COMPARISON AND ANALYSIS BETWEEN APD AND PIN FUNCTIONALITY IN AN OPTICAL COMMUNICATION SYSTEM

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“For my beloved mother WARSAN HERSI, my beloved father ABDIRASHID AHMED, my lovely brother’s and sister’s for their support. Thank you very much, may ALLAH grant them Paradise.

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ABSTRACT

In fiber optic communication, many factors affect the quality of the system which causes less desirable communication by clients between two optical networks. Therefore, optimizations of these systems become inevitable for telecommunication engineers. In this project, a performance comparison of the conventional PIN Photodiode with the APD photodiode in an optical communication system is presented. The effects of gain, extinction ratio, shot noise, thermal noise and responsivity are compared and studied in details. Set-up optimized optical transmission system with the best performance simulates for this project in terms of performance parameters using OptiSystem software. APD Photodetectors have been shown as the better candidate for communication system than PIN Photodetectors, due to their internal gain availability. In PIN Photodiode, thermal noise plays the dominant role in the performance of the receiver. In the APD, both the thermal and shot noise is significant. It was shown that the Maximum Q-Factor produced by each detector is heavily affected by both thermal and shot noise in the APD. The more responsivity increase then the Maximum Q-Factor increase for both APD and PIN. However, responsivity automatically increases as multiplication gain increases because multiplication process multiplies the number of electron generated.

ABSTRAK

Dalam komunikasi gentian optik, banyak faktor yang memberi kesan kepada kualiti sistem komunikasi yang kurang wajar oleh pelanggan antara dua rangkaian optik. Oleh itu, pengoptimuman sistem ini tidak dapat dielakkan untuk jurutera telekomunikasi. Dalam projek ini, perbandingan prestasi fotodiod *PIN* konvensional dengan fotodiod *APD* dalam sistem komunikasi optik dibentangkan. Kesan keuntungan, nisbah kepupusan, bunyi yang ditembak, bunyi haba dan responsitiviti dibandingkan dan dikaji secara terperinci. *Set-up* mengoptimumkan sistem penghantaran optik dengan prestasi terbaik menyerupai untuk projek ini dari segi *parameter* prestasi menggunakan perisian *OptiSystem. APD Photodetectors* telah ditunjukkan sebagai calon yang lebih baik untuk sistem komunikasi daripada *PIN Photodetectors*, kerana adanya keuntungan dalaman mereka. Dalam *PIN* fotodiod, bunyi haba memainkan peranan yang dominan dalam pelaksanaan penerima. Dalam *APD*, kedua-dua bunyi haba dan penembak adalah penting. Ia telah menunjukkan bahawa Maksimum *Q-Factor* yang dihasilkan oleh setiap pengesan adalah amat dipengaruhi oleh bunyi haba dan *shot noise* dalam *APD*. Dengan lebihnya peningkatan *responsiviti* kemudian peningkatan Maksimum *Q-Factor* untuk kedua-dua *APD* dan *PIN*. Walau bagaimanapun, *responsiviti* secara automatik depat meningkatkan keuntungan pendaraban bertambah kerana proses pendaraban mendarab bilangan elektron dihasilkan.

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LIST OF ABBREVIATIONS

Q	–	Quality Factor
SNR	–	Signal Noise Ratio
CW	–	Continuous Wave
RZ	–	Return-to-Zero
NRZ	–	Non Return-to-Zero
CD	–	Chromatic Dispersion
R	–	Responsivity
PD	–	Photodetector
APD	–	Avalanche Photodetector
F	–	Excess Noise Factor
M	–	Multiplication Gain
K	–	Carrier Ionization Ratio
PRBS	–	Pseudo-Random-Bit-Sequence
ISI	–	Inter Symbol Interference
ER	–	Extinction Ratio
EDFAs	–	Erbium Doped Fiber Amplifiers
Hz	–	Hertz
GHz	–	Giga hertz
BW	–	Bandwidth
dB	–	Decibel

PDF	–	Probability Distribution Function

CHAPTER 1

INTRODUCTION

1.1 Introduction

For over 20 years, since the invention of the laser and the development of low-loss optical fiber, fiber systems have become the dominant backbone of the information carrying infrastructure around the world, due to their high capacity, high speed, low cost and high security. There are three essential parts in an optic communication system: a transmitter, a transmission medium and a receiver. A laser is the core of a transmitter, with its output beam modulated by an input electric signal and then coupled into an optical fiber, which serves as the transmission medium to carry the signal to the receiving end. A Photodetector (PD) serves as the heart of an optical receiver and converts the optical signal back to an electrical signal.

Receiver component is considered as the most important and complex part in an optical communication link because it determines the quality of the output signal. Hence, optimizing this part will ensure the stability and performance of the entire system.

1.2 General System Description

Typically, the optical fiber communication system shown in Figure 1.1, the basic components of such an optical communication systems are the transmitter, the medium of transmission and the photoreceiver. There is also an optical encoder, through which the electrical information signal is converted to an optical signal by modulating the optical emission from the optical transmitter. This optical transmitter is usually a light emitting diode or a laser diode together with a relevant modulating and driving circuits. After that, the optical signal is transmitted through a medium that provides suitable propagating conditions for the carrier signals. This transmission medium is usually an optical fiber with optical amplifiers and repeaters depending on its length. Finally, at the photoreceiver, the optical signal is converted back into an electrical signal [1].

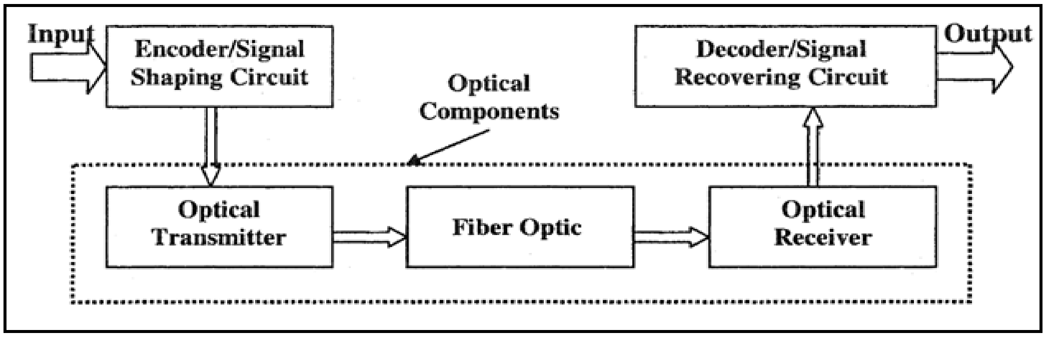

Figure 1.1: Schematic representation of an optical fiber communication system [1].

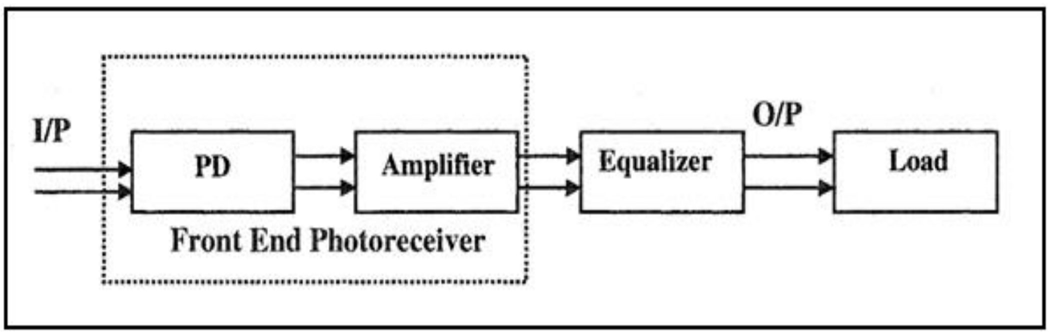

Figure 1.2: Schematic representation of the photoreceiver of the optical communication system [1].

The front end photoreceiver contains a Photodetector and electronics amplifier with relevant biasing and demodulating circuits [1]. A schematic representation of the photoreceiver of the optical communication system is shown in Figure 1.2.

The primary advantages of optical telecommunication systems are their high bandwidth due to high frequency of the optical carriers (100 GHz), low signal attenuation and low dispersion which are achieved by a choosing a suitable laser wavelength and optical fiber. Optical signals are immune to a crosstalk and hence several communication links can be supported by a signal fiber. They are also immune to the interference from inductive coupling and they offer more secure communications.

Conventional fiber is made of silica with a core having higher refractive index than its cladding. These changes in the refractive index result in a total internal reflection of a propagating signal, thus allowing for the signal to propagate over a long distance. Single mode fiber may be preferred as a transmission medium over multimode fiber because it could be optimized for low dispersion and attenuation for a certain wavelength. A dominant mechanism of attenuation in the signal mode fibers is impurity scattering.

With the present level of impurity control in manufacturing of single mode fibers, today's commercial fibers are very close to the theoretical attenuation limit of 0.15dB/km at wavelength (λ) of 1.55µm. Zero dispersion in the commercial fibers can be achieved at 1.3µm. Depending on the system requirement, either 1.3µm or 1.55µm is used as a carrier wavelength [2].

1.3 Problem Statement

Most of the research has been focused on the optical to electrical conversion process. The Photodetector is a key component in optical communication systems. The basic parameters used to characterize a Photodetector are responsivity, quantum efficiency, gain. There is a need and motivation to improve the parameters.

This work gives designers a comparison overview to wisely implement the suitable Photodetectors (PDs) according to their applications based on their requirements, reliability and price.

Such simulation for optimized communication system can help in analyzing the device under development and predict the performance for a given link distance. The simulation output helps eliminating any possible performance degradation before implementing the actual hardware.

1.4 Project Objectives

The objectives of this project are:

1. To optimize Photodetectors different parameters such as gain, dark current, thermal noise and shot noise, extinction ratio and responsivity.
2. To investigate the APD and PIN performances in term of Maximum Q-Factor.

1.5 Scope of the Project

The scopes of this project are as follows:

1. Set-up optimized optical transmission system with the best performance.
2. Simulate the project in terms of performance parameters using OptiSystem software.
3. Optimize the proposed communication system to different parameters such as Maximum Q-Factor.
4. Analysis optimized system’s result for all outcomes of this project.

1.6 Summary

In this chapter, an overview of the optical fiber communication system is presented. This overview concentrates mainly on the photoreceiver which is one of the critical components that affects the performance of the optical communication system. In fact, Photodetectors plays the major role in the performance of the Photoreceiver. Both the performance characteristics of the Photodetectors and the different material that can be used for the absorption and multiplication layers of the Photodetectors are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The two major trends in Photodetector (PD) development are aimed at developing a large bandwidth efficiency product and a high saturation current. A paper by Kashino. K first outlines a resonant cavity enhanced Photodetector (RCE) provides wavelength selectivity in detection [3]. Kato. K discusses how Photodetectors are generally designed with a balance of bandwidth, efficiency, power handling capabilities that are then to be used in telecommunications and optoelectronics [4].

Caria, M has performed responsivity measurements on commercial silicon Photodetectors in the UV range, 200-400 nm [5]. High sensitivity Photodetectors are crucial for optical communications, information and sensing systems. Various types of Photodetectors, such as MSM Photodiodes, PIN Photodiodes and Avalanche Photodiodes (APD), large-area APD have been developed [6-8].

2.2 Classification of Photodetectors

Semiconductor Photodetector can be broadly classified into two categories: those without internal gain and those with internal gain. The first category, P-N Photodiode, PN Photodetector, Schottky barrier Photodetector and metal semiconductor metal Photodetecter (MSM-PD) are extensively used in the fiber communication systems.

In order to improve the overall sensitivity of the front-end Phetodetector, it is desirable to provide an initial gain mechanism. Photodetectors with internal gain include Photoconductors, phototransistors and Avalanche Photodetector (APD). In the following sections, these types of the Photodetectors are briefly reviewed [9, 10].

2.2.1 P-N Photodiode

A P-N Photodiode is simply a PN junction diode operating under a reverse bias. The incident photons may be absorbed in both of the depletion and the diffusion regions, where the number of the generated electron-hole (e-h) pairs is proportional to an optical power [11]. The e-h pairs get separated in the depletion region and drift under the effect of the applied electric field. The depletion region should be wide enough to achieve high quantum efficiency, but the thickness of the absorption layer should not be so large because the drift time through the depletion region increases, resulting in a decrease of the bandwidth of the Photodiode. This exemplifies the general compromise problem between the quantum efficiency and speed for almost all Photodetectors [12, 13].

2.2.2 PIN Photodetector (PIN-PD)

Photodetectors are one of the most popular types used in fiber optic communications. PIN-PDs performance has superseded that of P-N Photodiodes because it can be easily tailored for optimum quantum efficiency and bandwidth. The basic PIN-PD consists of three regions, heavily doped P+ and N+ layers and an intrinsic layer that is sandwiched between them. This intrinsic layer may have small residual n or p type background carrier concentration. A schematic cross section of back illuminated InP/InGaAs PIN-PD is shown in Figure 2.1.

The photon absorption takes place mainly in the intrinsic region that is depleted when reverse bias voltage is applied to its terminals. The collection process for the generated carriers is therefore fast and efficient. Thus, the intrinsic bandwidth is very high and the overall bandwidth that is limited by the extrinsic effects can be up to a few tens of GHz. Fabrication of PIN Photodetectors is relatively easy with well-established processes and the fabricated devices are very reliable and of low noise. Typically, PIN-PD's are combined with erbium doped fiber amplifiers (EDFAs) in order to increase the overall sensitivity or the receiver.

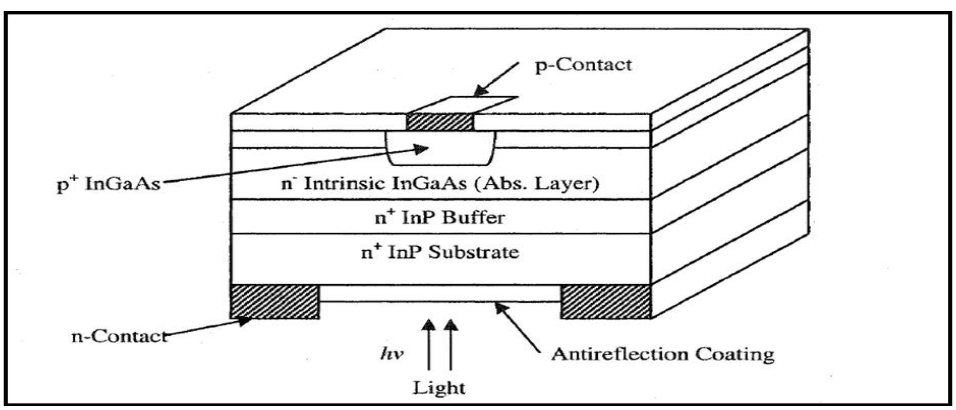

Figure 2.1: Schematic cross-section view of bock-illuminated planar InP/InGaAs PIN-PD [14].

Similar to the P-N Photodiode, the compromise problem between the quantum efficiency and the bandwidth is a major concern when designing a PIN-PD. For an optimized structure, the quantum efficiency-bandwidth product (*ή-BW*) is nearly constant the bandwidth can be increased from a few tens of GHz to 100-110GHz by using a matching network and decreasing the device size, but this reduce the quantum efficiency [14].

If a side-entry or a waveguide fed PIN-PD is fabricated, then the *ή-BW* product can be improved. A bandwidth of 172Hz and *ή-BW* product of 76GHz were demonstrated with the state of art waveguide Photodetector (WG-PD) which were a significant improvement over the conventional front entry devices [15]. This is achieved by a contact deigned to take into account a carrier distribution along the absorption on layer.

This *ή-BW* product can also be increased by inserting the PIN-PD inside a resonant cavity as in RCE-PDs where the quantum efficiency is enhanced even for a thin absorption layer due the reflections of the light through the bottom and the top mirrors of the cavity, resulting in the multi-passes of the light through the absorption Layer. High performance PIN-PDs use hetero junctions between different layers as the low bandgap InGaAs is suitable for absorption at 1.3-1.55µm wavelength and high bandgap InP layers on both sides act as windows at those wavelengths. Due to the hetero junction at the InGaAs/InP interface, potential barriers are created at the interface, causing the photogenerated carriers to be trapped there. The slow emission of carriers from the trap gives rise to a long tail in the time response of the Photodetector current which leads to a lowering of the bandwidth. To reduce the effective barrier height at the interface, grading layers of intermediate bandgap materials are used. The effective potential barrier is also a function of the applied reverse bias [16, 17]. The barrier height decreases gradually with applied bias until the barrier height vanishes for a large enough bias. The effective barrier height for electrons in the conduction band (ecd) is smaller than the effective barrier height for holes in the valence band (evd) and also electronic in the conduction band (ecd) vanishes earlier than valence band (evd) with bias. Thus, whole trapping is more important than electron trapping.

The incorporation of Ge into the base of a silicon bipolar transistor can significantly increase the bipolar transistors performances. It also provides access to a material with meaningful absorption at much longer wavelengths than native Si. In particular, it becomes possible to consider Photodetector diodes with both increased absorption and longer wavelength sensitivity. In a Ge 0.29 Si 0.71 waveguide P1N-PD operating at λ=1.31 µm is presented, such Photodetectors have operated in waveguide geometry, since the Si Ge region has a higher refractive index than Si and it can be used to form a waveguide in the Si material, thereby permitting significant absorption with smaller thickness of the Si Ge alloy. For this device, the internal quantum efficiency is about 27%, but the external quantum efficiency is still limited to 7% for 500 Mbits/sec. The dark current is 27 pA/µm2 while the responsivity of the Photodetector is 2.57 A/W.

A Ge 0.72 Si 0.28 PIN-PD with an area or 10x1000 µm2 for the detection of light at λ = 0.96 µm. This Photodetector suffers from very low quantum efficiency that is about 5% at 1 Gbits/sec. A dark current of 10 pA is achieved for this devices at -5 V is presented [18].

2.2.3 Avalanche Photodetector (APD)

The Avalanche Photodetectors (APD) is the most important Photodetector with internal gain that have been widely used in optical communication systems. They are commonly used for the detection of optical radiation of extremely low intensity as it is very sensitive to the incident optical signal [19]. There are many variations of APD's using Si and Ge. The APD's internal gain is realized by the Avalanche multiplication process that is achieved through impact ionization. The impact ionization phenomenon has been extensively investigated both theoretically and experimentally [19]. APD are operated under a sufficiently high reverse voltage to generate highly energized e-h pairs. Under a high electric field in the conduction band, the high energy electrons initially scatters with an electron in the valence band and knocks it out into the conduction band, resulting in multiplication of the number of electrons in the conduction band. Hence, the number of current carrying charges has multiplied in this avalanching process. This Avalanche process could also happen to high energy holes that excite extra holes. In the valence band, the required minimum carrier energy for causing impact ionization is the ionization threshold energy that should be larger than the bandgap energy.

The process of ionization is exponentially dependent on the magnitude of the electric field. The ionization coefficients defined as the inverse of the mean distance between ionization collisions. But the electrons and holes can lose energy in non-ionizing collision processes such as photon scattering. One carrier undergoing the impact ionization process creates a pair of free carriers. All three carriers get accelerated, and then continue to undergo impact ionization events and generate more free carriers. This process terminates when all the free carriers are swept out of the high electric field region. In the end, one initial electron or hole generates Mo extra e-h pairs, where Mo is called the multiplication gain of the Photodetector [20].

Therefore, an APD itself provides gain without the help of any amplifier, but its main limitation come from its bandwidth. Because of the long Avalanche build-up time, the inherent bandwidth of APD is small. However, they have attracted interest because their internal gain is suitable for communication systems with a minimum number of repeaters and also for dense wavelength division multiplexing systems. Besides, special structures can be used to improve the high frequency performance.

Unlike PIN-PDs even for moderate or high applied bias, the absorption layer may be at a low bias. This is because the multiplication layer should be under a high field for impact ionization. For the separate absorption, grading, charge and multiplication (SAGCM) APM), its structure is basically the same as in Figure 2.2, except that the absorption, grading charge and absorption layers occur in sequence. Thus, the interface trapping at the absorption layer ends will lead to low bandwidth. This interface trapping effect on the bandwidth of the APD is modeled in [21].

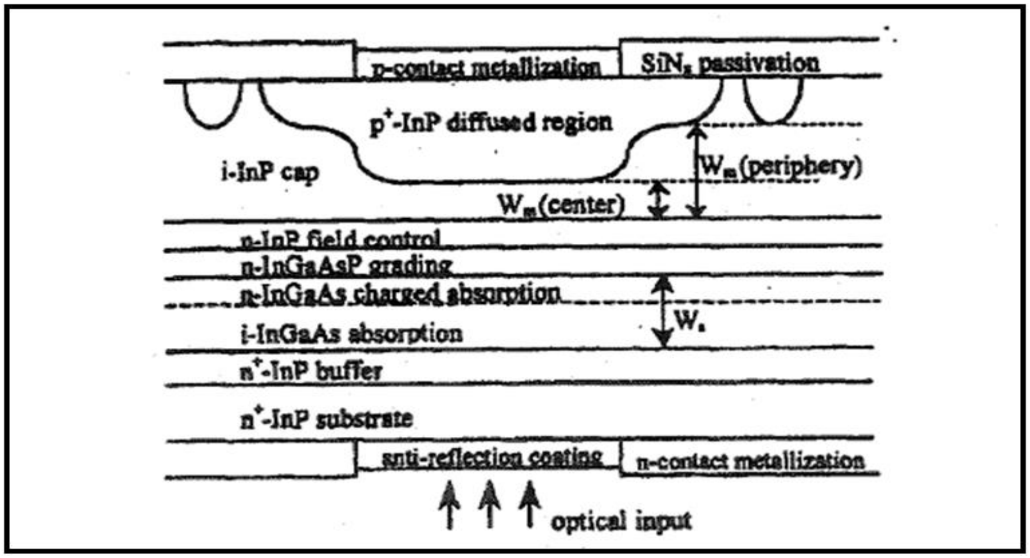

Figure 2.2: Schematic structure of a SACM APD device [21].

In a manufacturable bulk InP Avalanche Photodiode suitable for 10 Gb/s applications was introduced. It employs a separate absorption and multiplication (SAM) structure with a bulk InP multiplication layer and an InGaAs absorption layer. Three InGaAsP grading layers between the field control and absorption layer are included to minimize whole trapping resulting from the valence band discontinuity that forms at an InGAsa-InP hetero interface. Edge breakdown is controlled by shaping the diffusion profile using a double diffusion technique to create a wider multiplication region with higher breakdown voltage around the device periphery. The back illuminated geometry minimizes capacitance and dark current for a given optical coupling diameter [22].

2.3 High Speed Photodetectors Concept

An APD has its sensitivity advantage over a PIN Photodiode, high bit-rate fiber optical communication systems, due to its internal gain. The gain of an APD comes from a process called impact ionization, illustrated in Figure 2.3. APDs are essentially PINs that operate under high reverse bias. Photo-generated carriers travel in *he* high electric field region, gaining energy from the field. In k-space, these electrons occupy the energy states well above the bottom of the conduction band (E_c).

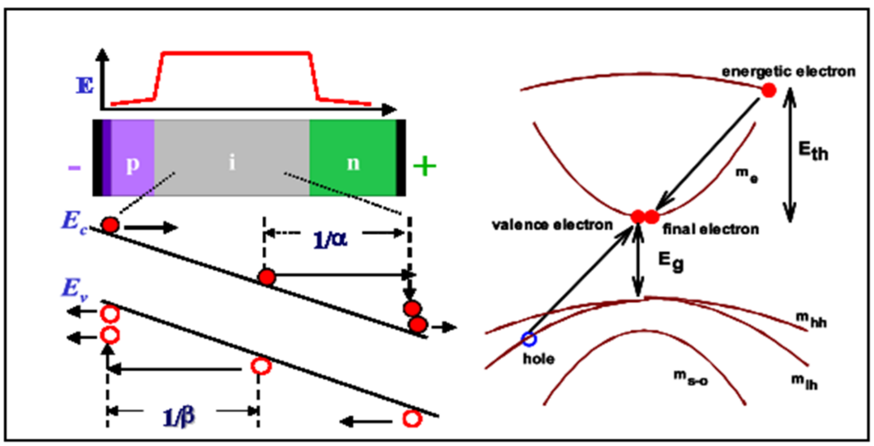

Figure 2.3: An illustration of the carrier impact ionization process. Left: The schematic, field profile and i-region band diagram of the simplest APD (PIN under high reverse bias) Right: impact ionization process illustrated in the *k*-space [23].

As shown in Figure 2.3, when the extra energy above E_c is greater than a specific value, which is referred to as the threshold energy, *Eth*, an energetic electron can impact with the lattice, stimulating a valence band electron into the conduction band, and leaving a hole behind. This creates an electron-hole pair. The secondary electron and hole can repeat this process by generating their own offspring. Through this impact ionization process, a photo-generated electron or hole can result in the generation of multiple electron-hole-pairs, resulting in Avalanche gain [23-26]. The electron and hole impact ionization coefficients α and β, respectively, are important parameters in characterizing multiplication region materials. In local field theory says the physical meaning of α (or β) is the average distance that an electron (or a hole) travels between two consecutive ionization events, as shown in Figure 2.3.

The gain of an APD comes at costs. An APD gain, bandwidth and excess noise level are all closely linked to the specifics of the impact ionization process. Since the multiplication process takes time to build up and die-out, an APD is often slower than a PIN Photodiode. As Avalanche gain increases, the Avalanche build up time becomes the limiting factor of APD speed [24]. The gain-bandwidth product is a constant in this regime, which is an important Figure of merit for APD speed performance. Another performance penalty is the excess noise over PIN shot noise. The excess noise originates from the stochastic nature of the impact ionization process, and is detrimental to the signal- to-noise ratio of an APD based optical receiver.

In this section, we briefly review the theories, both analytical and numerical, that have been developed to study the impact ionization process. These models have been used to better understand an APD performance.

2.4 Avalanche Photodetector (APD) versus PIN

The length of an optical link is determined by dispersion consideration or by the minimum signal that can be detected at a given transmission bit rate. As opposed to PIN Photodetectors, the internal gain of an APD helps to increase the signal-to-noise ratio (SNR) and thus the sensitivity of receivers that employ APD. This gain also relaxes the requirements on the following amplifiers in receivers.

The main noise sources of a PIN Photodiode are shot noise and thermal noise. Since these two noise sources are statistically independent, the total noise at a given bandwidth *B* may be expressed as:

$$\langle i^2{}_{PIN}\rangle = 2e\left(I^{-}{}_{ph} + I_B + I_D\right)B + \frac{4kTB}{R} \qquad (2.1)$$

Where I_{ph}, I_B, I_D are the photocurrent, background radiation and dark current, respectively, *R* is the equivalent resistor determined by both the device and the following input resistance of the amplifier. Typically, at the front end of a PIN receiver, as shown in Figure 2.4, this noise power is much less than the equivalent amplifier noise power, therefore the noise of the PIN does not appear in the SNR term in Figure 2.4. On the other hand, due to the statistical nature of the multiplication process that provides gain, the principle noise source of an APD is multiplication noise. According to local-field theory, the total equivalent noise of an APD can be written as:

$$\langle i^2{}_{AY\,AL}\rangle = \langle i^2{}_{thermail}\rangle + \langle i^2{}_{av}\rangle = 2e\left(I^{-}{}_{ph} + I_B + I_D\right)BM^2F + \frac{4kT}{R}B \qquad (2.2)$$

Where *F* is the excess noise factor, the figure of merit of APD for noise performance. *F* is a function of the Avalanche gain *M*.

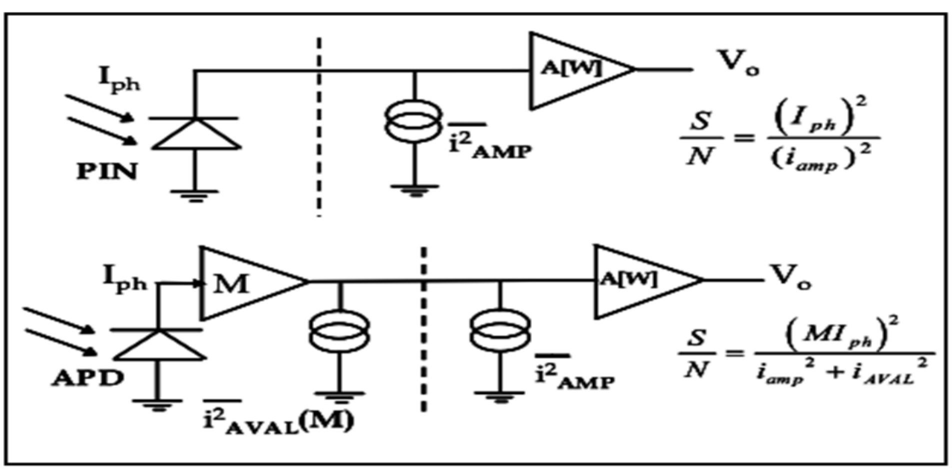

Figure 2.4: Signal-to-noise ratios for two configurations of the front-end of an optical receiver: Photodetectors (PIN or APD) with an amplifier [27].

Although the signal level is boosted by a factor of *M2* in an APD-amplifier configuration, the excess noise level must be reduced to achieve higher sensitivities as compared to PIN-amplifier combinations. As a result, APD with low excess noise factor, *F*, are preferred.

In comparison with PIN Photodiode, APD normally have more complicated structures, higher working voltages and increased temperature sensitivity. Additionally, APDs usually operate at lower speeds than PIN Photodiodes because the multiplication process takes time to build up and to decay. As seen from Figure 2.4, given that excess noise is low, improvements in the SNR of an APD lead to detection of very weak signals. This situation establishes a unique strong point for APD in optical communication systems, and also provides the fundamental motivation for studying low-noise APD.

2.5 APD Noise

2.5.1 Local Field Theory

The gain of an APD comes at a cost. Since the impact ionization process is a random process, there is some excess noise associated with an APD gain. Normally, the noise is described in terms of noise power spectral density (i^2), which is the quadratic mean of the noise current within a *1Hz* bandwidth. The most widely used APD developed this theory is based on the locality assumption, i.e. α, β, and the impact ionization probability distribution function (PDF) only depend on the local electric field in the multiplication region. In the local-field theory, α, β, and their ratio k ($k < 1$) is important in determining an APD performance. For a given gain, a smaller *k* ratio leads to a lower noise. The noise power spectral density in an APD is expressed as:

$$S = 2eI_{unity}\, M^2\, F\,(M)\, R\,(\omega) \tag{2.3}$$

Where *R (ω)* is the impedance of the device and the measurement circuit. *M* is the average multiplication gain, unity is the unity-gain photocurrent, and *e* is the electron charge. The excess noise factor *F(M)*, the measure of APD noise performance, is due to the gain fluctuation at the output and can be expressed as

$$F(M) = \frac{\langle M^2 \rangle}{\langle M^2 \rangle} = kM + (1-k)\,(s - \frac{1}{M}) \tag{2.4}$$

Where the local field model has been widely accepted for the past 35 years and has provided analytical formulas for describing an APD gain, excess noise, and bandwidth. It has been an effective theoretical tool for calculating the characteristics of APDs with thick (greater than 200nm) multiplication region. However, this model fails to predict the gain and noise of thin devices, where non-local models prevail [28, 29].

2.5.2 Non-Local Field Theory

The local field theory assumes that carrier ionization is a continuous, local process and that the ionization coefficients and probabilities are only determined by the local electric field. Therefore, the history of carriers is not taken into consideration. In reality, however, after an ionization event, a carrier needs to travel a certain distance, called the dead space, before it can gain sufficient energy and ionize again. The dead space is a function of the carrier ionization threshold energy and the electric field profile. In the models that take the dead space into account (non-local models), the carriers history (i.e. the process of scattering and gaining energy from the electric field) is included in the picture of Avalanche multiplication. The dead space can be neglected when it is small compared to the multiplication region thickness. When the multiplication region is reduced to merely a few times the dead length, the assumption of locality fails and a nonlocal model is needed. Many analytical and numerical models address the non-local nature of impact ionization in thin devices. Monte Carlo is a numerical technique that can take the carrier history into account when modeling impact ionization. Under non local model Equation (2.5) and (2.6) are still valid for calculating APD gain. But α and β have complicated expressions since they are history dependent [30]. As to the noise, low excess noise has been achieved by submicron scaling of the thickness of the multiplication region, *Wm*. But we still use *k* value solely for reference because the effective *k* value has been widely used as figure of merit for excess noise. As *Wm* is reduced, in order to maintain the same gain, the electric field intensity must increase in order to reduce the distance between ionization events. However, for high electric fields the electron and hole ionization coefficients tend to merge so that *k* approaches unity.

$$M_n = \frac{1}{1 - \int_0^W \alpha exp\left[- \int_0^W (\alpha - \beta\right] dx'} \tag{2.5}$$

$$M_n = \frac{exp\left[- \int_0^W (\alpha - \beta) dx\right]}{1 - \int_0^W \alpha exp\left[- \int_0^W (\alpha - \beta)\, dx'\right] dx} \tag{2.6}$$

Consequently, based on the excess noise expression in Equation (2.5), higher excess noise would be expected for the same gain. We recall, however, that the local field model is only valid when the dead space can be ignored; this has been proved not to be the case for thin multiplication regions. Since impact ionization is a stochastic process, it can best be described in terms of the probability distribution function (pdf), p(x), which is the probability per unit length that a carrier ionizes a distance x from the injection point or the point where it is created by another impact ionization event. For the local field theory, as shown in Figure 2.5 of part (a), the pdf for electrons is an exponential distribution in the form.

Figure 2.5 part (b) illustrates qualitatively how incorporating the dead space alters the pdfs. First we observe that the dead space length decreases with increasing field. As carriers transit the multiplication region they continuously gain energy from the electric field and lose energy by optical phonon scattering. At the highest field phonon scattering becomes less significant because the phonon energy is small, only a few tens of meV. As a result, the carrier transport becomes quasi-ballistic and the dead space length is to good approximation, equal to $E_{th}/_{qF}$ where E_{th} is the threshold energy for impact ionization, q is the electron charge and F is the electric field strength.

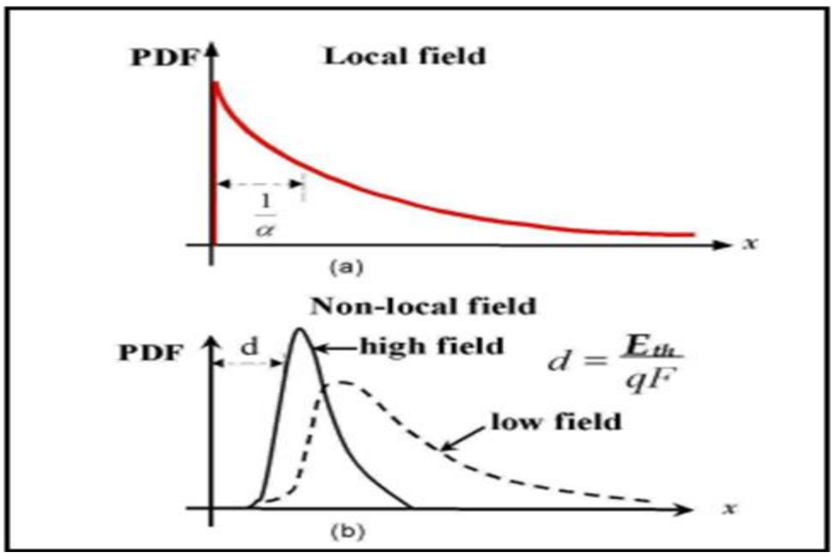

Figure 2.5: For (a) the local field model and (b) Inclusion of the dead space for high field (solid line) and low field (dashed line) [32].

The decrease in dead space length with increasing field tends to make it less significant at high fields. However, we note that the pdf also narrows significantly with increasing field. Since the width of the pdf decreases faster than the contraction in the dead space, the net result is that the ionization process becomes more deterministic, which reduces the variation in *M* and ultimately the noise.

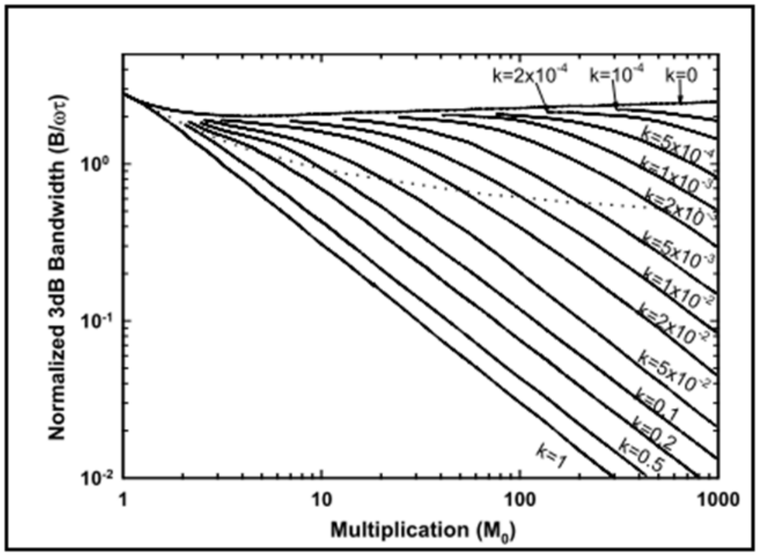

Figure 2.6: Bandwidth as a function of gain for different *k* values in a PIN structure, based on local field theory. The dotted line is the *M*=*k* curve [33].

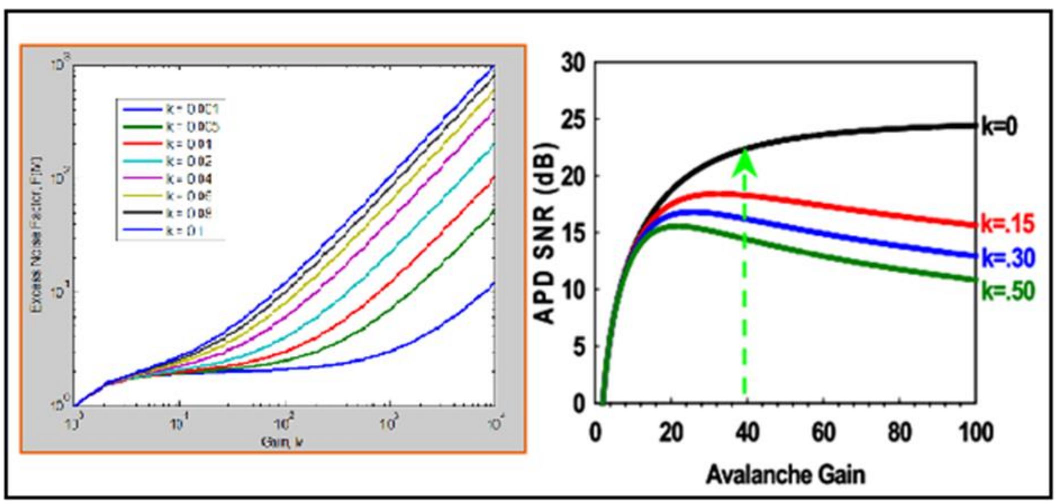

Figure 2.7: Excess noise factor *F(M)* (left) and signal-to-noise ratio (right) of an APD as a function of gain for different *k* values, based on local-field theory [34].

2.6 Responsivity, R

Consider the semiconductor slab shown schematically in Figure 2.8. If the energy *hv* of incident photons exceeds the bandgap energy, an electron–hole pair is generated each time a photon is absorbed by the semiconductor. Under the influence of an electric field set up by an applied voltage, electrons and holes are swept across the semiconductor, resulting in a flow of electric current. The photocurrent I_p is directly proportional to the incident optical power P_{in},

$$P_{in} = RI_p \qquad (2.7)$$

Where, *R* is the *responsivity* of Photodiode (in units of *A/W*). The responsivity, *R* can be expressed in terms of a fundamental quantity η, called the *quantum efficiency* and defined as:

$$\eta = \frac{electronic\ generation\ rate}{photon\ incident\ rate},\ \eta = \frac{\frac{Ip}{q}}{\frac{Pin}{hv}} \qquad (2.8)$$

Thus, $R = \frac{\eta q}{hv}$ (2.9)

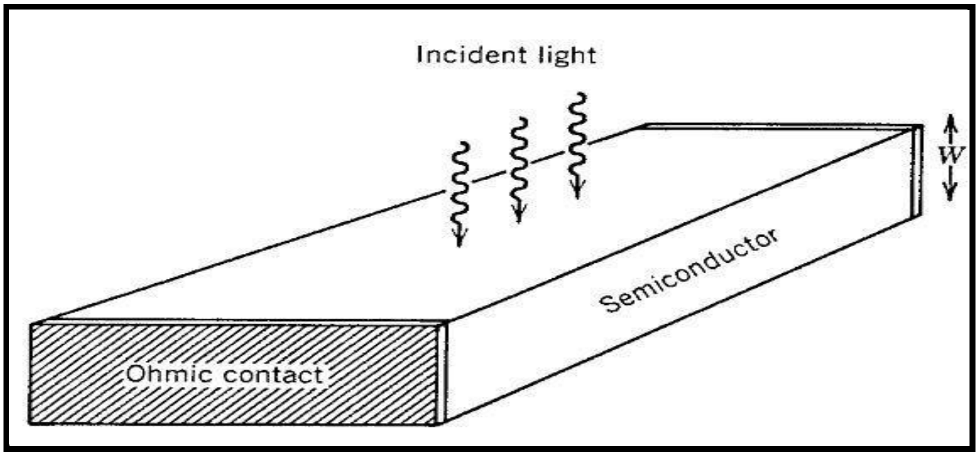

Figure: 2.8: A semiconductor slab used as a Photodiode [36].

APD can have $R \geq 1$ where other type of Photodiode does not have due to APD multiplication effect. Usually, a common Photodiode will have responsivity lower than 1 [36].

2.7 Design Procedure

Since optical communication systems are quite complex and difficult to analyze, it is useful to predict the effects of various parameters and characteristics of the Photodetectors used in optical systems prior to their practical their construction [37]. This work simulates the effects of varying parameters on the performances of both types of device. Such simulation, as a tool can accurately predict the performance of any proposed system to be implemented by analyzing the device under development in order to eliminate any performance degradation. The objective of the fiber optic link used is merely to transport data signals and from the device under scrutiny. We include in our system an optical fiber length, where we can simulate real fiber span. Throughout this work we use the Maximum Q-Factor as metric to assess all cases.

In the PIN Photodiode, the net noise is given by:

$$\langle i^2{}_{PIN}\rangle = 2e\left(I^-{}_{ph} + I_B + I_D\right)B + 4kTB/R \qquad (2.10)$$

The thermal (Johnson) noise is assumed to be *4kTB*, where *k* is the *Boltzmann constant* and *T* is the absolute Photodiode temperature *(K)*. Shot noise is assumed to be $\langle i^2{}_{PIN}\rangle = 2e\,(I_D)B$

Where *e* is the charge of an electron and I_D is the dark current. In the APD, the net noise is given by:

$$\langle i^2{}_{AY\ AL}\rangle = \langle i^2{}_{thermail}\rangle + \langle i^2{}_{av}\rangle = 2e\left(I^-{}_{ph} + I_B + I_D\right)BM^2F + \frac{4kT}{R}B \qquad (2.11)$$

The shot noise is assumed to be

$$\langle i^2{}_{AY\ AL}\rangle = \langle i^2{}_{thermail}\rangle + \langle i^2{}_{av}\rangle = 2e\,(I_D)BM^2F$$
(2.12)

Where *e* is the charge of an electron and I_D is the dark current. Due to the statistical nature of the Avalanche process, Avalanche Photodiodes generate excess noise *(F)*:

$$F = kM + (2 - \frac{1}{M})(1 - k) \qquad (2.13)$$

This excess noise factor (*F*) is a function of the carrier ionization ratio, *k*, where k is usually defined as the ratio of hole-to-electron ionization probabilities (*k* < *1*), and M is the multiplication gain. We have regenerated a conventional representation of equation (2.13).