2 modes of operation photovoltaic and photoconductive mode of operation and we have discussed in detail the design characteristics here and how to choose the load resistance.

(Refer Slide Time: 05:58)

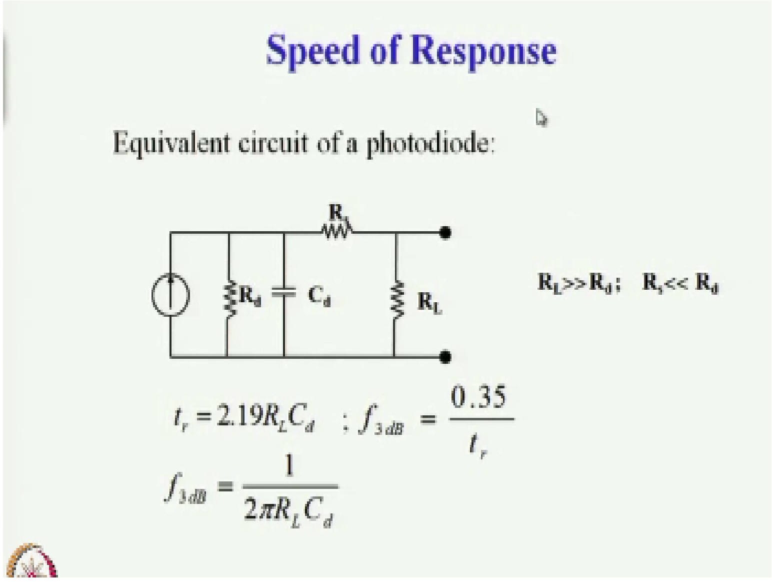


Inference:

1. Choose large R_L for high output voltage
   (suitable for low power incident on the detector)
   i.e. Higher Sensitivity
2. Choose small R_L for large dynamic range
   (i.e for linear V_0 vs P_0 characteristic over a wide range of power).
   Typ: 60dB Dynamic Range

And 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 that is Higher sensitivity. However, choose small RL for large dynamic range that is for linear output versus optical power input characteristics over a wide range of power. Typically, 60, 70 dB dynamic range is possible.

(Refer Slide Time: 06:30)



Speed of Response

Equivalent circuit of a photodiode:

$R_L >> R_d$; $R_s << R_d$

$$t_r = 2.19 R_L C_d \quad : f_{3dB} = \frac{0.35}{t_r}$$

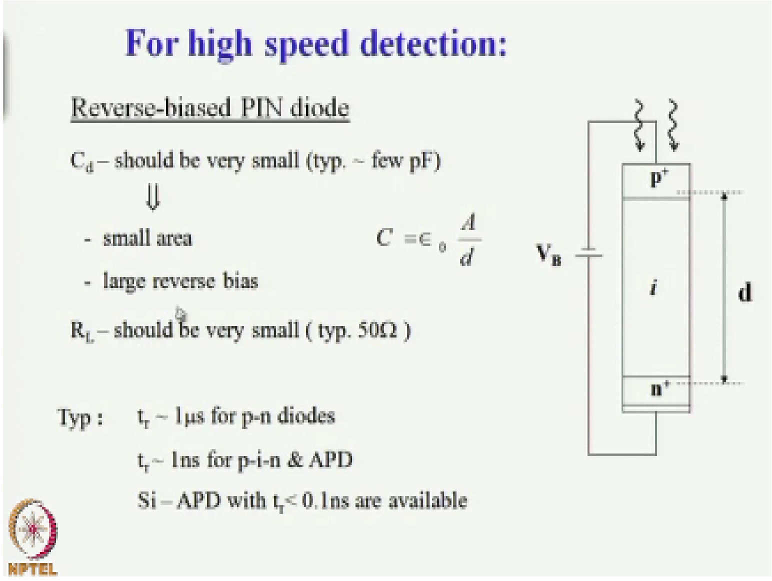
$$f_{3dB} = \frac{1}{2\pi R_L C_d}$$

So a small topic of importance is also speed of response of PIN photo diodes here and the equivalent circuit of a typical diodes here is shown in this diagram here. This is a current source with resistance across the diodes resistance the reverse diode resistance which is a very large resistance. And a Junction capacitance here the diode capacitance which is the CD or CJ and a series resistance and the load resistance.

This makes the equivalent circuit of a photo detector. The load resistance RL this is much smaller than RD because the reverse bias under the assumption that RD is much larger than RS and RL. We can show that the rise time is given by tr=2.19 RL* Cd and the 3 dB bandwidth of the photo detector is 0.35/ rise time and the frequency or the cut off frequency or the 3 dB frequency as you know the photo detectors respond right from Vc all the semiconductor photo detectors respond from Vc.

And this f3 dB here refers to the higher cut off frequency and that is given by ½ pi RL *Cd. RL here is the load resistance and Cd is the junction capacitance approximately given by this formula. The important point to see is the 3 dB cutoff frequency depends on the load resistance RL and the junction capacitance CD.

(Refer Slide Time: 08:15)



For high speed detection:

Reverse-biased PIN diode

C_d – should be very small (typ. ~ few pF)

$\Downarrow$

- small area $\qquad C = \epsilon_0 \dfrac{A}{d}$
- large reverse bias

R_L – should be very small (typ. 50Ω)

Typ : $t_r \sim 1\mu s$ for p-n diodes

$t_r \sim 1ns$ for p-i-n & APD

Si – APD with $t_r < 0.1ns$ are available

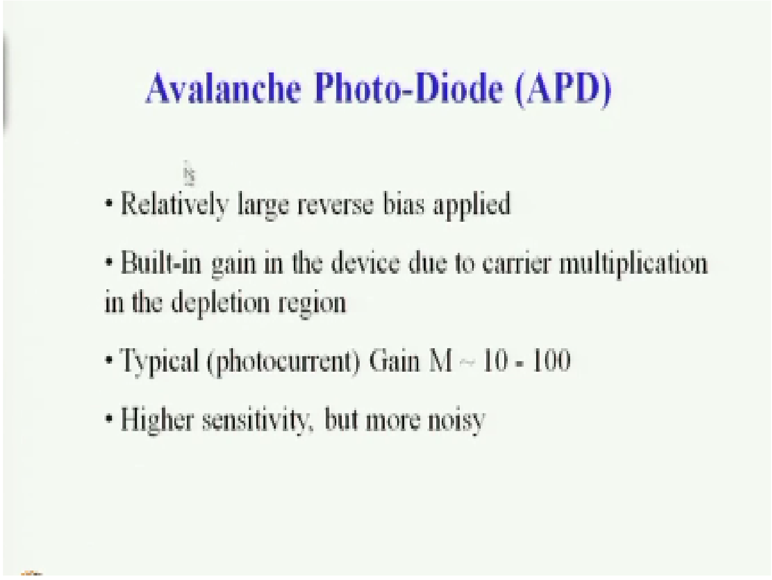
And therefore for high speed detection reverse biasing much helps reverse-biased PIN diodes are used for high speed photo detectors CD here should be very small because it is in the denominator if you want to have a large cut off frequency typically few (()) (08:34) and Cd will be small. If you have a small area and large reverse-biased leads to a 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 parallel plate capacitor has a capacitance given by C= epsilon 0 A/d A is the area and d is the separation between the capacitor plates and a large reverse-biased leads to a relatively large d. We can look at this diagram here. So it is a p-i-n diodes which is reverse-biased. The depletion region extends under reverse-biased relatively large reverse-biased the depletion region extends over the entire intrinsic region here entire d is extending over the entire region here

So the d is relatively large which means C is small and the if we make a small area detector then this C will be further reduced and therefore to reduce d one applies a large-reverse biased and take a small area detector. Typical area is 0.1 or 0.01 millimeter square is the typical area of small area detectors whereas large area detectors can be one centimeter square when the speed is not important.

But sensitivity is important 1 chooses large area photo detector large area PIN detectors. So RL should be very small typically 50 ohm as I mentioned in one of the earlier classes. The data sheets typically specify the rise time at 50-ohm load resistance. If you change the load resistance, then the rise time would also change. So typically TR is about 1 microsecond for normal PIN diodes and t rise time is of the order of 1 nanosecond for PIN and APDs. Silicon APDs with the rise time < 0.01 nanosecond are also available.

(Refer Slide Time: 11:09)



Avalanche Photo-Diode (APD)

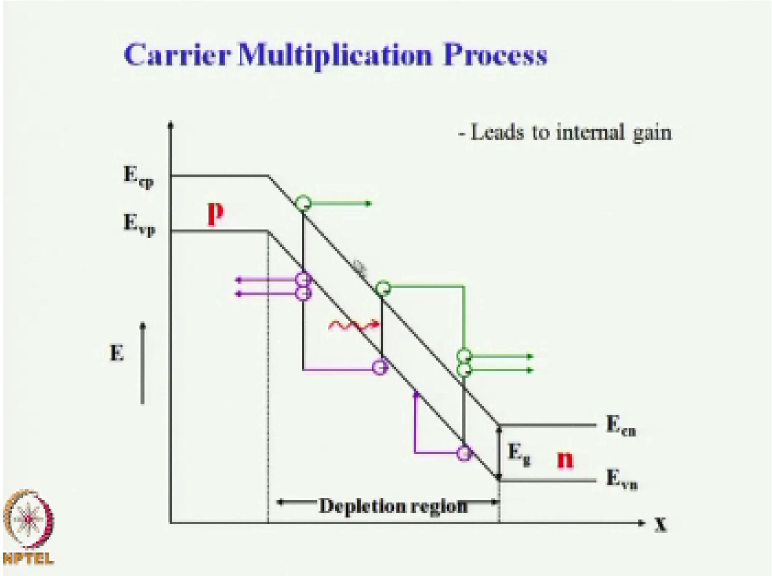
- Relatively large reverse bias applied
- Built-in gain in the device due to carrier multiplication in the depletion region
- Typical (photocurrent) Gain M ~ 10 - 100
- Higher sensitivity, but more noisy

With this we switch to the next device which is the Avalanche photo-diodes. It is basically a PIN diode, but with a large reverse-biased which provides Avalanche gain. So relatively large reverse-biased Avalanche photo diodes 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-biased what order of reverse-biased are applied. I will give some number towards 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 this Avalanche process? So built in gain in the device. Typical photo current gain M is of the order of 10 to 100 so M here is basically the ratio of primary photo current 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 is typically 10 to 100. Its higher sensitivity so this gives because of the current gain the sensitivity is higher. However, it is little bit more noisy because the Avalanche process by its very nature is noisy. It is relatively random process and therefore we have a relatively noisy output.

(Refer Slide Time: 12:49)



Carrier Multiplication Process

- Leads to internal gain

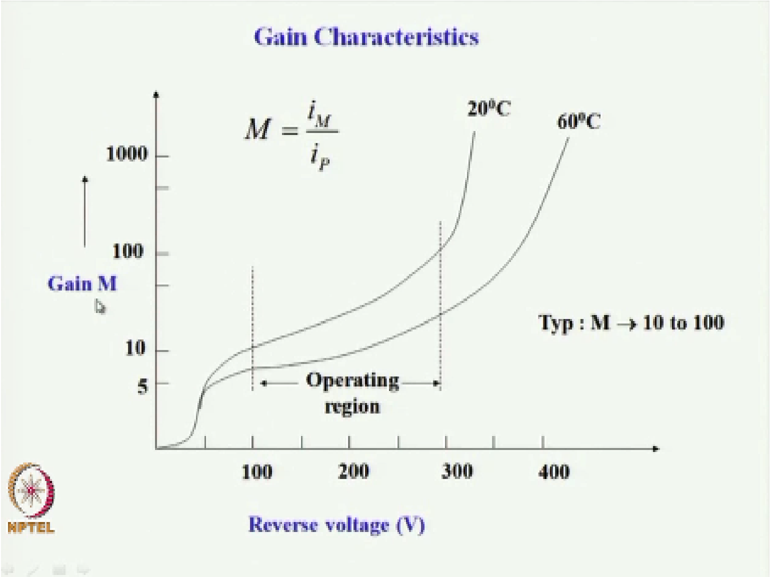
So here is the energy band diagram of the PIN structure here because of the large reverse-biased we can see that now the potential barrier here or the potential energy diagram has a large slope here in the active region in the depletion region because of the large-reverse biased. So this is the P psi. This is the n psi. EVP the valence band energy and conduction band energy as because of the large potential slope here potential energy slope an incident photon that generates an election and hole pair a hole and electron.

Because of the large potential energy slope the electron goes down the slope, travels 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 (()) (13:52) high electric field which the kinetic energy of the electron is such that it knocks down another electron and creates additional electrons by the Avalanche process.

It knocks down another electron from another bound electron and creates an 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 pair, electron hole and electron pair. This is the primary hole which has created a secondary path which leads to carrier gain that is increase in the number of carrier by the Avalanche process.

So I have shown just 2 events 1 here at this end and 1 here, but actually there are large number of carrier multiplication events take place as the carrier travel up and down the potential energy slope. So this clearly illustrates the increase in the number of carrier due to the Avalanche process.

(Refer Slide Time: 15:15)

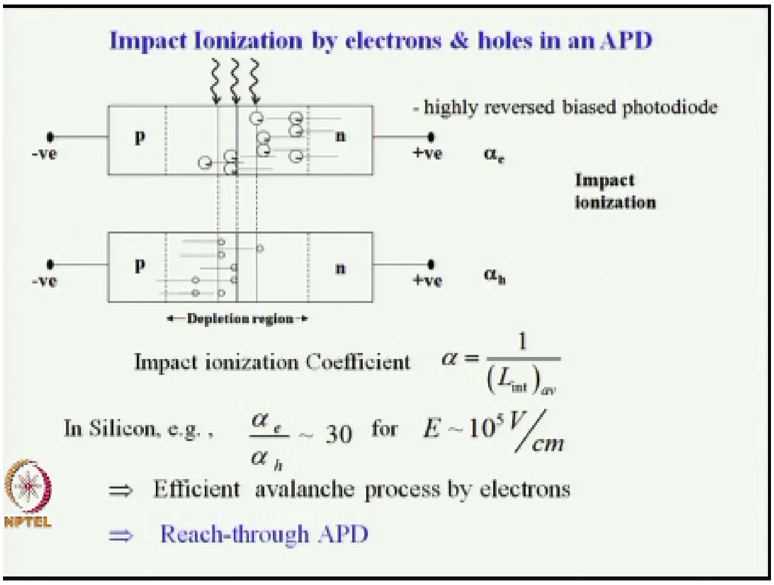


The gain characteristics of a typical APD is shown here reverse voltage the numbers are here now. Typically, 100, 200, 300 volts are applied for as the reverse-biased and what is plotted is the gain the current gain M. M is defined here iM./iP. This is the gain after the multiplication process and this is the primary photo current due to the incident photon. So at 20 degree centigrade for example 20 degree Celsius the current gain increases initially as the voltage increases.

And then it goes over to a relatively slow region here the slow rise here and then finally it again goes rapidly and this is where the Avalanche process is so rapid that the device would lead towards breakdown. So this is not the operation region. The operation region is here between these 2 lines. So typically for this example is typically between 100 and 300. Normally the operating voltage is specified like 220, 250 volts DC.

So these characteristics shows the current gain here for an APD. At a different say at higher temperature characteristics varies. So it is indeed temperature sensitive and the characteristics changes because at higher temperature here we have more agitation of the atoms in the lattice. And therefore the electrons and holes undergo more collisions that is the separation between that is the special separation or the average length.

(Refer Slide Time: 17:20)



Impact Ionization by electrons & holes in an APD

- highly reversed biased photodiode

Impact ionization

Impact ionization Coefficient $\alpha = \frac{1}{(L_{\text{int}})_{av}}$

In Silicon, e.g., $\frac{\alpha_e}{\alpha_h} \sim 30$ for $E \sim 10^5 \, V/cm$

⇒ Efficient avalanche process by electrons

⇒ Reach-through APD

So let me discuss in the next slide here and then come back. We can see that there is a parameter called impact ionization coefficient alpha which is defined as 1/L internal average. This here refers to a collision the distance the average distance travelled between 2 successive collisions so this is L impact. So the average distance 1/L impact is called the impact ionization coefficient this is per unit length.

And this depends on L if you have for example if the temperature is higher than the electrons do not have enough energy between 2 collisions and therefore the number of collisions which lead to generation of additional carrier pair decrease and therefore the current gain decreases. So this is just an example to show that it is temperature sensitive and higher the temperature than lower will be current gain.

In fact, most of these detectors are cooled one can cool this further down and curve would qualitatively look like this. It will go up the characteristics will go up if you cool the detector further and it will be less noisy as well. So we come to this discussion here the impact ionization by electrons and holes in an APD. What is shown here is the same APD PIN. The incident photons here generate electrons and holes in this region.

That is the catchment region. Here only electrons are shown the electrons are swept towards the positive potential here that is the negative end which is reverse-biased diode. So there is a positive potential at this end. So the electrons are accelerated in this direction. When the electron gains sufficient energy it leads to generation of a secondary electron and hole pair which further travels in this direction.

And get the electron travel in this direction and of course the holes travel in the opposite direction. I have not shown holes in this diagram holes are shown in the next diagram. First please see only the first diagram where the secondary electrons are also getting accelerated and creating more and more electrons as the accelerates towards the positive end. The holes on the other hand are accelerated to the other end.

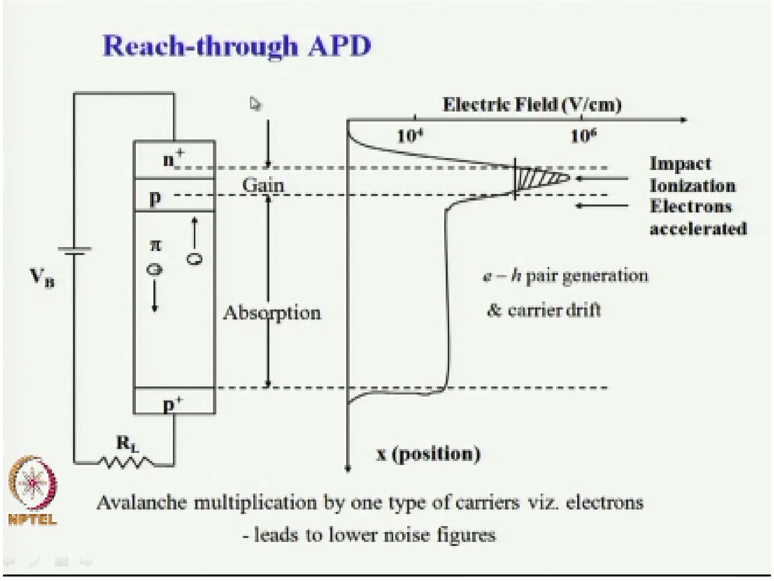
As you know electron mobility is higher and therefore they gain a higher velocity in the same electric field. When the electric field magnitude is the same they gain higher velocity much higher velocity and therefore much higher kinetic energy and lead to rapid Avalanche of further carriers. Holes get accelerated to the other end and as they proceed whenever they gain sufficient energy they also generate additional electron hole pair.

And the holes continue to proceed towards the negative end that is the P end. The impact ionization coefficient and this is at a given temperature the impact ionization coefficient is defined as alpha=1/average length average distance between 2 successive collisions. In silicon for example alpha e that is the impact ionization coefficient for electrons is much greater compared to the impact ionization coefficient of holes.

Alpha e/alpha h is of the order of 30 for a field when the applied field in this medium is of 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 30 times efficient more efficient compared to secondary pair generation due to holes. So the efficient Avalanche process is by electron and to make use of this fact making use of this fact in new design of APD has been proposed.

And this is currently widely used design for APD which is called the Reach through APD.

(Refer Slide Time: 22:29)



Reach-through APD

Avalanche multiplication by one type of carriers viz. electrons
- leads to lower noise figures

We will see what is this Reach through APD. Here is the APD structure a high n + region then a P region here and pi that is (()) (22:41) near intrinsic or (()) (22:43) here p and then this is the p p+. So because of a large n + so there is a reverse-biased here applied because of high doping concentration here at this junction close to the junction we have large density of immobile positive ions because the electrons have migrated here.

And large density of immobile positive ions. Therefore, if we 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 we can see here that it is approaching the peak value is approaching 10 to the power of 6 volts per centimeter.

So this shaded region is the region where the electric field is about 10 power 5 volt per centimeter where the Avalanche process takes place that is the kind of field that is required for Avalanche process to take place and the field drops down rapidly because we have already discussed the field E is nothing but rho times dx rho is the charge density here. So carrier charge density.

So it drops down because on the P side there are negatively charge immobile ions. So the sum drops down so electric field drops down further and it drops down here and in the pi region there are both negative and positively charge immobile ions and therefore the electric field almost remains constant in this region as you integrate rho dx. So the electric field almost remains constant actually there is a small slope here which is sloping down like this here.

But it is not shown here it looks almost as if it is flat. There is a small slope, but the important point to see is the electric field here 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 5 volt per centimeter. In this region the electric field is much lower because the electric field is much lower any carrier which is in this region accelerating either to this side or to this side will not be able to have enough kinetic energy to create additional electron hole pairs.

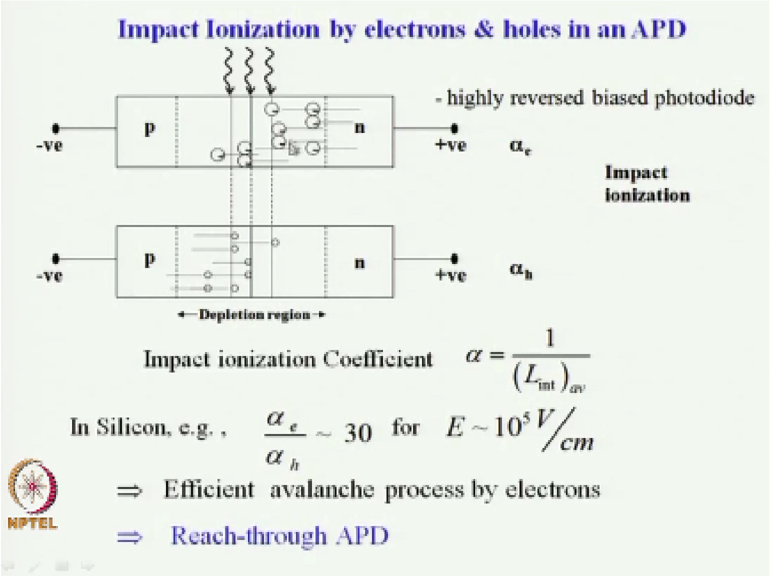
Please see that in this design this is primarily the catchment area the photons are incident in this region. Photons are absorbed primarily in this region. This is not correct exactly to scale because the thickness of this region the thickness of this region and this region are much smaller compared to the thickness here much, much smaller. So the photon the light which is incident on the photo detector is primarily absorbed in this region.

There are electrons and holes which are created in this region. So this is why I call it as the catchment area. And the electrons 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 this region is not strong enough to accelerate the electrons to energies where they can generate additional electron hole pairs or there is no Avalanche process taking place in this region.

However, when the electron accelerating in this region enters this zone here. We note that the electric field is very high in this zone. And therefore the electron immediately creates very large number of electron hole pairs by impact ionization. The electrons which are the secondary electrons which are generated are further accelerated and collected by the electrodes here.

The hole which is generated move into this direction, but they are moving in a region where the electric field is much smaller or electric field is not strong enough to create additional Avalanche process. And therefore this means that the Avalanche process in this design of this structure is primarily due to electrons. So the Avalanche multiplication is primarily by 1 type of carrier namely electrons. This leads to much lower noise figure.

(Refer Slide Time: 27:54)



Impact Ionization by electrons & holes in an APD

Impact ionization Coefficient $\alpha = \frac{1}{(L_{\text{int}})_{av}}$

In Silicon, e.g., $\frac{\alpha_e}{\alpha_h} \sim 30$ for $E \sim 10^5\, V/cm$

⇒ Efficient avalanche process by electrons

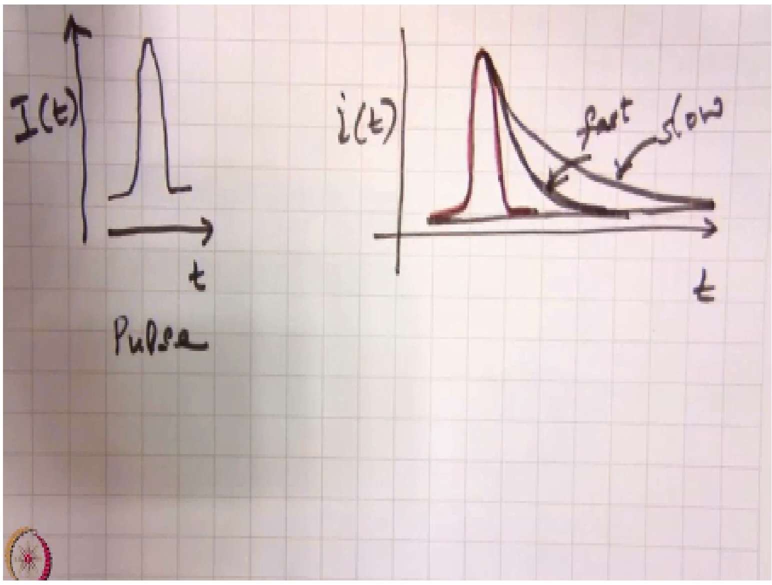
⇒ Reach-through APD

In fact, if we look at the previous diagram here please see that a carrier pair generated here electron gets accelerated in this direction, hole get accelerated in this direction. As the electrons proceed it creates additional electron hole pair and the 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, a hole which is generated here as it accelerates in this direction it creates additional electron hole pair. The process would continue almost un-awaited even if the incident light is just an impulse or pulse. It appears as if the process would continuously continue or it is never ending. However, in practice it does quench after a relatively long time. Whereas if you create in the next design in the Reach through APD design since the Avalanche process is taking place only at this end.

The secondary electrons created are immediately collected here the holes which are created are moving in this direction, but they are not creating any further Avalanche and therefore the quenching of the Avalanche process that is stopping of the Avalanche process soon after the light pulse has been switched off or light pulse is absorbed will be very rapid. So let me illustrate what I have been saying. So let me just illustrate what it means.

(Refer Slide Time: 30:03)



So if I have let say an incident pulse this is an optical pulse which is incident on the photo detector. So this is time access and this is of course the light energy or intensity I of t. So this is the incident pulse on the photo detector. The current response of the photo detector if I take an APD so because of the pulse so this right now I am plotting APD current I of t. Ideally, when the intensity goes up I should have the current going up like this and when the intensity comes down current should come down.

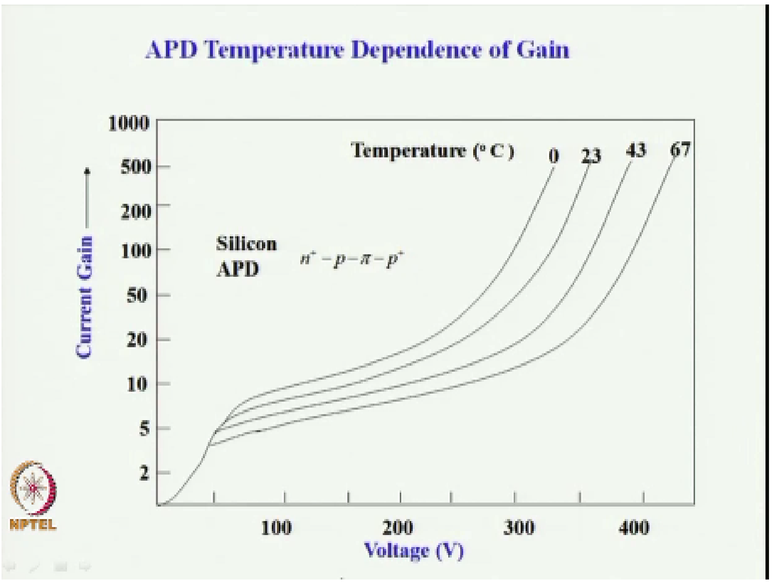
This means if the detector is responding fast enough that means the current pulse which is generated is identical to the input optical pulse. However, in general there is a delay because even after the pulse disappear that is in time even after the pulse is absorbed or light pulse is no more there it takes some time for the carriers to recombine and the current co come down. In other words, the current pulse.

So this is what I have 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 continuous even after the incident pulse has been absorbed or pulse has passed through. So this still here is because of the carriers which are there in the medium or with reference to the Avalanche process.

This corresponds to a rapid drop or a drop which flow here corresponds to how fast the Avalanche process quenches. So this is slow which means the Avalanche process takes longer time to quench or to stop whereas in this case it is faster. So the Reach through APD ensures that that the Avalanche process is primarily due to electrons and electron mobility is much higher and therefore the current drops down rapidly and the device becomes faster.

So this is what I was referring to with this fast and slow detector.

(Refer Slide Time: 33:14)

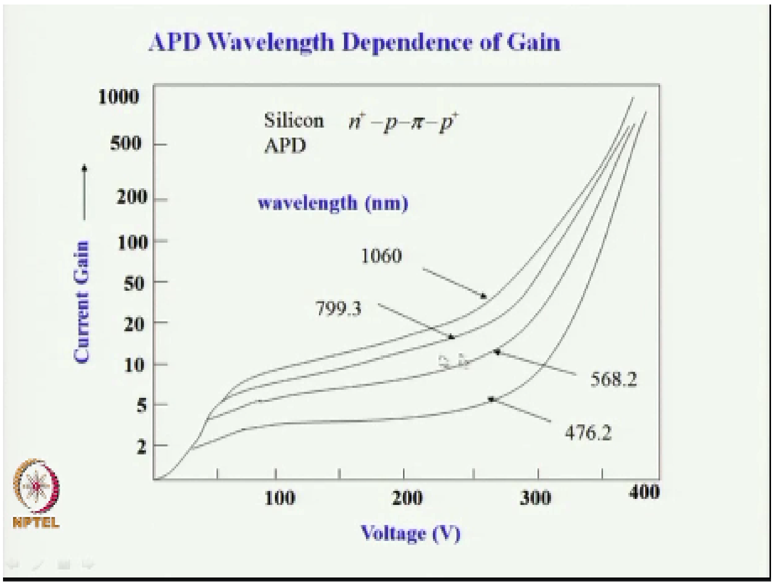


APD Temperature Dependence of Gain

So let me show the current gain characteristics for a typical silicon Reach through APD n p pi p+. So at 0 degree centigrade as we have already discussed this as the temperature increases because of more number of collisions the carriers which undergo more number of collisions with the atoms in the lattice. The average distance between 2 collisions is much smaller. And therefore they 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 drops down. However, as voltage increases further the kinetic energy gain becomes sufficiently large and then it leads to a higher current gain.

(Refer Slide Time: 34:23)

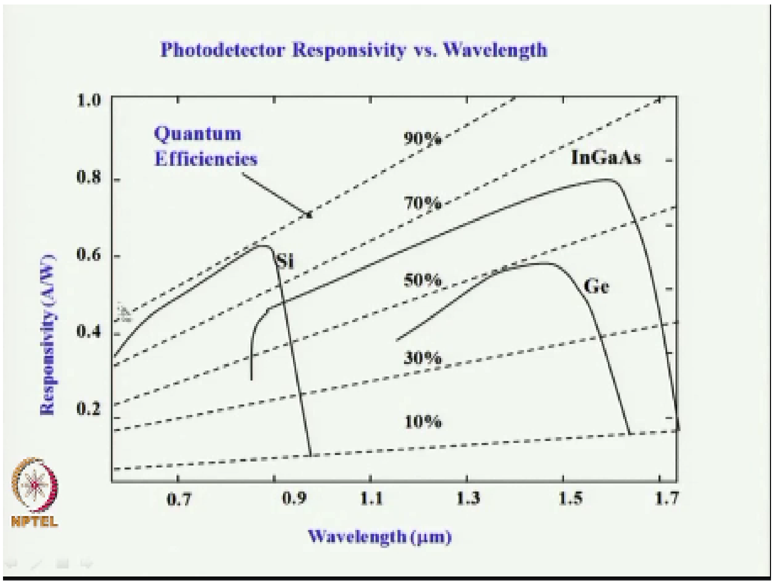


APD Wavelength Dependence of Gain

This is characteristics which shows the wavelength dependence of current gain the typical silicon APD current gain here. And you see that at lower wave length here the current gain is smaller and as the wave length increases up to around 1 micron or 1000 nanometer the current gain increases. This increase is this low value of current gain and higher values of current gain here are primarily because of the quantum efficiency.

We know that the quantum efficiency of silicon. We have already seen this in one of the earlier curves or may be let me show right here. We have seen the quantum efficiency here.

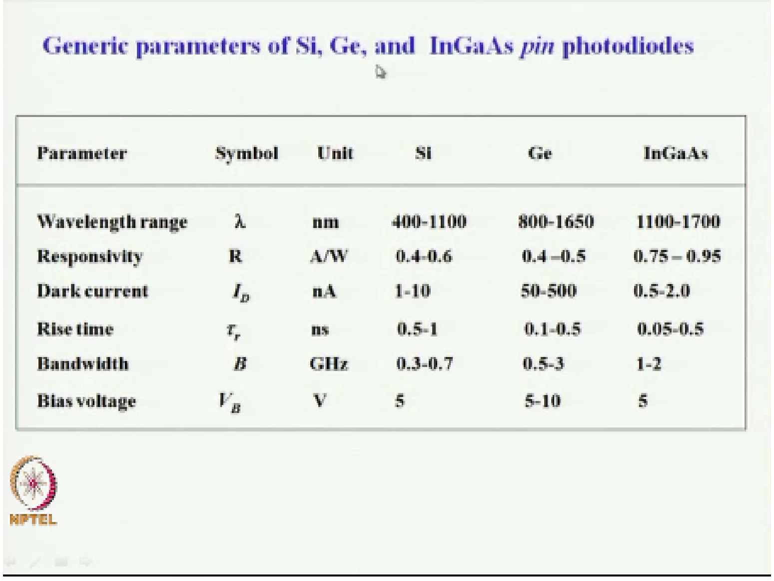
(Refer Slide Time: 35:21)



Photodetector Responsivity vs. Wavelength

So silicon it has a smaller quantum efficiency at lower wave length and the quantum efficiency is relatively large the responsivity is large as the wave length increases. Of course once as we reach near the band gap wave length the quantum efficiency drops down and this is the primary reason for the characteristics that I have just shown that is dependence of current gain on wave length.

(Refer Slide Time: 35:55)



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 parameters of silicon germanium and Indium gallium arsenide PIN photo diodes. So if you take a typical data sheet this is the kind of numbers that you would see. Wave length range that is wave length range over which this is the detector is useful operating wavelength range lambda here in nanometer. Silicon it is around 400 to 1100.

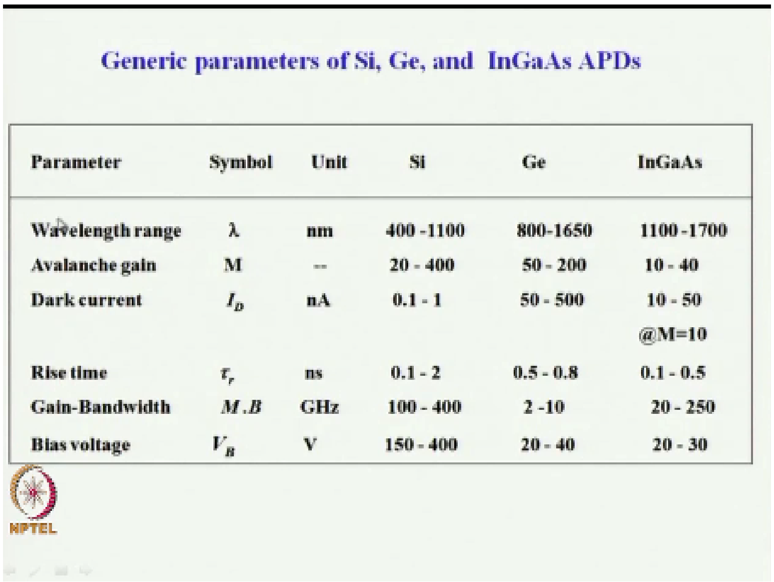
So we have discussed this in detail so this is primarily because of eta or the quantum efficiency of the detector whereas germanium has a smaller band gap and therefore it is useful detector in this range 800 to 1650 or may be 1700 whereas Indium gallium arsenide is primarily a good detector is this wave length range and that covers the optical fiber communication window.

And as we have seen as we have discussed earlier this is the detector which is widely used in optical fiber communication. The responsivity typical numbers are here amperes per watt. It is current generated per optical power incident that is why amperes per watt. So typical numbers 0.4 to 0.6, 0.4 to 0.5 and 0.75 to 0.95 responsivity is quite high. Dark current in nanoampère, 1 to 10 50 to 500 and 0.5 to 2 is the typical dark current for detectors.

Of course it depends on the material, the 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 5 and once can have detectors with the 0.05 to 0.5 nanosecond rise time of the photo detectors. Bandwidth that is the detection bandwidth in gigahertz. So this is primarily inverse of the TR here of the order the bandwidth detection bandwidth is of the order of just under 1 gigahertz.

Here of the order of gigahertz and of the order of gigahertz. The bandwidth is almost similar as you can see it is primarily depending on the inverse of the rise time how fast a detector is and the biased voltage for PIN photo diodes typical biases are between 5 and 10 volts. Normally they are reverse-biased in the 5 to 10 volts.

(Refer Slide Time: 39:05)



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. The wave length range again is the same is listed the same wave length range. Main difference is the Avalanche gain we have current gain here typically 20 to 400 50 to 200, 10 to 40 of course it depends on the operating voltage, but this is the range of gain typically of the order of 100 is the current gain which is employed in practice and the dark currents are again listed here.

The dark current are again listed here. The dark current in this case as you can see are relatively large because you have applied a larger reverse voltage corresponding to at gain of M=10 current gain M=10 the rise time are typically sub nanosecond fraction of nanoseconds here. And the gain bandwidth is again similar numbers hundreds of megahertz to few gigahertz.

And one can have detectors with the very large bandwidth and biased voltage as you can see earlier we had 5 to 10 volts, but now we have biased voltages of 50, 100 typically 10s of volts or silicon for example can withstand much higher reverse biases and that is why we have typical operating voltages of about 250 for silicon, but relatively lower operating voltages for germanium and Indium gallium arsenide.

We know that they have a much smaller band gap and therefore you cannot apply very large reverse biased that could lead to breakdown of the device. I think with that we come to the end of this talk on photo detectors. So today I will stop at this point.