Introduction to Photonics
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Semiconductor Detectors-4

Ok good morning welcome to Introduction to Photonics, in our last lecture we were talking about avalanche photodiodes and we got to the point of saying that when you looking the avalanche photodiodes the multiplication factor is a function of the bias voltage so larger the bias voltage more will be the multiplication factor. But we were insisting that what matters is not just that number but the quality of that multiplication factor, meaning whether that multiplication factor is achieved without accumulating noise right.

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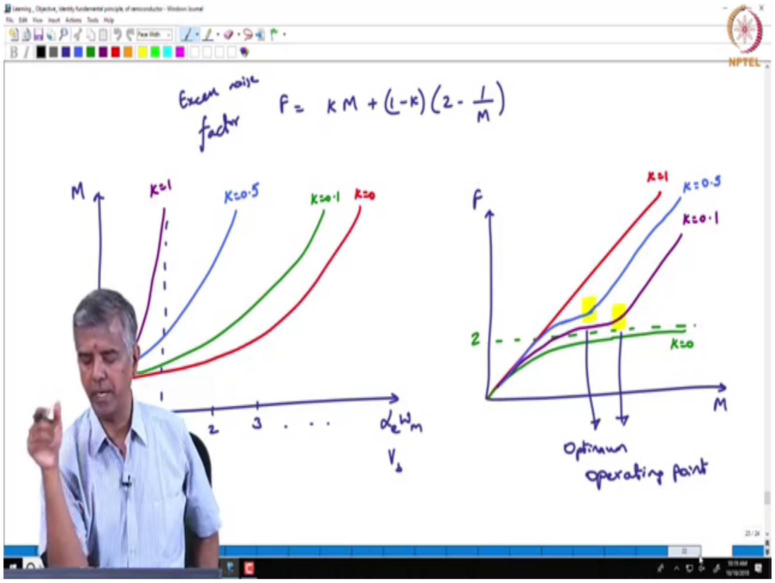

And so we had to look at that picture on the right side where we said ok the noise is actually given by this excess noise factor and if you look at the excess noise factor you are saying that when K equals to 1 which corresponds to the ionization coefficient of electrons is equal to the ionization coefficient of holes.

In that case even as you accumulate gain you are also accumulating noise so overall we are not really gaining much we are not gaining in terms of the signal to noise ratio, whereas if we say k equal to a 0.1 upto a certain multiplicative gain there is not as much increase in the noise and so there may be some optimum operating point for this APD’s right.

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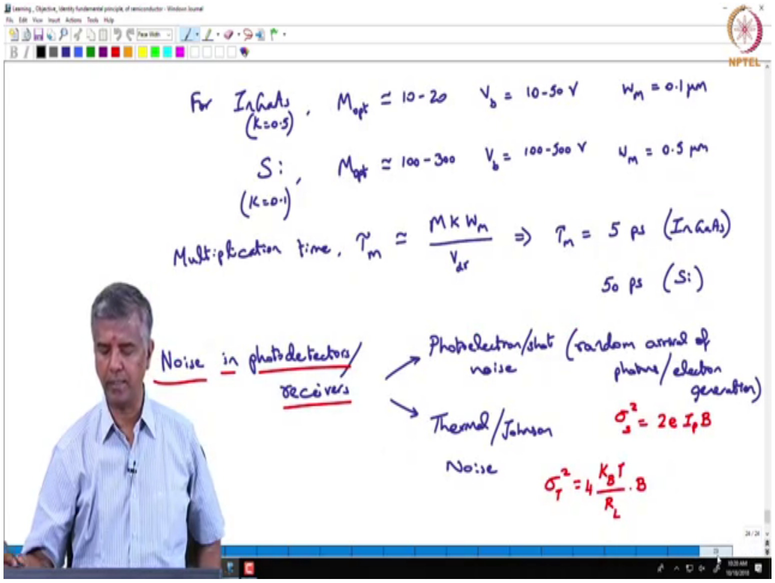

For InGaAs $(k=0.5)$, $M_{opt} \simeq 10-20$ $V_b = 10-50\text{ V}$ $W_m = 0.1\,\mu m$

Si $(k=0.1)$, $M_{opt} \simeq 100-300$ $V_b = 100-500\text{ V}$ $W_m = 0.5\,\mu m$

Multiplication time, $\tau_m \simeq \frac{MkW_m}{v_{dr}} \Rightarrow \tau_m = 5\text{ ps}$ (InGaAs)

50 ps (Si)

Noise in photodetectors/receivers

→ Photoelectron/shot noise (random arrival of photons/electron generation)

$\sigma_s^2 = 2eI_pB$

→ Thermal/Johnson Noise

$\sigma_T^2 = 4\frac{K_BT}{R_L}.B$

So we considered that and then we said ok we looked at some sample numbers for silicon and gallium arsenide sort of APD’s and then we said ok let us since we have started talking about signal to noise ratio we want to look at what is noise, what is noise mean in a photodiode and is in a typical case is not just the photodiode that matter you need to extract the current in the external circuits so you have to looked at it overall as a photo-receiver.

So when we looked at the receiver noise overall we are basically saying there will be one component which is the short noise and the other component is the thermal noise, short noise is due to the random arrival of photons and the subsequent electron hole pair generation and we quantify that the short noise variance is proportional to the photocurrent and then also the bandwidth of your receiver and similarly you have the thermal noise which is given by this expression which is due to the fact that the electron flow inside the current flow inside resistor tends to be you know random in nature and that actually depends on the value of the resistor.

Now we will go further on this the primary thing that we want is to establish is when does it make sense to use an APD and when are you better of just using a PIN photodiode ok, can we actually define the regimes over which APD makes a little more sense ok.

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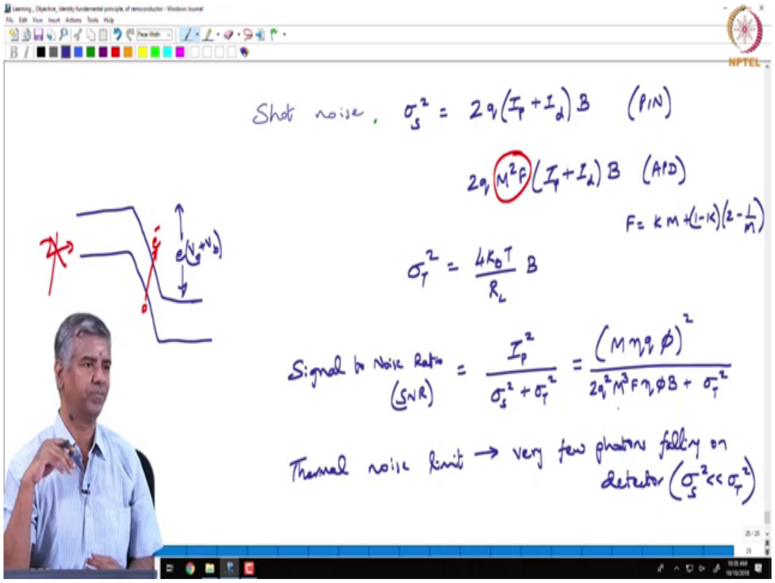

Shot noise, $\sigma_s^2 = 2q(I_p + I_d)B$ (PIN)

$2q\boxed{M^2F}(I_p + I_d)B$ (APD)

$F = kM + (1-k)\left(2 - \frac{1}{M}\right)$

$$\sigma_T^2 = \frac{4k_BT}{R_L}B$$

Signal to Noise Ratio (SNR) $= \dfrac{I_p^2}{\sigma_s^2 + \sigma_T^2} = \dfrac{(M\eta q\phi)^2}{2q^2M^3F\eta\phi B + \sigma_T^2}$

Thermal noise limit → very few photons falling on detector $(\sigma_s^2 << \sigma_T^2)$

So let us go into that little more detail and when we talk about short noise ok we define it as sigma s square is equal to 2 times I said E but your book is actually insisting Q so let me just switch over to Q you understand the Q is just representing the charge of an electron. So 2 Q multiplied by IP but also there is one more component that you typically have noise component that you typically have and that component is called the dark current.

Ok multiplied by v so what is the dark current? When we talk about these biased photodiodes we are typically talking about you know this barrier height this is in terms of energy so the barrier height is v knot plus v b where v b correspond to a reverse bias right. So the barrier height keeps on increasing with higher reverse bias and in this sort of a scenario even at room temperature you might have an electron jumping from the valence band to the conduction band and so this is a case where there is no photon going in right so it is dark right there is no photon that is incident on the photodiode but nevertheless you have thermally excited carriers which jump the band gap and they go they become like a free electron ok and that process actually depend on the barrier height because as you can see with larger and larger barrier height with a little bit of vibration energy itself some phonon energy you can tunnel across that electron from the valence band can tunnel across and get to the conduction band ok.

So you have more dark current happening at higher bias voltages ok but even at you know even when you do not apply a bias voltage there is a finite probability that an electron can jump over there the conduction band which is called thermally generated carrier and that can also give you a photocurrent in the external circuits so which is what we are calling as the dark current ok. So you have this sort of an expression for your PIN photodiode and when it comes to an APD photodiode your total noise is going to be something like this there is a factor m square multiplied by F that comes about in an APD.

Once again I am not deriving that formula it is a fairly long derivation but you know you have that sort of an expression where f is given by like I mentioned in one of the previous lectures it is k multiplied by m plus 1 minus k multiplied by 2 minus 1 over m ok that is actually called the excess noise factor ok. So we have short noise and we have thermal noise now which is 4 KBT over R L multiplied by v so when you look at the overall signal to noise ratio, signal to noise ratio is defined as your signal power over the noise power.

The signal power is going to be given by this IP square and your noise power is given by now it has two components sigma x square plus sigma t square that is the short noise variance and then the thermal noise variance right and if you write this out you can basically say that the photocurrent is going to be given by you have a multiplicative gain as far as in general case in an APD eta multiplied by Q that is the responsivity eta Q divided by H mu is the responsivity multiplied by the incident power right but the incident power over H mu is nothing but the photon flux so I can just write this as m into eta q multiplied by the photon flux right.

He flux is representative of the incident power divided by the photon energy ok so this the whole square divided by your it is 2 Q multiplied by IP let s actually neglect ID you know because ID tends to be relatively small number so will neglect that for a minute so for simplicity and then you have 2 Q multiplied by once again IP which is corresponding to that term in the numerator so there is actually a q that comes from there so you can write it as 2 Q square m square f Eta phi multiplied by b right where m square f actually corresponds to the noise he extra factor that comes about when you use an APD plus you have your sigma t square ok.

You can further simplify this right and you can actually try to get to the point where when you have you know a very few photons falling on the detector right so you have what is called the short noise limit which corresponds to very few photons no actually that would be very few photons falling on the detector will be the will be what is called the thermal noise limit because there is no short noise. You understand that short noise comes about when we have light ore light falling on the detector but when there are very few photons falling on the detector the you have what is called the thermal noise limit.

So in this case what you have is sigma s square is far-far less than sigma t square. Now m is actually the multiplicative gain, so yes so you yeah IP will have m cube that is right, so yeah we had neglecting dark current yeah so yeah thanks for pointing out so this should be m cube here there is a extra m that comes about through IP ok so we can just say that when you have the thermal noise limit that is sigma t square is far-far greater than this other factor then you know that your short noise is so low that you can afford to use an APD and increase the short noise.

So my in my thermal noise limit where a very few photons falling on the detector and thermal noise is over here the thermal noise depends on the receiver gain that I will setup right. So more the gain more will be my thermal noise ok. So my thermal noise will be over here but my short noise is over here ok. Now if I use my APD I can afford to go up on my short noise without affecting the overall noise that is accumulated right because this is so low initially now if I use an APD and increase my gain my short noise is going to increase ok but until it reaches thermal noise it is actually not affecting the denominator until it becomes comparable to the thermal noise is not affecting the denominator.

So as but it is affecting numerator right because your gain is actually that multiplicative gain is contributing to the numerator ok so the overall signal to noise ratio is going to increase you understand that. When you have very few photons falling on the detector so that your short noise is very small compare to the thermal noise in that sort of an scenario you can afford to increase your short noise you can afford to increase your short noise by going to a multiplicative gain which actually boost up the numerator by quite a bit by that square factor m square right and now because of that you are able to increase your signal to noise ratio with that multiplication factor. Do you have any question on that? You understand what I am saying?

Yes, so it becomes equal then you have twice that noise variance then t becomes significant but just before it becomes equal that is all controlled by your gain right your multiplication factor controls you know you have only few photons falling so you not going to be able to do anything (())(17:08) but you can control how many electron hole pairs you are generating with that through that multiplicative gain, yes, so with APD we are by changing the bias voltage we are controlling the m factor that multiplicative gain factor so through that you can actually control the signal to noise ratio.

So initially as you increase you just get free improvement in the signal to noise ratio so to say right. It does not have a penalty until the short noise becomes comparable to the thermal noise. So intuitively you can say when you have very few photons falling on your detector such that that short noise is much lower than the thermal noise which we call as the thermal noise limit right if you have a thermal noise limited receiver it actually makes a very good case for using an APD ok but beyond that in the short noise limit, short noise limit is where the first factor in the denominator is larger than the second factor then in that case what happens? It basically is like you have a 1 over m dependence right you have a 1 over m dependence so in that case you are as you increase your gain you are actually lowering the signal to noise ratio right.

The short noise limit you have a m square factor in the numerator you have a m cube factor in the denominator so it overall becomes a signal to noise ratio becomes inversely proportional to m and in that case you know increasing the m is only going to reduce the signal to noise ratio ok so let us actually try to put all of this together in some meaningful form so to do that let us actually say you have you can count the number of photoelectrons it is a mean number of photoelectrons.

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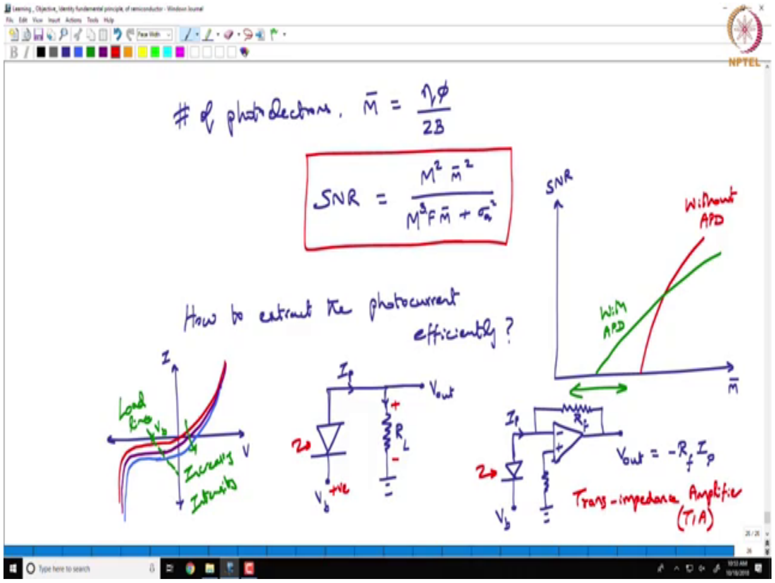

# of photoelectrons. $\bar{m} = \frac{\eta\phi}{2B}$

$$\boxed{SNR = \frac{M^2 \bar{m}^2}{M^3 F \bar{m} + \sigma_n^2}}$$

How to extract the photocurrent efficiently?

$V_{out} = -R_f I_p$

Mean number of photoelectrons is given by eta multiplied by phi which is what we have in the previous case divided by 2 B where 2 B corresponds to the you know well two times the bandwidth of your photo receiver ok. So the number of photoelectrons will be given by this so if you substitute this in that previous expression what you get is SNR is now going to be given by you have a m square in the numerator and then you have that factor Eta phi and you have a 2 B factor in the denominator so you going to have m square multiplied by the mean photoelectron square divided by m square f multiplied by the mean photoelectron plus some sigma q square, sigma q square is nothing is going to be nothing but sigma t square divided by 2B right this is going to be some normalization factor but sigma q square is a representation of the thermal noise but what we have done here is we have represented the entire thing in terms of number of photoelectrons.

So that can actually give us more insight into this entire scenario so you have SNR plotted as a function of the number of photoelectrons and in this what you will find is without APD you are going to have something like this you going to have your SNR increase with mean number of photoelectrons and so more the photoelectrons more will be your SNR but if you so this is without APD but with the APD what you will find is it goes something like this so when you have low number of photoelectrons it helps to use an APD but beyond d a certain point right the APD is going to actually give you more noise if you keep increasing your if you have a large number of photoelectrons falling in your APD that short noise component is going to dominate and when that short noise component dominates then you essentially have you know lower signal to noise ratio ok.

So this actually this sort of a picture determines when you use the APD use the APD typically in these regions where you have very few photoelectrons falling on the photodiode. So this is no-no the number of photoelectrons that is right that should be m cube so that is yeah that should be m cube over there because we have just counting in terms of number of photoelectrons. So (()) (24:11) what is sigma q square? Sigma q square there is actually a normalization factor because we have taken 2 b in the numerator there is actually a normalization factor that corresponding to the2 b that comes in so signal q square is actually sigma t square multiplied by 2 b I think I am not absolutely sure but it is actually sigma t square multiplied by 2 b is what it will come.

If you just substitute instead of Eta phi what Eta phi you substitute basically that factor m bar then you will get this ok but the primary idea is that you know you can look at it in terms of photoelectrons or you can go one step before this and say I want to look at it in terms of the number of photons that are falling on the photodiode right so that is that will be a very similar picture that you will see here. So when you have very few photons on the detector then you use an APD but if you have a large number of photons falling on your detector then you better of just using a PIN photodiode ok. Now ofcourse then you would say I can then use an APD in all my applications and just change the bias voltage right because if I keep my bias voltage low it acts like a PIN photodiode.

So I can actually determine where I operate right that is one thing that you can do but for the fact that an APD is more expensive than a PIN. So in applications where you know you going to have a lot of photons that are going to fall on your photodiode like in set in sensor applications you know you may actually have a lot of photons falling on your photodiode then in that case you are better of just the PIN photodiode but on the other hand let us say in a communication type of application we are going long distance and you have to when you have very few photons remaining after it is gone through all that distance then you may want to put an APD there because that is going to give you a better signal to noise ratio ok.

So you just need to see what is the relative components of your short noise and thermal noise and based on that you decide whether you want to use APD or PIN. So any other questions about this before we move on? So far we had been talking about what is happening to the photodiode we have not actually figure out what is happening in the external circuit ok so the question is how to extract the photocurrent efficiently right so we have been saying ok yeah this electron hole pairs are generated they are swept out into the external circuit and they are going to generate that photocurrent and we said ok life is nice and (())(28:08) right so there is nothing to worry about but in reality you do have to worry about.

Because let us say you take this simple example of photodiode which is reverse bias means that the cathode is connected to a positive bias let us say and let us say you are just trying to extract the output through just a load resistor R L right. So you just take V out like this so what is the problem with this now problem is that you have a photocurrent that is flowing through this flowing through this resistor and when that photocurrent flows through this is going to be at higher bias compare to this right you are going to have a potential drop across that resistor R L. so when photocurrent flows through this R L it is going to have a potential drop corresponding to IP multiplied by R L ok and that voltage drop if you look at it is acting against this V b because V b here is positive right.

Now if this potential is actually acting on this anode side that is actually like forward biasing so through V b we are trying to reverse bias the photodiode but because of as you extract more and more photocurrent there is a voltage drop across the R L that actually is forward biasing the photodiode so it is counteracting the reverse bias in other words right. So that is actually going to be problem because if it is counteracting the reverse bias then the reverse bias voltage effective reverse bias voltage that the photodiode is seeing is going to keep decreasing as you go to higher and higher photocurrent as you pick up more and more light ok.

So let just represent this through the what we have previously looking at as your I V characteristics right and what we said previously is the I V characteristics are like this and as you increase you’re the light that is falling on the photodiode you going to have a corresponding increase in your in the photocurrent right. So this is basically with respect to increasing intensity of light falling on the photodiode ok but because of this what we are saying is we are starting with some reverse bias over here but as you increase the intensity the photocurrent gets increases I mean photocurrent is increased and that is actually reducing the effective bias across the photodiode so my load line the so called load line is going to be like this.

This is called what is called the load line as I am loading the photodiode right the corresponding current that I am going to have is actually going to be limited by this load line because effectively the my reverse bias which I started with this right this value V b that reverse bias is getting compromised as you go to higher and higher intensity of light falling on the photodiode as you extract higher photocurrent ok so my load line is like this ideally you want a load line that looks that is straight it is vertical what it means is that even as I increase the photocurrent I am not changing the reverse bias affecting the reverse bias.

So how can you achieve that? The way you can achieve that I am running out of time so I will just quickly mention this and I will stop here is by going for an OP-AMP based circuits so you typically connect the negative of the OP-AMP and the positive terminal is a virtual (bias) virtual ground and then you have a feedback resistor R F over here ok so this one is called a trans-impedance amplifier because the output is given by R f multiplied by IP is converting a photocurrent generator due to light falling on the detector just the same way this is right it is converting the photocurrent to an output voltage so that is why it is called a trans-impedance amplifier.

In short it is called TIA ok in this case what is different? What is different is you are trying to push a photocurrent into this OP-AMP the OP-AMP an ideal OP-AMP would not allow any photocurrent any current to flow into the terminals right and it will always try to keep the potential at both this points potential difference to be zero, how does it keep the potential difference to be zero? It basically generates a current its sources current at the output which actually you know flows through this and then it negates the potential that you have over here right.

So that is how you see this V out as minus R f into IP so irrespective of whatever current it generates right as long as this OP-AMP as the capability to negate that OP-AMP is able to source a current to negate that you are going to be fine. If you are coming to a condition where you are generating much more photocurrent than what the OP-AMP can supply then you are in trouble but that usually does not happen because the photocurrents that you generate in the order of milliamps and the OP-AMPs can easily you know provide 10's of milliamps ok so in this sort of a case you do not have loading like this instead your load line will be like this or if you keep a bias it will be like this.

It will be just a vertical line ok so you are not compromising your bias while you are extracting more photocurrent. So in most of these conventional applications you use a trans-impedance amplifier as the way of extracting photocurrent and converting it to a external this thing. There are some very special cases when you want to have very high bandwidth very high very good response in OP-AMP base circuit you are always going to be limited by what is called the gain band with your OP-AMP. Meaning the bandwidth that the OP-AMP that can provide for even say unity gain is going to be limited. So beyond that bandwidth you cannot use that OP-AMP right for this purpose whereas in those sort of cases you can use the what is called the direct loaded configuration and so you would see that high speed circuits whether you want to have

Giga hertz type of bandwidth you use a direct loaded configuration whereas relatively lower speed circuit you go for a trans-impedance amplifier.