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REVIEWS ON AVALANCHE PHOTODIODE FOR OPTICAL COMMUNICATION TECHNOLOGY

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ABSTRACT

This paper presents a review of avalanche photodiode in optical communication technology. Avalanche photodiode is one of photodiodes can be operated in high electric field in order to achieve high bit rate optical fiber communication systems. In long distance optical communication, the avalanche photodiode (APDs) is frequently the photo detector of choice owing to its internal gain, which provides a sensitivity margin relative to PIN photodiode. Previously, studies and research has improved the performance of APDs in optical communication systems, the research include development and improvement in terms of materials used in device structures of avalanche photodiodes. A review of Avalanche photodiode and the principle of avalanche photodiode work, as semiconductor will be discussed. This reverse bias device also used guard ring as is to remove the high electric fields and to drain the surface currents due to high reverse bias voltage. It also showed the mode of operation used in avalanche photodiode and potential materials that can be used optimum in looking for best avalanche photodiode. In last section, this paper reviews about future works in the research of avalanche photodiode.

Keywords: avalanche photodiode (APDs), III-V materials, guard ring, optical communication.

INTRODUCTION

The explosive spread of the internet has increased the demand for highly sensitive optical detectors for high-bit rate optical fiber communication systems. The avalanche photodiode is now finding acceptance in an increasing range of applications including optical communications, ranging, and laser systems. Its advantages lie in its small size, high quantum efficiency, internal current gain, high-frequency response, and it usually requires a relatively low supply voltage (Mun M.H, 2009) (Pin Jern Ker, 2012).

Avalanche photodiodes are p-n junction photodiodes purposely made to be operated at high electric fields in order to achieve an internal gain. In reverse biased photodiodes, the electric field increases with the applied voltage, causing the drift velocity and kinetic energy of charge carriers injected in the depletion region to increase (S.M. Sze *et al*., 2007).

By doing so, an electron (or a hole) can reach an energy high enough to break a bond when colliding with lattice atoms, thus generating a new electron-hole pair, and losing part of its energy in this process, which is called impact ionization (S.M. Sze *et al*., 2007).

Both the original carrier (electron or hole) and the secondary electron and hole will be accelerated by the electric field and possibly contribute to the generation of more electron-hole pairs, this resulting in a positive feedback loop which gradually increases the overall number of carriers, hence the term avalanche (S.M. *Sze et al*., 2007).

The avalanche photodiode is commonly used in optical communications system. The basic construction of avalanche photodiodes is very similar to that of a pin photodiode. The difference is that for every photon, which is absorbed by the intrinsic layer, more than one electron-hole pair may be generated (A. Biber *et al*., 2000).

As a result, avalanche photodiode have a photocurrent gain of greater than unity, while pin photodiodes are fixed at unit gain (A. Biber *et al*., 2000).

Joe C. Campbell *et al*., avalanche photodiodes (APDs) have been utilized for a wide range of commercial, military, and research applications. In recent years, the primary driving force for research and development of APDs has been focused on the uses of avalanche photodiode in optical communication. It is well known that the internal gain of APDs provides a higher sensitivity in optical receiver than PIN photodiode (Mun M.H, 2009).

Compared to PIN photodiodes, APDs can measure even lower level light and are used in a wide variety of applications requiring high sensitivity such as long distance optical communications and optical distance measurement. APDs are very suitable for long-distance fiber-optic communication, because less repeaters are required, thus drastically reducing the systems cost (B. E. A. Saleh *et al*., 1991).

In Figure-1, the avalanche photodiode structure is relatively similar to that of the more commonly used PN photodiode structure or the structure of the PIN photodiode. However as the avalanche photodiode is operated under a high level of reverse bias a guard ring is placed around the perimeter of the diode junction. This prevents surface breakdown mechanisms (Pallab Bhattacharya, 1997).

In a general photodiode light is absorbed on both sides of the metallurgical junction. For the wavelengths of interest, one electron-hole pair is generated for each absorbed photon. The minority carriers from these pairs either recombine or flow across the junction. The minority carriers, which cross the junction, constitute the photocurrent.

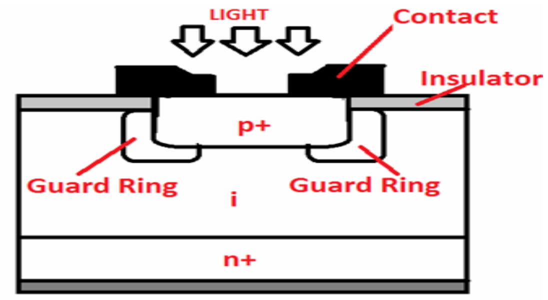

Figure-1. Avalanche PIN photodiode basic structure (Pallab Bhattacharya, 1997).

The situation in avalanche photodiode is the same except that the carriers crossing the junction acquire enough energy in the high field near the junction. They are enabled to ionize lattice atoms, thereby creating secondary pairs. The mechanism results in an increase of the signal current by the avalanche-multiplication factor (Steve Hranilovic, 2004). Overall APDs are very attractive device for their high sensitivity in low light level and even high-speed application such as long distance, optical communications and optical distance measurement factor (Steve Hranilovic, 2004).

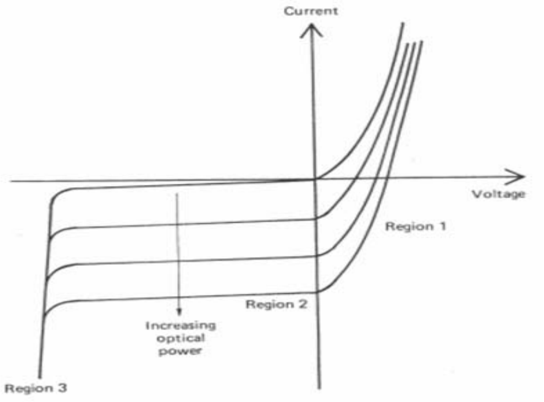

Figure-2. V-I characteristic of a photodiode, with varying amounts of incident optical power (Joe C. Campbell, 2007).

Figure-2 shows the I-V Characteristic of a photodiode where there are three operating regions: forward bias (region 1), reverse bias (region 2) and avalanche breakdown (region 3), through the following plot of the last equation for varying amounts of incident optical power. Forward bias in region (1) so-called photovoltaic mode, is not frequently used in optical links because the frequency response of the diode is poor.

In this mode, a change in incident power is resulted by a change in terminal voltage. Meanwhile reverse bias in region (2) so-called photoconductive mode, is mostly used for detectors in optical links. In this mode, a proportional change in diode current is produced by a change in optical power. In last region (3), Avalanche breakdown region, which is called avalanche photodiodes, APDs, has the V-I characteristic.

Therefore, in order to prevent spontaneous breakdown, the bias voltage has to be tightly controlled. In this region, avalanche breakdown is caused by a photo-generated electron-hole pair and results in a large diode current for a single incident photon (Joe C. Campbell, 2007).

Principle operation

In its most basic form, an APD is a strongly reverse biased pin photodiode. The strong reverse bias results in a strong electric field in the charge depleted i layer (depletion layer), which also refer to the avalanche multiplication layer. They operate in a fully depleted mode; the reverse bias creates a depletion region in the diode that extends from the junction through the absorption region where photons are absorbed. Absorbed photons create electron-hole pairs in the depletion region. Each charge carrier can acquire sufficient amount of energy, as they drift under the influence of the electric field to enable it to impact ionize, a process that results in the excitation of a new pair of offspring carriers that contribute to the electric current just as their parent carrier. Carriers are swept via drift toward a very high field region near the junction called the avalanche (multiplication) region. Here, carriers create additional e-h pairs through impact ionization, starting the chain reaction of avalanche multiplication; the internal gain mechanism of APDs. (www.radio-electronics.com/info/data/semicond/photo_diode/structures-materials).

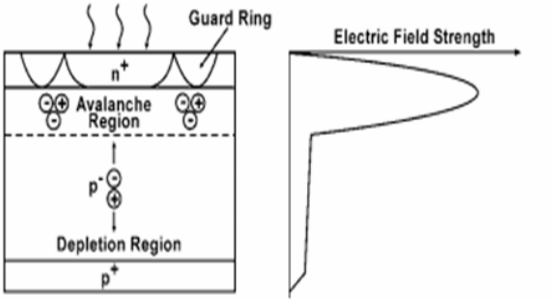

Figure-3. Basic operation APDs in reverse bias (www.radio-electronics.com/info/data/semicond/photo_diode/structures-materials).

In reverse biased photodiodes, the electric field increases with the applied voltage, causing the drift velocity and kinetic energy of charge carriers injected in the depletion region to increase. By doing so, an electron (or a hole) can reach an energy high enough to break a bond when colliding with lattice atoms, thus generating a new electron-hole pair, and losing part of its energy in this process, which is called impact ionization (S.M. Sze *et al.*, 2007).

In APDs the absorption of an incident photon first produces an e-h pair (electron to holes pair) just like in a PIN photodiodes. The large electric field in the depletion region causes the charges to accelerate rapidly. Such charges propagating at high velocities can give part of their energy in the valence band and excite it to the conduction band. This results in an additional e-h pair. These in turn can further accelerate and create more e-h pairs.

This process leads to an avalanche multiplication of the carriers (Sibley *et al*., 1995).

The process by which this gain arrives is known as avalanche multiplication of generated carriers. For avalanche multiplication to take place, the diode must be subjected to large electric fields. Thus, in APDs one uses several tens of volts to several hundred volts of reverse bias. A high intensity electric field is established in the depletion region. This field accelerates the generated carriers so that the collisions with the lattice generate more carriers. The field also accelerates the newly generated carriers, repeating the impact generation for carriers. In wired fiber networks, the amplifying effect of APDs improves the sensitivity of the receiver allowing for longer distances between repeaters in the transmission network (Sibley *et al*., 1995).

The basic configuration of avalanche photodiode operation is drawn in Figure-4. Based on, the theory from Marikina, the avalanche photodiode (APDs) operates under the principle of avalanche multiplication that occurs in reverse biased diode. It consists of heavily doped p+ and n+ regions. The depletion region is lightly doped, almost intrinsic. The light is made to incident on the depletion region and electron hole pair produced where electrons move towards the p region. Due to the strong reverse biasing, there is a depletion of charge carriers in the p region. The electrons in the p region undergo avalanche multiplication because of high reverse bias. The holes move towards the p+ regions without producing further multiplication. The avalanche photodiodes has better noise performance, because the carrier multiplication is limited to electrons only. The diode is reversing biased using 50 to 300V (M M Hayat, 2011).

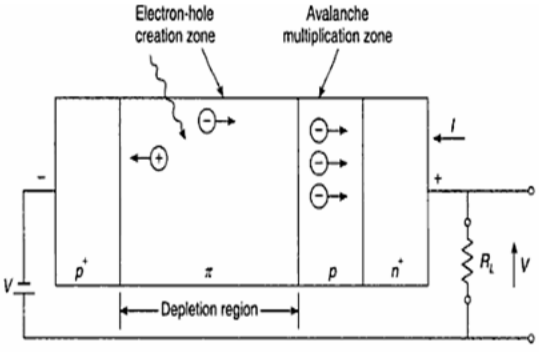

Figure-4. Avalanche photodiode configuration (M M Hayat, 2011).

The avalanche photodiode has a number of differences when compared to the ordinary p-i-n diode. APDs differ from PIN photodiode designs in having additional p-type layer between the intrinsic and a highly doped n region. The e-h pairs are still generated in the i region but the avalanche multiplication takes place in the p-type region. The avalanche process means that a single electron produced by light in the un-doped region is multiplied several times by the avalanche process. As a result the avalanche photo diode is far more sensitive (S.M. Sze *et al*., 2007).

APDS STRUCTURES

Among the commercially available avalanche photodiodes, the three most common structures are: bevelled edge diode, reach through diode and guard ring diode (Gian-Franco Dalla Betta *et al*., 2011).

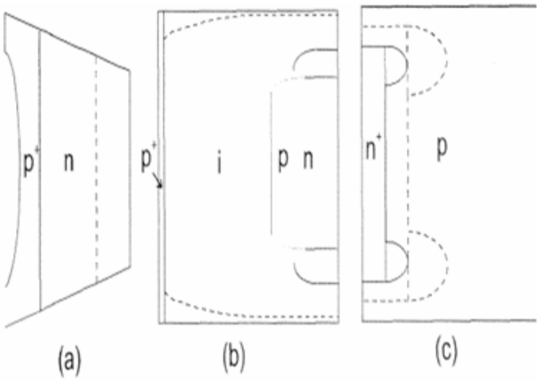

Figure-5. Commercially available silicon avalanche photodiodes (a) bevelled edge, (b) reach-through, (c) guard ring structure (Steve Hranilovic, 2004).

The bevelled edge diode in Figure-5(a) is a p+-n junction. In this diode, the breakdown voltage is very high at 1800-2600 V. Such high breakdown voltage devices have strong electric field values with the large depletion region, allowing gains of up to several hundred. The depletion region is very wide, typically 250 µm and the junction depth is between 50 and 75 µm. The dark current generated in the n region is not multiplied significantly since this current is due to holes, which have a lower ionization rate than electrons. Due to its structure however, the response is slow but with high gain for short wavelengths (below 0.9 µm). The same device has a very fast response but low gain for longer wavelengths (over 0.9 µm) (Gian-Franco Dalla Betta *et al*., 2011). Device operation is near the breakdown voltage, but not above it since the large dark current would lead to thermal runaway (Steve Hranilovic, 2004).

The reach through diode (Figure-5(b)) has been developed extensively by company like Radio Corporation of America, RCA (Gian-Franco Dalla Betta *et al*., 2011). The high speed and high gain are combined with low noise. The trick in this diode is to separate the depletion region into two different areas: a wide drift region for absorption and a narrow multiplying region for multiplication. The applied voltage causes the depletion region to extend rapidly through the lightly doped n region all the way to the backside p+ contact. The field in this device increases only slowly, also due to the lightly doped region. At 100 V reverse bias it is possible to have a 200µm depletion region (Steve Hranilovic, 2004).

The last type of common diode is the guard ring diode in Figure-5(c). This type of diode is often used in dedicated APDs because the structure is inherently compatible with planar technologies such as CMOS. This device can be made with n+ on p or p+ on n or even an Schottky barrier. The depth of the junction is fairly small, usually less than 2 µm, but the depletion region can be extended to as thick as 10 µm, depending on the doping concentration. Thus, this silicon guard ring structure works well in the wavelength range of 0.6 to 0.8 µm.

Light of longer wavelengths tends to penetrate deeper, generating a good number of carriers in the depletion region. The strong electric field that resides there sweeps the carriers across the junction at which point they contribute to the photocurrent. Light of even longer wavelengths penetrates even deeper generating carriers in the area below the depletion region (A. Marikani, 2009). Electron hole pairs generated in the high field region of the diode are detected more quickly than generated pairs, which have to diffuse to the depletion region first. The carriers collected by diffusion are slow and contribute to the low frequency response only. As an example, a high frequency response with 30% quantum efficiency is possible at 0.9 µm, whereas at 1.06 µm the response only has 1-2% quantum efficiency (Steve Hranilovic, 2004).

Basically, a guard ring is normally been used in avalanche photodiode. Guard ring means an electrically biased field plate or surrounding diode used in some photodiodes. It normally used to control surface recombination effects and thus reduces the leakage current in the detection circuit (Steve Hranilovic, 2004).

Guard ring

A guard ring structure is provided on certain photodiodes intended for high voltage operation and takes the form of an isolation ring surrounding the active area. When this is biased at a similar potential to the photodiode then the surface leakage current from the periphery of the active area is minimized. A guard ring offers most significant benefits when it is necessary operates at very high bias voltage and has little or no effect in most cases when it biased below than 50 volts. In the stage of high-speed optical communications, researchers focused their research on maintaining breakdown voltage because APDs are operated near breakdown voltage. Commercially available APDs use deep guard rings to prevent breakdown at the periphery of p-n junction (Alice Irene Biber, 2005).

Figure-6 shows the basic of APDs configuration. Their main difference from a regular photodiode is the addition of guard rings at the junction perimeter to control leakage current under high bias. The guard ring profile must have a low impurity gradient with a sufficiently large radius of curvature such that the guard ring junction will not breakdown before the central p+-n junction does (S.M. Sze *et al*., 2007).

For the metal semiconductor APDs, a guard ring must also be used to eliminate high electric field concentration at the periphery of the contact based on Figure-6. A mesa or beveled structure can have a low surface field across the junction and uniform avalanche break down occur inside the device. This is more common for compound semiconductor device due to their inferior planar technology. To detect wavelength near the intrinsic absorption edge, a side illuminated APDs can be used to improve both the quantum efficiency and the signal to noise ratio (S.M. Sze *et al*., 2007).

It is easy to use two separate diffusion processes to form an n-type guard ring and n+-p active junction in Si. Under a breakdown bias, the thickness of the depletion layer is normally several microns, and is smaller than the depth of the guard ring. This structure is suitable for detecting relatively short wavelength (0.4-0.8µm) photons. Through the guard ring enhances the devices breakdown voltage. It also increases the device capacitance, and hence is disadvantageous for high-speed applications (S.M. Sze *et al*., 2007).

A guard-ring structure is required to obtain a uniform high gain in the photosensitive area. A planar structure with guard ring is anticipated to improve the leakage dark current and to obtain high reliability in system application. The guard ring can be provided by a graded junction, whose breakdown voltage is higher than that of an abrupt junction for the photosensitive area. A diffusion technique of p-type impurities in n-InP is considered to be appropriate for guard-ring formation in an InP- APD and an InGaAs/InP SAM-APD (S.M. Sze *et al*., 2007).

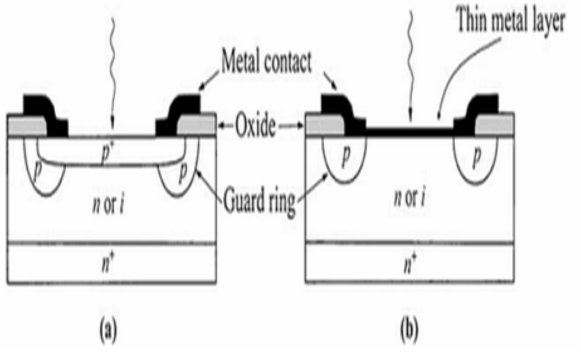

Figure-6. Basic device configurations of avalanche photo diodes (a) p-n or p-i-n structure b) metal semiconductor structure (S.M. Sze *et al*., 2007).

P-type diffusions in InP, Zn, and Cd are well known, some experimental results have been reported. It had been carried out in a relatively high-temperature range. Recently, a planar-type InP-APD with a guard ring was fabricated by low-temperature Zn diffusion, and high multiplication characteristics were realized uniformly in the photosensitive area. A similar guard-ring effect was also reported in low temperature Cd diffusion. Low-temperature Zn and Cd diffusions are appropriate for the formation of a guard ring, while an abrupt junction suitable for the photosensitive area is obtained by high-temperature diffusion (S.M. Sze *et al*., 2007) (Tatsunori shirai *et al*., 1982).

To produce a planar InP/InGaAs (P) APD, a guard ring and an active region must be included in this thin InP layer. A guard ring is usually formed by a linearly graded junction to achieve a higher breakdown voltage rather than in the active region where it is formed by an abrupt junction. An abrupt junction can be formed by diffusion of cadmium (Cd) and zinc (Zn) which are generally used to form the p+-region in n-InP (Tatsunori shirai *et al*., 1982).

The avalanche photodiode in CMOS uses lighter doped p-base material as the guard ring. The circular geometry avoids locally enhanced edge effect at the corners. The lighter doped guard ring and the larger radius of curvature reduce the electric field. Thus, the breakdown voltage in this region is increased, protecting the device from breakdown at the edge. For low noise multiplication, only one type of carrier should continue avalanching. In silicon at room temperature, the primary carrier should be an electron since the electron ionization probability is larger than that of holes. Thus, the noise behavior of the n+p diode should be better than the p+n diode. Unfortunately, the n+p diode does not allow a low voltage readout node. Therefore, the p+n diode was selected (A. Biber *et al*., 2000).

EFFECT ON DIFFERENT MATERIAL IN AVALANCHE PHOTODIODE

The materials used in avalanche photodiode structure have a major effect on determining the characteristics of the avalanche photodiode. There are three main materials that been used in avalanche photodiodes, germanium, silicon and group III-V compounds.

Germanium can be used for wavelengths in the region 800 - 1700 nm. This material has high level of multiplication noise. Besides that, silicon can be used for wavelengths in the region between 190 - 1100 nm. Diodes exhibit a comparatively low level of multiplication noise when compared to those using other materials, and in particular germanium. Indium gallium arsenide can be used for wavelengths to 1600 nm and has a lower level of multiplication noise than germanium (Pallab Bhattacharya, 1997).

For optimum noise performance the large difference in the ionization coefficients for electrons and holes is needed. Silicon provides a good noise performance with a ratio between the different coefficients of 50. Germanium and many group III-V compounds only have ratios of less than 2. While the noise performance of these materials is much inferior, they need to be used for longer wavelengths that require the smaller energy gap offered (Pallab Bhattacharya, 1997).

Due to silicon photodiode's low absorption rate above 1100 nm because of the silicon band gap, germanium and alloys of similar compound semiconductors are used to replace silicon for the used in the 1300 to 1500nm range (Pallab Bhattacharya, 1997).

The structure of a basic germanium avalanche photodiode is shown in Figure-7. Figure-7 showed that the diode consists of a lightly doped p-type germanium substrate surrounded by an n-doped guard ring with p-n junction produced on the surface by diffusion or ion implantation. An anti-reflective coating like silicon oxide can increase the quantum efficiency of the diode (P. P. Webb, 1974). The avalanche photodiode in CMOS uses lighter doped p-base material as the guard ring. The circular geometry avoids locally enhanced edge effect at the corners. The lighter doped guard ring and the larger radius of curvature reduce the electric field.

Thus, the breakdown voltage in this region is increased, protecting the device from breakdown at the edge. For low noise multiplication, only one type of carrier should continue avalanching. In silicon at room temperature, the primary carrier should be an electron since the electron ionization probability is larger than that of holes. Thus, the noise behavior of the n+p diode should be better than the p+n diode. Unfortunately, the n+p diode does not allow a low voltage readout node. Therefore, the p+n diode was selected (A. Biber *et al*., 2000).

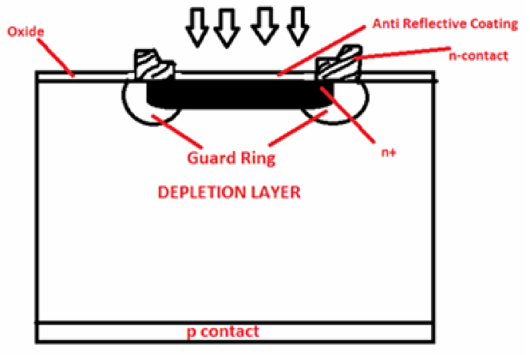

Figure-7. Basic germanium avalanche photodiode structure (P. P. Webb, 1974).

Basic silicon photodiodes are very suitable for optical receivers because of their small capacitance and low dark current noise. However due to their absorption rate being limited by the silicon band gap, for silicon avalanche photodiode are normally restricted to use in the 800 to 900nm range.

Figure-8 shows the structure of a silicon avalanche photodiode. Light passes through p-layer (which is protected by a thin coating of silicon nitrate to prevent reflection losses) and separation of carrier pair is achieved in the depletion layer (electrons to the n-side and holes to the p-side) (P. P. Webb, 1974).

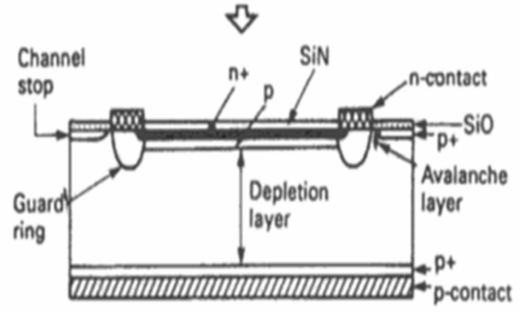

Figure-8. Basic structure of silicon avalanche photodiode (P. P. Webb, 1974).

Figure-9 shows InP based devices. Normally it is used for the wavelength range of 1.2-1.6μm. The example is APD with separated absorption and multiplication region p+ -InP/n -InP/n -InGaAsP/n+ -Inp, which is similar to the Si reach throuch devices. The absorption occurs in the relatively wide InGaAsP layers and avalanche multiplication of the minority carriers proceeds in the n-InP layer (www.perkinelmer.com/CMSResources/Images/44-3447APP_Photodiodes.pdf).

The example of III-V material combination in avalanche photodiode is as in Figure-9. Indium Phosphide (InP) is widely used as the multiplication layer material in commercially available APDs for applications in the 0.9-1.7 μm wavelength region with In0.53Ga0.47 As grown lattice-matched to it as the absorption layer. It has been predicted that Indium Aluminium Arsenide In0.52Al0.48As will replace InP, as a more favourable multiplication layer material due to its lower excess noise characteristics (Kinsey *et al*., 2000).

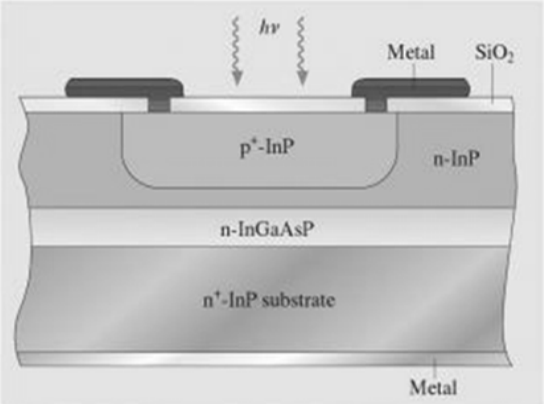

Figure-9. A cross section of a typical APD structure base on III-V compound (www.perkinelmer.com/CMSResources/ Images/44-3447APP_Photodiodes.pdf).

In comparison to InP, tunnelling currents remain lower in InAlAs due to its larger bandgap. While holes ionise more readily than electrons in InP, the opposite holds true for InAlAs and InGaAs, as electrons ionise more readily than holes, thus. making the InGaAs/InAlAs combination superior to InGaAs/InP in a SAM APD, in terms of lower excess noise, higher gain-bandwidth product, and improved sensitivity (Ray Tricker, 1990).

The multiplied dark current increases faster with applied voltage than one would expect from a normal avalanche multiplication. Although devices may have quite low reverse bias dark currents at 0.5 and 0.9 of the breakdown voltage, the dark current becomes very large in the region of useful avalanche gain. These materials with k values near to unity are close to breakdown. The implication is that the dark current can be reduced to an acceptable level only by keeping the high field region to low-doped with large band-gap material.

GaAs based devices is one of examples material that can be used in avalanche photodiode. When using GaAs based devices, the gain wills increases more due to avalanche effect that happened in GaAs layer. GaAs/ Al0.45 Ga0.55As structures are used below 0.9 μm. Meanwhile by applying InGaAs layers in avalanche photodiode, it will allow the sensitivity to extend nearly to 1.4 μm (Ray Tricker, 1990).

InP based devices are used for the wavelengths between 1.2 to 1.6 μm. The example of III-V material combination in avalanche photodiode is as in Figure-9. Indium Phosphide (InP) is widely used as the multiplication layer material in commercially available APDs for applications in the 0.9-1.7 μm wavelength region with In0.53Ga0.47As grown lattice-matched to it as the absorption layer. It has been predicted that Indium Aluminium Arsenide In0.52Al0.48As will replace InP, as a more favourable multiplication layer material due to its lower excess noise characteristics (Daniel *et al*., 2011).

In comparison to InP, tunnelling currents remain lower in InAlAs due to its larger bandgap. While holes ionise more readily than electrons in InP, the opposite holds true for InAlAs and InGaAs, as electrons ionise more readily than holes. Thus making the InGaAs/InAlAs combination superior to InGaAs/InP in a SAM APD, in terms of lower excess noise, higher gain-bandwidth product, and improved sensitivity (Ray Tricker, 1990). Studies have also shown that the breakdown voltage of InAlAs APDs is less temperature dependent compared to InP (Kinsey *et al*., 2000)., which would be useful in temperature sensitive applications, thus making temperature control less critical (Daniel *et al*., 2011).

This compound has shown many advantages as alternatives to germanium and silicon device. By adjusting the alloy composition, the wavelength response of the device can be tuned. The high absorption among the direct bandgap of III-V compound can have high quantum efficiency even a narrow depletion width is used to provide high-speed response (Daniel *et al*., 2011).

As can be seen, depending on the integrated photodiode the spectrum ranging from 400 - 1100 nm (Si diodes), 1100 - 1650 nm (InGaAs diodes), or 800 - 2100 nm (Ge diodes) can be detected very efficiently up to a bandwidth of 3.5 GHz. In addition, Keiser et.al concluded that Si devices that operate around 850 nm provide relatively inexpensive solutions for short-distance links. InGaAs based devices are used for longer links as an operating in the 1300-nm and 1550-nm windows is usually required for these links (Tan *et al*., 2010).

By using the separate-absorption-and-multiplication (SAM) to InGaAs APDs or PINs, InGaAs will show high performance. In order to improve the performance of InGaAs APDs or PINs various complex device architectures have been devised. One widely used structure is the separate-absorption-and-multiplication (SAM) APD configuration (Tan *et al*., 2010).

This structure uses different materials in the absorption and multiplication regions, with each region being optimized for a particular function. Variations on the SAM structure include adding other layers to the device. These include by using a grading layer between the absorption and multiplication regions to increase the response time and bandwidth of the device. Then by adding a charge layer that provides better control of the electric field profile, incorporating a resonant cavity that decouples the optical and electrical path lengths to achieve high quantum efficiencies and wide bandwidths simultaneously (Tan *et al*., 2010).

The material of InGaAs has the lowest rise time. So, it is faster than Si and Ge. Low band-gap means that photodiodes exhibit a high leakage current (>100 nA). InGaAs has the biggest band-gap (1.42 eV) and direct as well. So, it has the lowest leakage current and is used in long-haul routes. At long wavelengths, > 1 µm, detectors for 1.3 and 1.55µm wavelengths must be made out of low band-gap materials. Germanium has a band-gap of 0.67 eV, corresponding to a cut-off wavelength of 1.85 µm, and so would appear to be a suitable material. However, the low band-gap means that Ge photodiodes exhibit a high leakage current (> 100 nA). As the dark current is an additional source of noise, and so Ge photodiodes are rarely used in longhaul routes. The InGaAsP emits light in the band of 1.0-1.7 µm. Thus detectors made of a similar material should respond to 1.3 or 1.55 µm light (Tan *et al*., 2010).

InP/InGaAs avalanche photodiode review

A research on the transmitting speed in optical communication system is investigated vividly to increase the transmitting capacity. If the transmitting speed is up to Gb/s, the additive noise is also increased exponentially at the end point of receivers. In order to Figure out this problem, the avalanche photodiode (APDs), which is a photo detector with internal gain, have been widely researched and developed for optical receiver modules. The researches on APDs are focused on performance improvement of devices through bandgap engineering and optimization of device structures using InP compound semiconductor applied for optical communication system (Bongyong Lee *et al*., 2002).

Initial development of III-V compound avalanche photodiodes (APDs) was driven by fiber optic telecommunications, primarily for high-bit-rate, long-haul receivers. Compared to receivers with p-i-n photodiodes, those that utilize APDs achieve 5-10 dB better sensitivity. The recent increase in information traffic requires optical communication systems to operate at 10 Gb/s for local area networks (LANs) and metropolitan area networks (MANs). High-speed InGaAs/InP avalanche photodiodes (APDs) are preferred over p-i-n photodiodes, especially in long-haul applications, owing to their internal gain, which increases the sensitivity of an optical receiver. Various APD structures have been proposed with regard to device performance and reliability (Bongyong Lee *et al*., 2002).

Semiconductor photodetectors based on InP materials are the ones most often used in state of the art long wavelength optical fiber communication system. Mixed compounds such as InGaAs (P) and In (Al) GaAs lattice matched to InP are the materials responsible for detecting long wavelength light, specially the nondispersion wavelength (1.3 µm) and loss minimum wavelength (1.55 µm) of silica optical fibers. The characteristics of these InP-based photodectors are superior to those of conventional photodiodes composed of elemental Ge, which was the only material applicable for wavelengths below 1.55 µm (Alice Irene Biber, 2005).

By using a heteroestructure, which hadn't been expected in group IV elemental semiconductors such as Si and Ge, new concepts and new designs for high performance photodetectors have been developed. For example, the absorption region can be confined to a limited layer and the InP wide bandgap layer can serve as a transparent layer for specific communication wavelength (Kinsey *et al*., 2000). Recently InGaAs/InP avalanche photodiodes (APDs) with a SAM (separation of absorption and multiplication) configuration have become commercially available (S.M. Sze *et al*., 2007). (Bongyong Lee *et al*., 2002) (Kinsey *et al*., 2000).

The SAM configuration is thought to be necessary for high performance APDs utilizing long wavelengths. The InP/InGaAs avalanche photodiode (APD) is the one of key components in optical fiber communication systems. With the progress of semiconductor processing technology, avalanche photodiodes based on InP/InGaAs are used for high speed optical communication system (Kinsey *et al*., 2000).

The photodiodes may be operated under reverse bias, thus high quality semiconductor layers need to be produced. To obtain photodiodes that operate at a low bias and have a low dark current, it is necessary to produce epitaxial layers that are pure and have few defects (such as dislocations, point defects, and impurity precipitates) (Kinsey *et al*., 2000).

To get stable and uniform gain in APDs, in which internal gain is achieved through the carrier avalanche process, the layers in the avalanche region must be uniform and free of dislocations. Furthermore, a planar device structure requires that a guard ring be used to keep the electric field around the photoreceptive area from increasing too much. Fabrication and processing technologies such as impurity diffusion, ion implantation, and passivation will also play important roles in the production of reliable photo detectors (Kinsey *et al*., 2000).

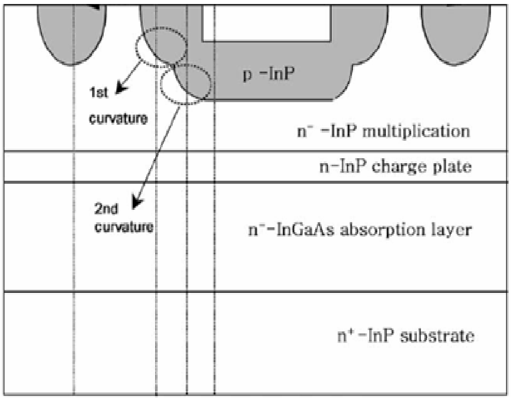

Figure-10. Schematics design for InP/InGaAs avalanche photodiode (Daniel *et al*., 2011).

A separate absorption, grading, charge, and multiplication (SAGCM) structure has been widely adopted for these applications due to its low dark current, high quantum efficiency, and high gain-bandwidth product. The light absorption and the carrier multiplication processes are separated from each other in the absorption and the multiplication layers, respectively. The charge layer provides a high electric field for the multiplication region and a low electric field for the absorption region to prevent the tunneling of current. The grading layer helps carriers generated in the absorption layer to be easily transported into the multiplication layer. The multiplication region of an APD plays a critical role in determining the gain-bandwidth product, as well as the breakdown voltage, which are two importance characteristics of APDs. Another benefit of the SAGCM-APD structure is that only a single type of carrier is injected into the multiplication region, which greatly reduces the multiplication noise arising from the stochastic nature of the multiplication process (Joe C. Campbell *et al*., 2004).

A SAGCM-APD operating at 10 Gb/s demands a combination of good crystal quality, careful design, and a high degree of process control. At high gain or high bias, the most significant limitation on the bandwidth of APDs is the avalanche buildup time, which is a function of the gain, the thickness of the multiplication region, the electron and the hole velocities, and the physics of the ionization process. It has been evident that a practical way to reduce the avalanche build up time is by decreasing the thickness of the multiplication layer. The reduction of the avalanche build up time in APDs with thin multiplication layers is primarily due to the reduction in the carrier’s transit time across the thin multiplication layer (Joe C. Campbell *et al*., 2004).

For APDs with thin multiplication layers, the conventional avalanche multiplication model, the so-called local model, does not account for the dead-space effect, so it will not be able to accurately predict the major performance values, such as the gain, the excess noise, the bandwidth, and the breakdown voltage. Furthermore, the electric field in the multiplication layer required to achieve sufficient gain increases as the layer thickness decreases, which in turn can lead to a tunneling leakage current and an early breakdown at the junction periphery. Thus, a very careful structural design using accurate models is essential to realize high-performance and high-speed APD (Joe C. Campbell *et al*., 2004).

The design of APDs is a particularly rich and active area of research, with many possible design options and potential material choices. The simplest implementation of an APD is a p-i-n photodiode operated under sufficiently high reverse bias so as to cause the photogenerated electron hole pairs (EHPs) to impact the ionization in the depletion region (Joe C. Campbell *et al*., 2004).

Since the choice of materials that can be used for the absorption region is constrained by the wavelength to be detected, compromise in the gain performance to achieve adequate absorption performance is inevitable in this simple structure. The noise performances of such a simple device in most relevant compound of semiconductors are poor. Consequently, structures that separate absorption and gain processes are generally favored. It can be shown that the best avalanche multiplication noise performance is achieved in materials for which avalanche processes are dominated by one carrier type only (Joe C. Campbell *et al*., 2004).

APDS ACT IN OPTICAL COMMUNICATION

The avalanche photodiode (APD) is widely used in optical fiber communications (Mun M.H, 2009) due to its ability to achieve high internal gain at relatively high speeds and low excess noise (Ana Luz *et al*., 2011), thus improving the system signal-to-noise ratio. Its internal mechanism of gain or avalanche multiplication is a result of successive impact ionization events. In an optical receiver system, the advantage of internal gain, in the APD, is experienced when the amplifier noise dominates that of a unity-gain photodiode. This increases the signal-to-noise ratio (SNR) and ultimately improves the receiver sensitivity as the gain increases until the APD noise rises to become dominant (Ana Luz *et al*., 2011).

The rapid growth of the fiber-optic telecommunication industry over the past several years has prompted two trends for increasing system capacity: first, wavelength channel counts are ever increasing at narrower channel spacing; and concurrently, the transmission speed continues to increase for each individual channel (Ana Luz *et al*., 2011).

The digital optical receiver is an indispensable component in fiber optic telecommunication links since it enables conversion of data from the optical to the electrical domain. High capacity in transmission system which support data rate 10Gb/s and the receiver performance parameters like sensitivity, return loss, delay, overload power and bandwidth are among the stringent requirement on receiver performance parameter (Ana Luz *et al*., 2011) .

Basically double heterostructure InGaAs/InP positive intrinsic negative (PIN) photodiode are commonly been used in 10Gb/s receiver modules The photocurrent of a PIN detector is primarily governed by its inherent quantum efficiency, and at best, each incident photon can generate a single electron-hole pair to contribute to the total photocurrent. Using avalanche photodiode can solve the problem of quantum limitation in the PIN detector. This is because an avalanche multiplication region with high electric field intensity is incorporated in the APD layer structure, where injected primary charge carriers accelerate and generate additional electron hole pairs through impact ionization. The average number of electron-hole pairs resulting from each absorbed photon is referred to as the multiplication gain M, and the total photocurrent of an APD is larger by a factor of M than that of a PIN diode with comparable absorption properties (Ana Luz *et al*., 2011).

In term of industrial world, a review of two biggest semiconductor companies like IBM and Intel in investigation of the best characteristics APDs in order to optimize design has been done. IBM has come up with a new way of removing noise from germanium-based photo detectors. The device is the fastest, which is converting optical signals at 40 Gbps about four times faster than the best conventional detectors. What is more, its small size means that it operates with just a 1.5 V power supply, compared with the 25 V of previous devices. These devices are used in telecommunications networks and the work is an important advance in the field of optical communications. The photo detector is made using germanium, which is compatible with silicon-chip-making technology and could therefore find use in next-generation high-performance computer systems (Osayd Kharraz *et al*., 2012).

Meanwhile Intel has collaborated with partners to develop a silicon-based avalanche photo detector (APD). The result of Intel's avalanche photo detector has a gain-bandwidth product of 340 GHz. Intel's avalanche photo detector breakthrough represents the first time that a silicon photonic device beats an equivalent made from traditional optical materials and this silicon-based avalanche photo detector has the highest gain-bandwidth product ever seen (340 GHz). The gain-bandwidth product is a standard measure for APD performance. This means that Intel's new APD device has the capability to detect signals at higher speeds and lower power levels than commercial APDs today. This breakthrough creates the possibility of using APDs for 40 Gbps optical communication (Osayd Kharraz *et al*., 2012).

CONCLUSIONS

Optical receivers for telecommunications have pushed the development of APDs with high bandwidth, low excess noise, and high gain bandwidth products. In the past decade, the performance of APDs for optical fiber communication systems has improved as a result of improvements in materials and the development of advanced device structures. Avalanche photodiode is better than PIN in term of long distance communication application, which is popular, and trends in long haul communication. From the review, we can see the development of avalanche photodiode in term of guard ring and materials that been used. The III-V materials are popular nowadays because their own characteristics like wavelength, noise, efficiency and helping giving the best performance to the photodiodes

Future works may include on design the schematic of avalanche photodiode by using TCAD and analyze the characteristics of IV in term of uses in optical communication and also RF signal. The TCAD software will include the analysis on ATHENA and also ATLAS.

In the future research, we will investigate the effect of variation type of guard ring in term of performance and efficiency of avalanche photodiode in order to help the optical communication. By using the information in the review of avalanche photodiode, we can conclude that the avalanche photodiode is good when operate with guard ring since it offers most significant benefits when it is necessary operates at very high bias voltage and has little or no effect in most cases when it biased below than 50 volts. In the stage of high-speed optical communications, researchers focused their research on maintaining breakdown voltage because APDs are operated near breakdown voltage.

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