Study of the Avalanche Multiplication and Signal-to-Noise Power Ratio in the Ternary In$_x$Ga$_{1-x}$As Avalanche Photodiode

1979

Susan Lee Wymer
University of Central Florida

Find similar works at: https://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

Part of the Engineering Commons

STARS Citation

https://stars.library.ucf.edu/rtd/459

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
STUDY OF THE AVALANCHE MULTIPLICATION AND SIGNAL-TO-NOISE POWER RATIO IN THE TERNARY In$_x$Ga$_{1-x}$As AVALANCHE PHOTODIODE

BY

SUSAN LEE WYMER
B.S.E., University of Central Florida, 1979
Orlando, Florida

RESEARCH REPORT
Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of the College of Engineering of the University of Central Florida

Fall Quarter
1979
STUDY OF THE AVALANCHE MULTIPLICATION AND SIGNAL-TO-NOISE POWER RATIO IN THE TERNARY In_xGa_{1-x}As AVALANCHE PHOTODIODE

Abstract

Major advances in fiber optic transmissions have brought about a need for highly sensitive photodetectors. In order to detect this type of transmission, the photodetector must be able to detect one of the two low loss windows of the fiber optics transmission. The photodetector must also be characterized by a high gain and fast speed of response without generating excessive noise power. This report compares different types of high speed photodetectors, with emphasis on the merits of using an avalanche photodiode. The report studies the avalanche multiplication and the signal-to-noise power ratio in the ternary InGaAs. The effects of the absorption coefficient, the depletion width, and the impurity concentration are studied. Finally, an optimization of the signal-to-noise power ratio is achieved by selecting the proper impurity concentration profile at suitable values of absorption coefficient and epitaxial width.

Aicha A. R. Riad
Committee Chairman
ABSTRACT

Major advances in fiber optic transmissions have brought about a need for highly sensitive photodetectors. In order to detect this type of transmission, the photodetector must be able to detect one of the two low loss windows of the fiber optics transmission. The photodetector must also be characterized by a high gain and fast speed of response without generating excessive noise power. This report compares different types of high speed photodetectors, with emphasis on the merits of using an avalanche photodiode. The report studies the avalanche multiplication and the signal-to-noise power ratio in the ternary InGaAs. The effects of the absorption coefficient, the depletion width, and the impurity concentration are studied. Finally, an optimization of the signal-to-noise power ratio is achieved by selecting the proper impurity concentration profile at suitable values of absorption coefficient and epitaxial width.
ACKNOWLEDGEMENTS

I would like to express my thanks to the many people who helped me with my Master's Degree.

Special thanks are extended to Glenn A. Birket, who wrote the computer graphing routine.

I wish to express my appreciation to my friends and family, especially my mother, who supported and encouraged me throughout this period.

I would also like to thank Lynda Harrell and Kathy Caldes for typing this manuscript.
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION.</td>
<td>1</td>
</tr>
<tr>
<td>II. PHOTODETECTION PHENOMENON</td>
<td>3</td>
</tr>
<tr>
<td>Photodetection Process.</td>
<td>3</td>
</tr>
<tr>
<td>Performance Criteria.</td>
<td>5</td>
</tr>
<tr>
<td>Materials</td>
<td>7</td>
</tr>
<tr>
<td>Photomultipliers.</td>
<td>8</td>
</tr>
<tr>
<td>Photodiodes</td>
<td>9</td>
</tr>
<tr>
<td>Photodetector Comparison.</td>
<td>17</td>
</tr>
<tr>
<td>Conclusion</td>
<td>18</td>
</tr>
<tr>
<td>III. THE DEVICE AND MULTIPLICATION MATERIAL AND STRUCTURE</td>
<td>21</td>
</tr>
<tr>
<td>Material and Structure.</td>
<td>21</td>
</tr>
<tr>
<td>Formula Derivation for Multiplication</td>
<td>22</td>
</tr>
<tr>
<td>Parameters.</td>
<td>28</td>
</tr>
<tr>
<td>Results and Discussion.</td>
<td>29</td>
</tr>
<tr>
<td>Summary and Discussion.</td>
<td>30</td>
</tr>
<tr>
<td>IV. SIGNAL-TO-NOISE POWER RATIO COMPUTATION AND OPTIMIZATION.</td>
<td>39</td>
</tr>
<tr>
<td>Signal-to-Noise Power Ratio Expression</td>
<td>39</td>
</tr>
<tr>
<td>Results and Discussion.</td>
<td>41</td>
</tr>
<tr>
<td>Optimization of the Signal-to-Noise Power Ratio</td>
<td>42</td>
</tr>
<tr>
<td>Conclusion</td>
<td>44</td>
</tr>
<tr>
<td>V. CONCLUSION.</td>
<td>58</td>
</tr>
<tr>
<td>APPENDIX A TMVSV COMPUTER PROGRAM</td>
<td>60</td>
</tr>
<tr>
<td>APPENDIX B TPMSN COMPUTER PROGRAM</td>
<td>63</td>
</tr>
<tr>
<td>LIST OF REFERENCES.</td>
<td>67</td>
</tr>
</tbody>
</table>
LIST OF TABLES

1. Summary of Photodetectors and Photoconductors ........ 20
2. Levels of Parameters ....................................... 29
3. Uniform Profile for Ternary Material ...................... 55
4. High-Low Impurity Profile for Ternary Material .......... 55
5. Low-High-Low Impurity Profile for Ternary Material ..... 56
6. High-Low-High Impurity Profile for Ternary Material ..... 57
LIST OF FIGURES

1. Energy-band Diagram for a p-i-n Photodiode .......................... 13
2. Energy-band Diagram Before Contact of a Schottky-barrier Photodiode .................................................. 15
3. Energy-band Diagram of a Schottky-barrier at Thermal Equilibrium .............................................................. 15
4. Variation of the Bandgap as a Function of Lattice Constant .......................... 23
5. Inverted Heterojunction III-V Alloy Mesa Photodiode ................. 24
6. Schematic Representation of the InGaAs Structure ...................... 24
7a. Effect of Absorption Coefficient and Epitaxial Width on Avalanche Multiplication, (NQ = 10^{14}/cc, Ternary) .... 32
7b. Effect of Absorption Coefficient and Epitaxial Width on Avalanche Multiplication, (NQ = 10^{15}/cc, Ternary) .... 33
7c. Effect of Absorption Coefficient and Epitaxial Width on Avalanche Multiplication, (NQ = 10^{16}/cc, Ternary) .... 34
8a. Effects of Impurity Concentration and Epitaxial Width on Avalanche Multiplication, (α = 10^{3} cm^{-1}, Ternary) .... 35
8b. Effects of Impurity Concentration and Epitaxial Width on Avalanche Multiplication, (α = 10^{4} cm^{-1}, Ternary) .... 36
8c. Effects of Impurity Concentration and Epitaxial Width on Avalanche Multiplication, (α = 10^{5} cm^{-1}, Ternary) .... 37
9. Effect of Breakdown Voltage at Different Depletion Widths and Concentrations (Ternary) .......................... 38
10a. Effect of Absorption Coefficient and Epitaxial Width on STN (NQ = 10^{14}/cc, Ternary) .......................... 46
10b. Effect of Absorption Coefficient and Epitaxial Width on STN (NQ = 10^{15}/cc, Ternary) .......................... 47
10c. Effect of Absorption Coefficient and Epitaxial Width on STN (NQ = 10^{16}\text{/cc}, Ternary) .......... 48

11a. Effect of Impurity Concentration and Epitaxial Width on STN (\alpha = 10^3 \text{ cm}^{-1}, \text{Ternary}) .......... 49

11b. Effect of Impurity Concentration and Epitaxial Width on STN (\alpha = 10^4 \text{ cm}^{-1}, \text{Ternary}) .......... 50

11c. Effect of Impurity Concentration and Epitaxial Width on STN (\alpha = 10^5 \text{ cm}^{-1}, \text{Ternary}) .......... 51

12. Effect of Absorption Coefficient and Epitaxial Width on Multiplication and STN (NQ = 10^{15}\text{/cc, Ternary}) .... 52

13. Types of Impurity Profiles ................. 53

14. Epitaxial Width ................................ 54
CHAPTER I

INTRODUCTION

This research report is concerned with the study of the avalanche multiplication and the signal-to-noise power ratio in the ternary In$_x$Ga$_{1-x}$As avalanche photodiode.

Major advances in fiber optic communications have brought about a need for highly sensitive photodetectors. The photodetector must be able to detect one of the two low loss windows of the fiber optics transmission. The first window occurs at 800 to 900 nm and the second, between 1000 and 1100 nm. The photodetector is characterized by having a high internal gain by using avalanche multiplication thus reducing excessive noise that may be generated. Various operating conditions are chosen to study their effects on the multiplication and the signal-to-noise power ratio. These operating conditions are the absorption coefficient, the depletion width, and the impurity concentration. An impurity profile is then suggested to achieve a high signal-to-noise power ratio at a certain level of multiplication.

Chapter I gives an introduction to this research report. Chapter II describes the photodetection phenomenon. A review of some high speed photodetectors and a comparison of these photodetectors will be included. In Chapter III, an expression for
the avalanche multiplication is developed. The possible combination of parameters that provides a high multiplication and a high breakdown voltage is selected. In Chapter IV, the signal-to-noise power ratio expression is developed. An optimization of the signal-to-noise power ratio at a certain level of multiplication is predicted by choosing a suitable impurity profile. Finally, conclusion is given in Chapter V.
CHAPTER II

PHOTODETECTION PHENOMENON

Introduction

Photomultipliers and photoconductive photodetectors are used for the detection of light at visible and near infrared wavelengths. Within recent years, great progress has been made in the technology of detector materials and in the design of the photodetectors to have a highly optimized performance for various light wavelengths and high speed of response.

This chapter gives a summary of the basic concepts of the photodetection process, the performance criteria of high speed detectors, and the material selection to build such detectors. The photodetectors described have a sensitivity to weak light sources in the visible and infrared wavelength range between 400 and 1600 nm. Some of the photodetectors to be discussed are photomultipliers, photoconductors and photodiodes. pn junctions, p-i-n diodes and Schottky-barrier diodes belonging to the photodiode family will be covered. Finally, special consideration is given to avalanche photodiodes, which exhibit a high speed of response (high gain-bandwidth product in comparison with other photodetectors).

Photodetection Process

The mechanism for converting photons into conducting
electrons is a common feature of all photodetectors called the photovoltaic effect. Regardless of the performance criteria or the type of photodetector to be used, the detector uses this effect to convert absorbed optical radiation into an electrical output signal.

The photodetectors are fabricated from semiconductor materials, characterized by having a moderate energy gap $E_g$, ranging from $0.67\text{eV}$ for Ge to $1.43\text{eV}$ for GaAs.

As the valence or conduction electron gains an energy $E$, equal to or greater than the energy gap of the photodetector material, the electron bridges the gap and enters the conduction band. The electron leaves behind a hole in the valence band, thus creating an electron-hole pair. When an electric field is applied, the electrons in the conduction band, and the holes in the valence band gain kinetic energy thus contributing to the conduction phenomenon.

There are various ways to supply this energy, light being one form of energy. Light striking an atom causes a valence electron to jump to the conduction band. Light is an electromagnetic radiation, indicating radiant energy at any wavelength. According to the quantum theory, the light can be considered as packets or discrete quanta called photons. The energy content of one photon is equal to:

$$E = hf = \frac{hc}{\lambda}$$

where $h$ is Planck's constant, $f$ is the frequency of incident
radiation, \( c \) is the speed of light in free space, and \( \lambda \) is the wavelength of the light. The long wavelength cutoff, \( \lambda_c \) is given by:

\[
\lambda_c = \frac{hc}{E_g} \text{ (\mu m)}
\]  

(2.2)

where \( \lambda_c \) is the upper wavelength limit to be detected, and \( E_g \) is the semiconductor bandgap. When a semiconductor is illuminated, there is a probability that the photons will not be absorbed, depending on the photon energy, \( E \), and the bandgap energy, \( E_g \). When the photon energy is less than the energy gap, photons are not readily absorbed because there is no energy state available in the forbidden gap to accommodate an electron. If the photon energy is equal to the energy gap, photons are absorbed to create electron-hole pairs. When the photon energy is greater than the energy gap, electron-hole pairs are generated and the excess \((E - E_g)\) is dissipated as heat (Class notes 1979).

### Performance Criteria

A photodetector must be chosen to provide the proper optimization for the application. Each application requires a different detector material. The major requirements for a photodetector with high performance are described by Melchior (1973). The photodetector must respond to the wavelength of the optical radiation with great efficiency. The speed at which the photodetector responds to the incoming optical signal must be fast, i.e., the bandwidth of the photodetector must be large. The
photodetector must generate a minimum amount of noise.

For a photodetector to have a good response to a particular wavelength, the photodetector material must have a suitable energy gap, and a high quantum efficiency. The quantum efficiency, $\eta$, is defined as:

$$\eta = \frac{I_{ph}}{q} \frac{hv}{P_{opt}}$$  \hspace{1cm} (2.3)

$I_{ph}/q$ is the number of photocarriers collected per unit time, $hv$ is the photon energy, and $P_{opt}$ is the number of incident photons per unit time that responded to $h\nu$.

The speed of response is limited by the number of carriers, the multiplication within the device, and the RC time constants within the photodetector. The current is limited by the number of carriers involved. At small concentrations, the amount of conducting carriers is limited, while at high concentrations, the current saturates. The same is true for the multiplication process. The RC time constants become significant when the photodetector is coupled to an amplifier. $C_D$ and $C_A$, the capacitance of the photodetector and of the amplifier, respectively, must be relatively small so that the photosignal can develop a high output voltage. Therefore, the photodetector can detect a low level signal. The resistance of the photodetector $R_D$ or the amplifier input is limited by the risetime $T_r$ and the bandwidth $B$ of the optical signal.

The noise in the photodetector and the amplifier must be
kept to a minimum value. The multiplied signal of the photodetector must overcome the noise sources of the photodetector and the amplifier.

If the intensity of the signal is relatively high compared to the noise level, high speed of response and adequate quantum efficiency are the only requirements for detection. On the other hand, for the low intensity signals, i.e. weak light sources, the sensitivity of the photodetector is limited. The sensitivity can be improved if the photocurrent is amplified within the photodetector before it reaches large noise sources, such as the amplifier and the load. The amplified photocurrent causes a current gain which raises the signal level above the amplifier noise. A high sensitivity can be obtained when a judicial choice of current gain or multiplication is chosen. Some useful devices that amplify the photocurrent within the photodetector with low noise and high speed of response, are photomultipliers and avalanche photodiodes (Melchior 1973).

Materials

The type of photodetector material must be determined by the wavelength of operation. As mentioned before, a photodiode is able to detect radiation provided the photon energy is greater than or equal to the bandgap energy.

The best investigated materials are silicon, germanium, and III-V compound materials, like GaAs and InP.
Silicon photodiodes are used in the near ultraviolet, visible, and the nearinfrared part of the spectrum, up to about 1000 nm (Melchior 1973). Silicon at 300°K has an energy gap of 1.12eV (Sze 1969).

The range of wavelength response can be extended to about 1600 nm using germanium photodiodes (Melchior 1973). At 300°K, germanium has a bandgap energy of .66eV (Sze 1969).

The III-V compound materials have a wide range of energy gap values, corresponding to the wavelength range of 500 nm to 7300 nm (Melchior 1973).

Photomultipliers

The photomultiplier is used to measure radiation in the near ultraviolet, visible, and near infrared parts of the spectrum. The device is characterized by having a high current amplification and low noise. The photomultiplier can detect power levels as low as 10^{-19} watts.

A photomultiplier consists of a photocathode and a series of electrodes called dynodes. With a potential difference of about 100 volts, the dynodes have increasingly higher potential with respect to the cathode. The anode is used to collect electrons.

The photocathode responds to the incident radiation and converts it to an electronic current, thus determining the sensitivity and wavelength response of the photodetector. Electrons are emitted from the photocathode and are electrostatically
focused and accelerated toward the first dynode. The electron has a kinetic energy of approximately 100eV. Multiplication of the initial current is caused by secondary emission from the dynode surface. The initial current therefore is amplified at each dynode resulting in a large factor. The total current multiplication \( G \) between the cathode and anodes is

\[
G = \delta^n
\]

where \( \delta \) is the average secondary emission multiplication and \( n \) is the number of dynodes. Typical values of \( \delta \) equal to 5 and \( n \) equal to 9, gives a \( G \) of approximately \( 2 \times 10^6 \).

The photocathode consists of materials such as Ag-O-Cs and Sb-Cs, having a typical quantum efficiency of less than 1% and 20 - 30%, respectively (Yariv 1976). A new material such as GaAs-Cs at a GaAs laser wavelength of 870 nm has a quantum efficiency of 18% (Melchior 1973).

**Photoconductors**

A photoconductor consists of a slab of semiconductor material in bulk or thin-film form. Free charge carriers are generated in the semiconductor when incident light is absorbed in the photoconductor. These free charge carriers add to the normal carrier concentration and cause the conductivity of the semiconductor to rise. The carriers are excited into their conduction bands by two methods, intrinsic excitation and extrinsic excitation. Intrinsic excitation involves band-to-band transitions; on the other hand, extrinsic excitation involves the
forbidden gap energy levels (Sze 1969).

**Intrinsic excitation occurs when pure semiconductor materials are used.** For an incident radiation possessing an energy greater than or equal to the bandgap energy of the material, electron-hole pairs are created. Some of the intrinsic semiconductor materials are CdS, ZnS, CdSe, ZnSe, GaAs, and InP (Class notes 1979).

**Extrinsic excitation occurs when free carriers are excited from dopants added to the intrinsic material.** The addition of the impurities provides less energy needed which allows operation at a longer wavelength than that for the intrinsic material (Sze 1969). Impurities can be chosen with lower ionization energies, thus detecting even lower energy photons. Photoconductors can operate at wavelengths from 1000 to 50,000 nm (Yariv 1976). Some of the photoconductor materials are Ge:Zn, Ge:Hg, and Ge:Au (Class notes 1979). An example of an extrinsic photoconductor is Cu added to Ge as an acceptor. Cu has an ionization energy of 0.04eV, which results in the Ge:Cu photoconductor with a long-wavelength cutoff of 32000 nm.

The main advantage of photoconductors compared to photomultipliers is the ability to detect longer wavelengths of incident radiation. The main disadvantage of photoconductors is the lack of current multiplication (Yariv 1976). Photoconductors are easier to fabricate than photomultipliers.
Photodiodes

Photodiodes are photodetectors characterized by having a depletion region resulting from a pn junction or a metal-semiconductor contact. A photodiode is a reversed biased semiconductor diode, producing electron-hole pairs in or near the depletion layer, by the absorption of light.

Photodiodes are classified as normal or non-avalanche and avalanche photodiodes. The photodiodes to be discussed are pn junction diodes, p-i-n diodes, Schottky-barrier diodes, and avalanche photodiodes.

pn Junction Diode

A pn junction photodiode consists of an abrupt or gradual transition between a donor-doped (n-type) region and an acceptor-doped (p-type) region. The depletion region extends in either the n or p region, or both, depending on the concentration of both sides. The light must fall within the depletion region, producing electron-hole pairs. The pairs produced by the photoabsorption are separated by the electric field existing in the depletion region.

A simple p⁺-n silicon photodiode is reported by Dash and Newman (1955). The device has a depletion region between 1 μm and 30 μm. It responds to a wavelength range between 450 nm and 600 nm. A germanium photodiode with the same depletion region, responding to wavelengths of 950 nm to 1500 nm. Both of the photodiodes have response time of 100 ps, with quantum
efficiencies of 40 to 50%.

p-i-n Photodiode

Another example of a pn junction diode is the p-i-n diode. A p-i-n diode is a pn junction with an intrinsic layer, "i region" doped between a p and an n layer. As described above, electron-hole pairs are produced in the intrinsic region i, or within a diffusion layer (1/α) of it, where α is the absorption coefficient of the diode material to the incident light. The electrons and holes are eventually separated by the electric field causing current to flow as carriers drift across the depletion region. The energy band diagram of such a diode is shown in figure 1.

The advantage of the p-i-n photodiode is the ability of the designer to design the depletion region, thus optimizing the sensitivity range (Sze 1969).

At longer wavelengths, p⁺-i-n⁺ photodiodes can be optimized for 600 and 1000 nm wavelengths. They have wide depletion regions, typically 20 to 50μm. Response time is generally 100ps with quantum efficiencies exceeding 90% (Melchior 1973). An actual device is fabricated and discussed by Mathur (1970). The germanium p⁺-i-n⁺ diode responds to wavelengths of 600 to 1650 nm. The depletion region area is 0.0025 cm². The quantum efficiency is approximately 60%. A silicon p-i-n has responded to a wavelength of 850 to 950 nm. The quantum efficiency is approximately 70% with a large depletion region of 20 to 50μm (Melchior 1973).
Fig. 1. Energy-band diagram for a p-i-n photodiode.
Schottky-barrier or Metal-semiconductor Diode

The Schottky-barrier diode is fabricated from a metal and a semiconductor material. In figure 2, the energy band diagram of a metal and a n-type semiconductor material is shown before contact. \( e\phi_m \) and \( e\phi_s \) are the work functions of the metal and semiconductor material, respectively. \( \chi_s \) is the electron affinity of the material. \( \phi_B \) is the height of the potential barrier. When the metal side and the n-type semiconductor side are joined, the Fermi levels become aligned. A depleted region is formed and band bending occurs, figure 3. The band bending results in a potential barrier being created \( \phi_B \). \( \phi_B \) can be varied by applying the appropriate biased voltage to the n-type semiconductor material. For this case, a positive voltage is applied to the semiconductor with respect to the metal, causing an increase in the barrier height.

Due to majority carriers contribution to the current, Schottky-barrier diodes are mainly used for high frequency, fast switching applications, typically in the gigahertz range. The Schottky-barrier diode has no minority carrier storage, therefore is not limited by the RC time constants. The biggest disadvantage of a Schottky-barrier diode is the leakage current, which causes special device fabrication design (Yang 1978).

A device reported by Lindley et al. (1969), is a Pt-GaAs material. The detector responds to wavelengths between 400 and 860 nm. The depletion region is varied from 1 to 2\( \mu \)m in size. The Schottky-barrier photodiode has a 30\% quantum efficiency at zero bias.
Fig. 2. Energy-band diagram before contact of a Schottky-barrier photodiode.

Fig. 3. Energy-band diagram of a Schottky-barrier at thermal equilibrium.
Avalanche Photodiode

Avalanche photodiodes are operated at high reverse bias voltages where internal amplification of the photocurrent (avalanche multiplication) occurs. By operating the photodiode in the avalanche mode, the gain can be substantially large, depending on the voltage applied (Melchior 1973).

At low reverse voltages, the diode operates as a regular photodiode. As the reverse bias voltage is increased, the carriers gain enough energy so that they can excite electron-hole pairs. When the electron (or hole) is created in the depletion region, there is a probability that it will create another electron-hole pair by collision, after acquiring enough energy. The creation of the electron-hole pair depends upon the strength of the electric field and the crystal orientation of the material. The electron (or hole) and the newly generated electron-hole pairs continue through the depletion region causing more impact ionizations. The electrons move against the electric field and the holes move with the electric field. The probability of creating an electron-hole pair is called the ionization coefficient. The electron and hole ionization coefficients, \( \alpha_n \) and \( \alpha_p \), respectively, are the number of electrons and holes produced per unit distance of travel by an electron or hole. The coefficients increase rapidly with the electric field, and avalanche breakdown occurs when the probability that a carrier will reproduce itself reaches unity.
The avalanche process must be controlled to provide useful current gain. The current gain is influenced by the magnitude of the avalanche current, and the fluctuations due to the nonuniformity of the multiplication process (Melchior 1973). Small microplasmas where the breakdown voltage is less than the junction voltage cause the nonuniformity of the multiplication process (Sze 1969). These variations of the current gain, along with the noise due to fluctuations in the recombination-generation process, leads to excess noise in the device. This is the reason why optimization of the signal-to-noise power ratio at a certain gain level must be considered.

A silicon avalanche photodiode reported by Anderson and McMurry (1966) has a quantum efficiency of 85% at 900 nm and only 10% at 1060 nm. The silicon photodetector material responds at wavelengths from 400 to 1100 nm. A germanium avalanche photodiode has a better response to wavelengths of 600 to 1600 nm. A similar device namely a n⁺-p photodetector was fabricated with a 1.2μm depletion layer. The quantum efficiency is approximately 50% and responds to wavelengths of 600 to 1650 nm.

**Photodetector Comparison**

The previous sections have outlined the material and some different types of photodetectors. The detection of certain wavelengths, namely 800 nm to 1100 nm becomes a critical factor in the material and device choice. In an article written by Eden (1975), the author outlines several detectors that are considered for
detection at those wavelengths, in particular 1060 nm.

The different types of photodetectors discussed in this chapter are summarized in table 2-1. The photodetectors have certain disadvantages that do not lend themselves for optimum use at 1060 nm. Specifically, the photomultiplier lacks the quantum efficiency needed to be useful (Eden 1975). The photoconductor and photodiode have comparable signal-to-noise power ratios at high intensities but at low intensities, the photodiode has better performance (DiDomenico 1964). A silicon avalanche photodiode does not have a high multiplication at 1060 nm, and the germanium photodiode has a higher gain but at a higher noise level (Eden 1975).

**Conclusion**

In this chapter, the photodetector process, the performance criteria of the photodetectors, the material selection of these detectors, and finally a review of high speed photodetectors were discussed. The most important criteria for choosing a specific photodetector is to specify the wavelength suitable for a particular application. The ideal photodetector operating at that wavelength, would have a high value of internal multiplication and a high breakdown voltage, with low leakage current and low capacitance value. These criteria lead to the choice of the avalanche photodiode. Although the avalanche photodiode had the disadvantage of a high multiplied noise power, the detector can be optimized to produce a good signal-to-noise power ratio at a certain level of
multiplication. In the next chapter, a semiconductor material will be discussed to detect the wavelength range of 800 to 1100 nm.
### TABLE 1

SUMMARY OF PHOTODETECTORS AND PHOTOCONDUCTORS

<table>
<thead>
<tr>
<th>Device</th>
<th>Type of Material</th>
<th>Wavelength nm</th>
<th>Quantum Efficiency</th>
<th>Depletion Region μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photomultiplier</td>
<td>GaAsCs Cathode</td>
<td>870</td>
<td>18</td>
<td>. . . . . . . .</td>
</tr>
<tr>
<td>p⁺-n</td>
<td>Si</td>
<td>450 - 600</td>
<td>40 - 50</td>
<td>1 - 3</td>
</tr>
<tr>
<td>p⁺-n</td>
<td>Ge</td>
<td>950 - 1500</td>
<td>40 - 50</td>
<td>1 - 3</td>
</tr>
<tr>
<td>p⁺-n</td>
<td>GaAs:Cr</td>
<td>600</td>
<td>. . . . . . . .</td>
<td>. . . . . . . .</td>
</tr>
<tr>
<td>p⁺-i-n⁺</td>
<td>Ge</td>
<td>600 - 1650</td>
<td>60</td>
<td>.0025</td>
</tr>
<tr>
<td>p-i-n</td>
<td>Si, Silicon</td>
<td>850 - 920</td>
<td>70</td>
<td>20 - 50</td>
</tr>
<tr>
<td>Schottky-barrier</td>
<td>Pt-GaAs</td>
<td>400 - 860</td>
<td>30</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Avalanche</td>
<td>Si</td>
<td>400 - 1100</td>
<td>85 at 700 nm</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 at 1060 nm</td>
<td></td>
</tr>
<tr>
<td>Avalanche</td>
<td>Ge</td>
<td>600 - 1600</td>
<td>. . . . . . . .</td>
<td>40</td>
</tr>
<tr>
<td>Avalanche n⁺p</td>
<td>Ge</td>
<td>600 - 1650</td>
<td>50</td>
<td>1.2</td>
</tr>
</tbody>
</table>
CHAPTER III

THE DEVICE AND MULTIPLICATION

Introduction

As discussed in Chapter II, an avalanche photodetector performs better than a nonavalanche photodetector. By using the avalanche photodetector, faster response (higher gain bandwidth product) can be achieved.

This chapter describes the photodetector considered. A good characterization of the avalanche detector is the amount of gain or multiplication it is able to give. An expression for the avalanche multiplication will be derived and the factor will be studied with different parameters.

Material and Structure

In order to optimize all of the performance criteria, the selection of the material and device structure is very important.

In $\text{Ga}_x\text{As}_{1-x}$ material is an attractive material for detection at the low loss window for fiber optics. By using this III-V ternary compound, the detector can respond to light at a longer wavelength than that for binary GaAs material. Figure 4 shows a variation of the bandgap as a function of lattice constant. The device reported by Pearsall (1975) is fabricated of
In$_{.14}$Ga$_{.86}$As. Ternary InGaAs is obtained from GaAs by trading gallium atoms with indium atoms. From figure 4, one can find that the bandgap energy is approximately 1.32eV. The device used is an inverted back-illuminated heterojunction III-V alloy mesa photodiode as shown in figure 5. The light is illuminated onto the n$^+$ substrate rather than the epitaxial side. This allows the light to penetrate without being absorbed by the metal contact. Light is passed through the n$^+$ substrate, to the depletion region, where it is absorbed in the n-type In$_x$Ga$_{1-x}$As layer. Typical depletion widths are on the order of 3 to 4µm.

A schematic representation of the In$_x$Ga$_{1-x}$As (ternary) is shown in figure 6. The photodiode has a depletion layer width W, with an epitaxial width $W_j$. For good efficiency, W must be kept greater than $W_j$. The reverse bias voltage is applied as shown.

**Formula Derivation for Multiplication**

Schockley's rate equations for holes and electrons, describing the carrier transport in a semiconductor, take the form (Schockley 1950),

$$\frac{\partial p}{\partial t} = \frac{-(p - p_0)}{\tau_p} + \frac{1}{e} \text{ div } J_p \quad (3.1a)$$

$$\frac{\partial n}{\partial t} = \frac{-(n - n_0)}{\tau_n} + \frac{1}{e} \text{ div } J_n \quad (3.1b)$$

$\frac{\partial p}{\partial t}$ and $\frac{\partial n}{\partial t}$ are the rates of change of the p and n type concentrations with time and $(p - p_0)$ and $(n - n_0)$ represent the excess holes
Fig. 4. Variation of the bandgap as a function of lattice constant for a number of ternary III-V compounds.
Fig. 5. Inverted heterojunction III-V alloy mesa photodiode.

Fig. 6. Schematic representation of the InGaAs structure.
and electrons, respectively. $\tau_p$ is the lifetime for holes in an n-type material and $\tau_n$ is the lifetime for electrons in a p-type material. $\frac{p - P_m}{\tau_p}$ and $\frac{n - n_0}{\tau_n}$ are the hole and electron recombination rates, respectively. $G$ is the electron-hole generation rate ($cm^{-3} sec^{-1}$), due to an external effect, such as light absorption and/or avalanche multiplication. $J_p$ and $J_n$ are the total hole and electron current densities, respectively.

Since avalanche multiplication is used, the recombination term can be neglected with respect to the generation term. Also, since there is a high field, the diffusion term can be neglected with respect to the drift term in the total current density expression (Class notes 1979).

At steady-state, equations (3.1a) and (3.1b) reduce to,

\begin{align*}
0 &= G - \frac{1}{e} \frac{dJ_p}{dx} \quad (3.2a) \\
0 &= G + \frac{1}{e} \frac{dJ_n}{dx} \quad (3.2b)
\end{align*}

where $J_p$ and $J_n$ equal to,

\begin{align*}
J_p &= e\mu_p E_p \quad (3.3a) \\
J_n &= e\mu_n E_n \quad (3.3b)
\end{align*}

$\mu_p$ and $\mu_n$ are the mobilities of holes and electrons, respectively, $p$ is the carrier concentration for holes and $n$ is the carrier concentration for electrons.

The electron-hole generation rate, $G$, a function of time and position, described by equation (3.4),
\[ G = G_0(x) + G_{AV} \]  

(3.4a)

where,

\[ G_{AV} = \alpha_n |v_n| n + \alpha_p |v_p| p \]  

(3.4b)

\( G_0(x) \) is the electron-hole generation rate due to light absorption. \( \alpha_n \) is the electron ionization rate. Similarly, \( \alpha_p \) is the hole ionization rate. \( v_n \) is the absolute value of the electron velocity. \( v_p \) is the absolute value of the hole velocity.

Substituting (3.4) in (3.2a) and (3.2b), the equations take the form,

\[ \frac{dJ_n}{dx} = eG_1(x) + e\alpha_n |v_n| n + e\alpha_p |v_p| p \]  

(3.5a)

\[ \frac{dJ_p}{dx} = -eG_1(x) - e\alpha_n |v_n| n - e\alpha_p |v_p| p \]  

(3.5b)

Assuming current continuity, equation (3.5a) takes the form,

\[ \frac{dJ_p(x)}{dx} + \left[ \alpha_p(x) - \alpha_n(x) \right] J_p(x) = eG_L(x) - \alpha_n(x) J \]  

(3.6)

where,

\[ |J_p| = -J_p \]

and,

\[ |J_n| = -J_n \]

Equation (3.6) represents a first order differential equation of the form,

\[ \frac{dy}{dx} + f(x)y = g(x) \]  

(3.7a)
according to Kells (1935), the solution is of the form,

\[ J_p(x) = \exp \left[ \int_0^x \left( eG_L(x) - \alpha_n(x)J \right) dx \right] \]

\[ \exp \left[ \int_0^x \left( \alpha_p(x) - \alpha_n(x) \right) dx \right] \]

\[ \alpha \approx (eG_L(x) - \alpha_n(x)) \exp \left[ \int_0^x \left( \alpha_p(x) - \alpha_n(x) \right) dx + J_p(0) \right] \quad (3.7b) \]

According to the structure considered, and the direction of the incident light, holes initiate the multiplication process at \( x \) equal to \( W \) and \( J_p(W) \) is approximately equal to zero. For current continuity, \( J_p(0) \) is approximately equal to \( J \). Thus by solving equation (3.6),

\[ J = -\int_0^W (eG_L(x) - \alpha_n(x)J) \exp \left[ \int_0^x \left( \alpha_p(x) - \alpha_n(x) \right) dx \right] \quad (3.8) \]

Solving for \( J \), equation (3.9) is obtained,

\[ J = \frac{-\int_0^W eG_o(x) \exp \left[ \int_0^x \left( \alpha_p(x) - \alpha_n(x) \right) dx \right]} {1 - \int_0^W \alpha_n(x) \exp \left[ \int_0^x \left( \alpha_p(x) - \alpha_n(x) \right) dx \right]} \quad (3.9) \]

where,

\[ G_o(x) = \alpha \phi_o \exp(\alpha(x - W)) \]

\( \alpha \) is the absorption coefficient of the material to the light at a certain wavelength. \( \phi_o \) is the light intensity at the heterojunction interface.
The avalanche multiplication, \( M_D \), is defined as,

\[
M_D \equiv \frac{\int_{-J}^{0} \alpha_n(x - W_j) \exp(\int_{0}^{x} (\alpha_p(x) - \alpha_n(x)) \, dx)}{1 - \int_{0}^{x} \alpha_n(x) \exp(\int_{0}^{x} (\alpha_p(x) - \alpha_n(x)) \, dx)}
\]

The avalanche multiplication, \( M_D \), can be evaluated numerically if the electron and hole ionization coefficients \( \alpha_n \) and \( \alpha_p \), respectively, are known.

**Parameters**

The device multiplication, \( M_D \) for the ternary material is calculated numerically, using the computer program TMVSV shown in appendix A (Riad 1977). \( M_D \) is graphed versus the applied reverse voltage in figures 7 and 8, at different conditions of operation.

The concentration of the heavily doped substrate \( N^+ \) is chosen to be equal to \( 1 \times 10^{18} \)/cc. The permittivity \( \varepsilon \) of the ternary material is equal to \( 1.13176 \times 10^{-10} \) F/m. The ionization rates for the material \( \alpha_p \) and \( \alpha_n \) take the form (Pearsall 1975),

\[
\alpha_p = 1.3 \times 10^8 \exp(-2.7 \times 10^6 / E)
\]

\[
\alpha_n = 1.0 \times 10^9 \exp(-3.6 \times 10^6 / E)
\]

The different conditions of operation are the absorption coefficient (\( \alpha \)), the thickness of the epitaxial layer (\( W_j \)), and the concentration of the epitaxial layer (\( NQ \)). The levels of these parameters used in the computations are shown in table 2.
### TABLE 2

**LEVELS OF PARAMETERS**

<table>
<thead>
<tr>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$W_j$ (µm)</th>
<th>NQ (/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
<td>2</td>
<td>$10^{14}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>3</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>$10^5$</td>
<td>4</td>
<td>$10^{16}$</td>
</tr>
</tbody>
</table>

**Results and Discussion**

Figures 7a, 7b, and 7c show the effect of absorption coefficient ($\alpha$) and epitaxial width ($W_j$) on multiplication $M$. The ternary concentration of the material is maintained constant at $1 \times 10^{14}$/cc. The general behavior of the graph exhibits a straight line characteristic (where it operates as a regular photodiode), and gently rises (starting the avalanche process), and finally reaching the avalanche breakdown voltage. As the epitaxial width is increased, the photodiode has a higher breakdown voltage. Also, as the absorption coefficient is increased, the diode can achieve a higher value of multiplication and a higher breakdown voltage at the same applied voltage. Figure 7b illustrates the same behavior but at a higher impurity concentration of $10^{15}$/cc. The breakdown voltage is slightly lower than in figure 7a. In figure 7c, the concentration is $10^{16}$/cc. At this higher concentration, the effect of both $\alpha$ and $W_j$ becomes insignificant.
In the next set of figures, the depletion width and the concentration are varied, while the absorption coefficient is kept constant. Figure 8 shows the pronounced effect of impurity concentration on the avalanche multiplication at higher epitaxial widths. At small epitaxial widths, there is practically no difference in the breakdown voltage as the impurity concentration is varied.

In figure 9, the breakdown voltage $V_R$ is plotted versus the ternary doping concentration $N_Q$, with the epitaxial width $W_j$ as the variable. It is readily seen that at the same epitaxial width, regardless of the absorption coefficient, the breakdown voltage approaches a constant value. At $N_Q$ equal to $10^{16}$/cc, the breakdown voltage is considerably lower than the $10^{14}$/cc or $10^{15}$/cc doping concentration.

**Summary and Conclusion**

From the results shown, one can conclude three basic conclusions. First, as the absorption coefficient ($a$) is increased, the multiplication is higher at the same applied voltage. Second, as the depletion width is increased, the breakdown voltage also increases. On the other hand, decreasing the depletion width causes less dependency on the impurity concentration. Third, as the impurity concentration increases, the breakdown voltage decreases.
These findings lead to a possible combination that provides high multiplication at an applied voltage in addition to a high breakdown voltage. A combination of absorption coefficient ($a$) equal to 4 or 5 μm, and a concentration (NQ) of $10^{14}$ or $10^{15}$/cc, seems to be suitable for the ternary material. But this is not the only criteria that the combination should be judged upon as will be seen in the next chapter when the signal-to-noise power ratio will be considered.
Fig. 7a. Effect of absorption coefficient and epitaxial width on avalanche multiplication ($N_Q = 10^{14}$/cc, ternary).
Fig. 7b. Effect of absorption coefficient and epitaxial width on avalanche multiplication (\(N_Q = 10^{15}/\text{cc, ternary}\))
Fig. 7c. Effect of absorption coefficient and epitaxial width on avalanche multiplication ($N_Q = 10^{16}$/cc, ternary).

\[ \alpha = 10^5 \text{ cm}^{-1} \]
\[ \alpha = 10^4 \text{ cm}^{-1} \]
\[ \alpha = 10^3 \text{ cm}^{-1} \]
Fig. 8a. Effects of impurity concentration and epitaxial width on avalanche multiplication ($\alpha = 10^3 \text{ cm}^{-1}$, ternary).
Fig. 8b. Effect of impurity concentration and epitaxial width on avalanche multiplication (α = 10^4 cm⁻¹, ternary).
Fig. 8c. Effect of impurity concentration and epitaxial width on avalanche multiplication ($\alpha = 10^5 \text{ cm}^{-1}$, ternary).
Fig. 9. Effect of breakdown at different depletion widths and concentrations (ternary).
CHAPTER IV

SIGNAL-TO-NOISE POWER RATIO:
COMPUTATION AND OPTIMIZATION

Introduction

One of the major requirements for an avalanche photodetector is to generate a minimum amount of noise power. A good performance criteria characterizing such a photodetector is a high signal-to-noise power ratio at a certain level of multiplication.

In this chapter, an expression for the signal-to-noise power ratio will be derived. The quantity will be computed for different conditions of operation; the absorption coefficient, the depletion width, and the impurity concentration. By investigating four different impurity profiles, an optimization of the signal-to-noise power ratio at a certain level of gain is performed by choosing a proper impurity profile.

Signal-to-Noise Power Ratio Expression

In deriving the expression for the signal-to-noise power ratio, the magnitude of the noise generated in the multiplication process must be derived first.

The equivalent generation-recombination normalized noise power density, known as shot noise, is due to the fluctuations in the number of carriers generated due to the photoabsorption and
avalanche multiplication in an avalanche photodiode (Yariv 1976).

The normalized shot noise power density is of the form,

$$\frac{i_{\text{sh}}^2}{\Delta f} = 2e dJ_p(x) M^2_D(x)$$  \hspace{1cm} (4.1)

where $\frac{i_{\text{sh}}^2}{\Delta f}$ is the normalized noise power density generated in an elemental distance $dx$, $\Delta f$ is the bandwidth, and $dJ_p(x)$ is given by,

$$dJ_p(x) = \frac{dJ_p}{dx} dx$$  \hspace{1cm} (4.2)

The incremental spectral noise density, $d\phi(x)$, is of the form,

$$d\phi(x) = 2e |dJ_p(x)| M^2_D(x)$$  \hspace{1cm} (4.3)

Integrating (4.3) yields the normalized spectral noise density,

$$\phi_n = \frac{\phi}{2e^2\phi_o} = \left[ \frac{e\phi_o}{dx} \right] M^2_D(x) dx$$  \hspace{1cm} (4.4)

where $dJ_p(x)/dx$ takes the form,

$$\frac{dJ_p(x)}{dx} = eG_n(x) - \alpha_p(x)J - \left[ \alpha_p(x) - \alpha_n(x) \right] J_p(x)$$

$M_D(x)$ is the multiplication at any position $x$. Inserting the expression for the first derivative and light generation into equation (4.4) yields,

$$\phi_n = \int_{\omega}^{\omega} \alpha_p \exp \left[ \alpha(x - W_j) M^2_D(x) dx + \int_{\omega}^{\omega} \alpha_n(x) \right] e\phi_o M^2_D(x) dx \\
+ \int_{\omega}^{\omega} \left[ \alpha_p(x) - \alpha_n(x) \right] \frac{J_p(x)}{e\phi_o} M^2_D dx$$  \hspace{1cm} (4.5)
where,

\[
\left| \frac{J_p(x)}{e\phi_0} \right| = \exp\left[ -\int_0^x (\alpha_p - \alpha_n) \, dx \right] \left[ -\int_0^x \left( \exp (x - W_j) + \alpha_n \frac{|J|}{e\phi_0} \right) \right]
\]

\[
\exp\left[ \int_0^x (\alpha_p - \alpha_n) \, dx \right] + \frac{|J|}{e\phi_0} \right] \, dx
\]

Having derived the normalized spectral noise density, the signal-to-noise power ratio can be derived. The quantity \( M_D^2 / \phi_n \), the square of the avalanche multiplication divided by the normalized spectral noise density, is a good representation of the signal-to-noise power ratio.\(^1\)

**Results and Discussion**

The signal-to-noise power ratio, abbreviated STN, is computed numerically at different applied voltages using the computer program TMVSV (Riad 1977). The same variations that were used in the multiplication program, namely the absorption coefficient (\( \alpha \)), the epitaxial width (\( W_j \)), and the impurity concentration (\( N_j \)) are repeated in this section. STN is graphed versus the applied reverse voltage (\( V_R \)) in figures 10 and 11 for the ternary InGaAs. In general, the graph STN vs \( V_R \) exhibits a straight line characteristic (where it operates as a regular photodiode), sometimes reaching a peak value. The graph gently decreases at higher voltages.

\(^1\) Actual signal-to-noise = \((M^2/\phi_n)(A\phi_0/2BW)\), where \( A \) is the active area and \( BW \) is the bandwidth.
Figure 10 exhibits the effects of the absorption coefficient (α) and epitaxial width (Wx) on the STN at different impurity concentrations (NQ) for InGaAs. As the epitaxial width is increased, the breakdown voltage also increases. As the absorption coefficient increases, the value of the STN is higher at the same applied voltage. NQ is increased from 10^{14}/cc, figure 10a to 10^{15}/cc, figure 10b. Figure 10b is characterized by having a slightly lower breakdown voltage in comparison to figure 10a. When the impurity concentration reaches a high value of 10^{16}/cc as in figure 10c, the effect on the lower breakdown voltage becomes pronounced.

Figure 11 shows the effect of the impurity concentration and the epitaxial width on the STN, at different absorption coefficients. As the depletion width is increased, the STN and breakdown voltage also increase. As the depletion width increases, the effect of the concentration becomes an important factor. Comparing 11a, 11b, 11c, it can be seen that as the absorption coefficient (α) is increased, a higher STN is noted.

**Optimization of the Signal-to-Noise Power Ratio**

The signal-to-noise power ratio can be optimized by selecting an absorption coefficient value, an epitaxial width, and an impurity concentration at a certain level of multiplication. Figure 12 represents a summary of the avalanche multiplication and the signal-to-noise power ratio computations at different applied reverse voltages for different values of
absorption coefficients and epitaxial width. The impurity concentration selected is $10^{15}\text{/cc}$, for the ternary material. It can be seen that the STN reaches a peak or maximum value at a multiplication of unity, i.e. when the avalanche photodetector is working as a regular photodiode. Operating the photodetector at a higher value of internal multiplication is at the expense of the signal-to-noise power ratio.

Doping Profile

An absorption coefficient of $10^5\text{ cm}^{-1}$ and an epitaxial width of $5\mu\text{m}$ are selected for the optimization procedure chosen to be optimized at a gain of 5. Four types of impurity profiles are assumed; uniform profile, high-low, high-low-high, and low-high-low, shown in figure 13. The breakdown voltage and signal-to-noise power ratio are calculated numerically, using the computer program TPMSN (Riad 1977) shown in appendix B. The epitaxial region is divided into three sections, figure 14.

The results are summarized in Tables 3 to 6 for the different cases of impurity profiles. The impurity concentration is normalized to $1 \times 10^{15}\text{/cc}$.

In table 3, a uniform profile for ternary InGaAs is shown. At low doping concentrations, the signal-to-noise power ratio, and the breakdown voltage are high.
Table 4 shows a high-low impurity profile. The profile of .25, .15, 0.05 shows a high value of STN over that of a uniform profile.

Table 5 shows a low-high-low impurity profile for the ternary material. For the ternary material a profile of 0.1, 1.0, 0.1 exhibits a high STN and a high breakdown voltage.

The last case of high-low-high impurity profile is shown in table 6. In table 6, the doping of the ternary InGaAs at levels 1.0, 0.1, and 1.0 shows an almost equivalent STN and breakdown voltage as the low-high-low impurity profile.

Conclusion

Having derived the signal-to-noise power ratio, three basic observations can be concluded. First, as the absorption coefficient is increased, the STN and the breakdown voltage both increase. Second, when the depletion width is increased, the breakdown voltage also increases. Third, as the impurity concentration increases, the breakdown voltage decreases.

These observations lead to an optimal condition of operation, that is an absorption coefficient (α) of $10^5$ cm$^{-1}$, a depletion width ($W_d$) of 5μm, and an impurity concentration (NQ) of $10^{15}$/cc.
The optimum selection of the impurity concentration profile is a low-high-low with levels combination of 0.1, 1.0, and 0.1 for ternary (normalized to $10^{15}$/cc), although the effect is minimal. The choice provides the highest signal-to-noise power ratio at a multiplication of 5, with a high breakdown voltage.
Fig. 10a. Effect of absorption coefficient and epitaxial width on STN ($N_Q = 10^{14}/cc$, ternary).
Fig. 10b. Effect of absorption coefficient and epitaxial width on STN (NQ = $10^{15}$/cc, ternary).
Fig. 10c. Effect of absorption coefficient and epitaxial width on STN (NQ = $10^{16}$/cc, ternary).
Fig. 11a. Effect of impurity concentration and epitaxial width on STN ($\alpha = 10^3$ cm$^{-1}$, ternary).
Fig. 11b. Effect of impurity concentration and epitaxial width on STN ($\alpha = 10^4 \text{ cm}^{-1}$, ternary).
Fig. 11c. Effect of impurity concentration and epitaxial width on STN ($\alpha = 10^5 \text{ cm}^{-1}$, ternary).
Fig. 12. Effect of absorption coefficient and epitaxial width on multiplication and STN ($N_Q = 10^{15}$/cc, ternary).
Fig. 13. Types of impurity profiles.
<table>
<thead>
<tr>
<th>Section</th>
<th>Section</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Fig. 14.** Expitaxial Width
### TABLE 3

**UNIFORM PROFILE FOR TERNARY MATERIAL**

<table>
<thead>
<tr>
<th>Profile</th>
<th>STN</th>
<th>Applied Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section 1</td>
<td>Section 2</td>
<td>Section 3</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

### TABLE 4

**HIGH-LOW IMPURITY PROFILE FOR TERNARY MATERIAL**

<table>
<thead>
<tr>
<th>Profile</th>
<th>STN</th>
<th>Applied Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section 1</td>
<td>Section 2</td>
<td>Section 3</td>
</tr>
<tr>
<td>5.0</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>0.15</td>
<td>0.05</td>
<td>0.025</td>
</tr>
<tr>
<td>Profile</td>
<td>Section 1</td>
<td>Section 2</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>1.0</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.0</td>
<td>5.0</td>
<td>0.1</td>
</tr>
<tr>
<td>0.1</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.1</td>
<td>5.0</td>
<td>0.1</td>
</tr>
<tr>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>0.25</td>
<td>2.0</td>
<td>0.25</td>
</tr>
<tr>
<td>0.15</td>
<td>2.0</td>
<td>0.15</td>
</tr>
<tr>
<td>0.15</td>
<td>2.5</td>
<td>0.025</td>
</tr>
<tr>
<td>0.25</td>
<td>2.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
### Table 6

**High-Low-High Impurity Profile for Ternary Material**

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>STN</th>
<th>Applied Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1.0</td>
<td>5.0</td>
<td>0.55930</td>
<td>89.87383</td>
</tr>
<tr>
<td>5.0</td>
<td>0.1</td>
<td>5.0</td>
<td>0.56673</td>
<td>95.31121</td>
</tr>
<tr>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.65215</td>
<td>120.68906</td>
</tr>
<tr>
<td>3.5</td>
<td>2.0</td>
<td>3.5</td>
<td>0.58228</td>
<td>96.83474</td>
</tr>
<tr>
<td>3.5</td>
<td>0.15</td>
<td>3.5</td>
<td>0.60639</td>
<td>107.47175</td>
</tr>
<tr>
<td>3.5</td>
<td>0.05</td>
<td>3.5</td>
<td>0.63046</td>
<td>117.92607</td>
</tr>
<tr>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
<td>0.64865</td>
<td>121.98550</td>
</tr>
<tr>
<td>0.25</td>
<td>0.05</td>
<td>0.25</td>
<td>0.64957</td>
<td>121.94246</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15</td>
<td>0.25</td>
<td>0.65065</td>
<td>121.88475</td>
</tr>
</tbody>
</table>
CHAPTER V

CONCLUSION

The purpose of this research report was to theoretically study avalanche photodetectors suitable for fiber optics communication from the point of view of multiplication and signal-to-noise power ratio.

After reviewing some high speed photodetectors in Chapter II, the avalanche photodiode was found to exhibit the best detection characteristics for low level signals. The avalanche photodiode can achieve high multiplication at a given applied voltage.

In Chapter III, the InGaAs ternary material was chosen to conduct the study. An expression for the avalanche multiplication was developed. Various parameters, namely the absorption coefficient \( \alpha \), the depletion width \( W_0 \), and the impurity concentration \( N_0 \) were varied to show the effect each had on the multiplication. Combinations of these parameters that exhibited high multiplication and a high breakdown voltage were chosen.

The signal-to-noise power ratio expression was derived in Chapter IV. Again, the same parameters were used and a combination of an absorption coefficient of \( 10^5 \text{ cm}^{-1} \), a depletion width of 5 \( \mu \text{m} \), and an impurity concentration of \( 10^{15} /\text{cc} \) were selected.
to yield a high signal-to-noise value.

The different types of impurity profiles had a small effect on the STN, although the highest value of STN was achieved with an impurity profile of low-high-low. The most important criteria to achieve a high value of signal-to-noise power ratio is to keep the concentration low.

Further recommendations for study are as follows:

A study of the depletion layer capacitance and temperature effects should be considered. A frequency response study in the In_{x}Ga_{1-x}As avalanche photodiode should also be conducted.
APPENDIX A
COMPUTER PROGRAM TMVSV

C: TMVSV WITH STNR
C: MD VS VR WITH SIGNAL TO NOISE RATIO
C: TERNARY VALUES

DIMENSION ALP(97),ALN(97),EAL(97),R(97),CJP(97),EM(97),F(97)
REAL*8 B9

C: ENP IS THE N+ CONCENTRATION
C: EPS IS THE PERMITTIVITY OF THE MATERIAL
C: Q IS THE CHARGE OF THE ELECTRON
DATA ENP,EPS,Q,B9/1.E18,1.1317E-12,1.60219E-19,E/
C: ALP IS THE HOLE IONIZATION RATE
C: ALN IS THE ELECTRON IONIZATION RATE
C: AP AND BP ARE CONSTANTS FOR THE MATERIAL
C: ALP(X) = AP EXP((BP/E)(X))
C: SAME FOR AN AND BN
DATA AP,BP,AN,BN/1.3E9,2.7E6,1.0E9,3.6E6/

COMMON NX,DX,CRCT,F
INTEGER P
TYPE 90
CALL ASSIGN (3, '',-1)
TYPE 91
CALL ASSIGN (2, '',-1)
ELMTP=BP/B9.
ELMTN=BN/B9.
P=2
NX=97
NX1=NX-1

C: ALF IS THE ABSORPTION COEFFICIENT
CALL AXPTR(ENP,'TERNARY ','CONCENTR','ATION ',B9)
CALL AXPTR(ALF,'ABSORPTI','ON COEFF',B9,B9)
CALL AXPTR(VR,'MIN VAL','UE OF V','OLTAGE ',B9)
CALL AXPTR(VR,'MAX VAL','UE OF V','OLTAGE ',B9)
CALL AXPTR(DVR,'INCREME','NT OF V','OLTAGE ',B9)
CALL AXPTR(WJM,'WJ IN MI','CRONS = ',B9,B9)
WJ=1.E-4*WJM

C: CALCULATION OF WJ
I W = SQRT ((2.*EPS/(D*ENQ)*(VR))
   IW=0
   DX=W/NX1
   IF (W.LE.WJ) GO TO S
   IW=1
   DX=WJ/(NX-2.)
   W = SORT((2.*EPS*VR/ENP)+(ENP-ENQ)*(WJ**2)/ENP)

C: CALCULATION OF THE LIGHT
S DO 25 I = 1,NX1
   X=(I-1)*DX
   EAL(I) = ALF*EXP(ALF*(X-WJ))
C: CALCULATION OF THE ELECTRIC FIELD

\[
E = (I - I_W \times (U - X) \times E_{NO} + I_W \times (W - U) \times E_{NO} \times (W - X) \times E_{NO}) \times Q / \varepsilon
\]

IF \( X.GT.WJ \) \( E = 0 \times \varepsilon \)
\[
\text{ALP}(I) = 0,0
\]
\[
\text{ALN}(I) = 0,0
\]
IF \( E.GT.E_{LMTP} \) \( \text{ALP}(I) = \text{AP} \times \exp(-B_P/E) \)
IF \( E.GT.E_{LMTN} \) \( \text{ALN}(I) = \text{AN} \times \exp(-B_N/E) \)
25 \( F(I) = \text{ALP}(I) - \text{ALN}(I) \)
IF \( W.GT.WJ \) \( \text{EAL}(\text{HX}) = \text{ALF} \)
\[
\text{ALP}(\text{HX}) = 0,0
\]
\[
\text{ALN}(\text{HX}) = 0,0
\]
\[
F(\text{HX}) = 0,0
\]
\[
\text{CRCT} = 0,0
\]
IF \( \text{IX} . \text{EQ} . I \) \( \text{CRCT} = W - WJ - DX \)
CALL \text{INTGRT}
DO 30 I = 1, NX
\[
R(I) = \exp(F(I))
\]
30 \( F(I) = \text{ALN}(I) \times R(I) \)
CALL \text{INTGRT}
C = 1 ./ (1. - F(NX))
DO 35 I = 1, NX
EM(I) = C \times R(I)
35 \( F(I) = \text{EAL}(I) \times EM(I) \)
CALL \text{INTGRT}
C: CJ IS THE MULTIPLICATION
\[
\text{CJ} = F(NX)
\]
DO 45 I = 1, NX
45 \( F(I) = (\text{EAL}(I) + \text{CJ} \times \text{ALN}(I)) \times R(I) \)
CALL \text{INTGRT}
DO 50 I = 1, NX
C: CJP IS THE CURRENT DENSITY OF HOLES
\[
\text{CJP}(I) = (\text{CJ} - F(I)) / R(I)
\]
50 \( F(I) = (\text{EAL}(I) + \text{CJ} \times \text{ALP}(I)) \times R(I) \)
CALL \text{INTGRT}
C: CJNZ IS CURRENT DENSITY OF ELECTRONS AT ZERO JN(\theta)
\[
\text{CJNZ} = \text{CJ} \times R(\text{NX}) - F(\text{NX})
\]
DO 60 I = 1, NX
\[
\text{ALN}(I) = \text{EAL}(I) + \text{CJ} \times \text{ALN}(I) + \text{CJP}(I) \times (\text{ALP}(I) - \text{ALN}(I))
\]
\[
\text{ALP}(I) = (\text{F}(I) + \text{CJNZ}) / R(I)
\]
60 \( F(I) = \text{ALN}(I) \times EM(I) \times \varepsilon \)
CALL \text{INTGRT}
C: FIN IS THE NORMALIZED SPECTRAL DENSITY
\[
\text{FIN} = F(\text{NX}) + \text{CJP}(\text{NX}) \times EM(\text{NX}) \times \varepsilon + \text{CJNZ} \times EM(1) \times \varepsilon
\]
C: STN IS THE SIGNAL TO NOISE RATIO
\[
\text{STN} = \text{CJ} / \text{FIN}
\]
WRITE (3, 94) VR, CJ, FIN, STN
WRITE (2, 92) VR, CJP(NX), CJNZ
VR = VR + DVR
IF (VR.GT.VRM) GO TO 80
GO TO 1
80 CONTINUE
CALL \text{CLOSE (2)}
CALL \text{CLOSE (3)}
STOP
SUBROUTINE AXPTR (R,T1,T2,T3,T4)
REAL*8 T1,T2,T3,T4
WRITE (7,2) T1,T2,T3,T4
2 FORMAT (1X,4A8,$)
READ (5,3) R
3 FORMAT (G20.10)
RETURN
END

SUBROUTINE AXPTI (I,T1,T2,T3,T4)
REAL*8 T1,T2,T3,T4
WRITE (7,2) T1,T2,T3,T4
2 FORMAT (1X,4A8,$)
READ (5,3) I
3 FORMAT (I4)
RETURN
END

SUBROUTINE INTGRT
DIMENSION F(1)
COMMON NX,DX,CRCT,F
S=0.
DO 10 I=2,NX
V=F(I-1)
F(I-1)=S
10 S=S+0.5*DX*(V+F(I))
F(NX)=S+0.5*CRCT*(F(NX-1)+F(NX))
RETURN
END
APPENDIX B

COMPUTER PROGRAM TPMSN

C: PROGRAM TPMSN
C: SIGNAL TO NOISE RATIO WITH PROFILE

DIMENSION ALP(97), ALN(97), EAL(97), R(97), CJP(97), EM(97), F(97),
X
PR(12), PRF(48), EF(97)
REAL *8 B8
C: ENP IS THE N+ CONCENTRATION
C: EPS IS THE PERMITTIVITY OF THE MATERIAL
C: Q IS THE CHARGE OF THE ELECTRON
DATA ENP, EPS, 0.88 /1.58, 1.0935E-12, 1.60219E-19, ’/’
C: ALP IS THE HOLE IONIZATION RATE
C: ALN IS THE ELECTRON IONIZATION RATE
C: AP AND BP ARE CONSTANTS OF THE MATERIAL
C: SAME FOR AN AND BN
DATA AP, BP, AN, BN/1.3E8, 2.7E6, 1.0E9, 3.6E6/
COMMON NX, DX, CRCT, F
INTEGER P
TYPE 98
CALL ASSIGN (3, ’,’,-1)
TYPE 100
CALL ASSIGN (2, ’,’,-1)
ELMTP=BP/88.
ELMTN=BN/88.
P=2
NX=97
NXI-NX-1
CALL AXPTR(ALF,’ABSORPTI’,’ON COEFF’,B8,B8)
CALL AXPTR(CJOP,’OPTIMIZI’,’NG AT M’,’= ’,B8)
DCJOP=0.084*CJOP
CALL AXPTR(WJM,’WJ IN MI’,’CRONS ’,B8,B8)
WJ=1.E-4*WJM
DX=WJ/(NX-2.)
C: CALCULATION OF THE PROFILE
CALL AXPTI(NPR,’* OF PRO’,’FILE SEC’,’= ’,B8)
CALL AXPTI(NLV,’* OF LEV’,’ELS IN E’,’ACH SEC’,’= ’)
CALL AXPTI(ILS,’TYPE 1 I’,’F LVLS S’,’AME 0:N’,’0 ’)
NT=NLV*NPR
NSC=NX*NPR
ILA=ILS*NLV+(1-ILS)*NLV*NPR
TYPE 91
ACCEPT 92, (PRF(I), I=1, ILA)
TYPE 97
DO 80 J=1, NT
DO 5 I=1, NPR
I=IPR-II+1
IJ=(J-1)/NLV*IPR(I)+1-(J-1)/NLV*IPR(I)
IF (ILS.EQ.0) IJ=IJ+(NPR-I)*NLV
PR(I)=PRF(IJ)
PRI=PRI+0.001
WRITE (3,93) PRI

DATA ENP, EPS, 0.88 /1.58, 1.0935E-12, 1.60219E-19, ’/’
C: ENP IS THE N+ CONCENTRATION
C: EPS IS THE PERMITTIVITY OF THE MATERIAL
C: Q IS THE CHARGE OF THE ELECTRON
C: SAME FOR AN AND BN
DATA AP, BP, AN, BN/1.3E8, 2.7E6, 1.0E9, 3.6E6/
C: ALP IS THE HOLE IONIZATION RATE
C: ALN IS THE ELECTRON IONIZATION RATE
C: AP AND BP ARE CONSTANTS OF THE MATERIAL
C: CALCULATION OF THE PROFILE
CALL AXPTI(NPR,’* OF PRO’,’FILE SEC’,’= ’,B8)
CALL AXPTI(NLV,’* OF LEV’,’ELS IN E’,’ACH SEC’,’= ’)
CALL AXPTI(ILS,’TYPE 1 I’,’F LVLS S’,’AME 0:N’,’0 ’)
NT=NLV*NPR
NSC=NX*NPR
ILA=ILS*NLV+(1-ILS)*NLV*NPR
TYPE 91
ACCEPT 92, (PRF(I), I=1, ILA)
TYPE 97
DO 80 J=1, NT
DO 5 I=1, NPR
I=IPR-II+1
IJ=(J-1)/NLV*IPR(I)+1-(J-1)/NLV*IPR(I)
IF (ILS.EQ.0) IJ=IJ+(NPR-I)*NLV
PR(I)=PRF(IJ)
PRI=PRI+0.001
WRITE (3,93) PRI
TYPE 93, PRI
5 PR(I)=PR(I)*1.E15
  U=WJ
  DW=1.E-6
  KK=20
  K=0
  L=0
10 DO 15 I=1,NX1
  IPR=1+(I-1)/NSC
15 F(I)=PR(IPR)
  CRCT=0.0
  CALL INTGRT
C: CALCULATION OF THE ELECTRIC FIELD
DO 20 I=1,NX1
20 R(NX-I)=Q*(ENP*(U-WJ)+F(I))/EPS
  CALL INTGRT
C: CALCULATION OF THE VOLTAGE
DO 25 I=1,NX1
  E=R(I)
  EF(I)=E
  X=(I-1)*DX
  EAL(I)=ALF*EXP (ALF*(X-WJ))
  ALP(I)=0.0
  ALN(I)=0.0
  IF (E.GT.ELMTP) ALP(I)=AP*EXP (-BP/E)
  IF (E.GT.ELMTN) ALN(I)=AN*EXP (-BN/E)
25 F(I)=ALP(I)-ALN(I)
  EAL(NX)=ALF*EXP (ALF*(W-WJ))
  IF (W.GT.WJ) EAL(NX)=ALF
  ALP(NX)=0.0
  ALN(NX)=0.0
  CALL INTGRT
DO 30 I=1,NX
30 R(I)=EXP (F(I))
30 F(I)=ALH(I)*R(I)
  CALL INTGRT
  C=1./(1.-F(NX))
DO 35 I=1,NX
  EM(I)=C*R(I)
35 F(I)=EAL(I)*EM(I)
  CALL INTGRT
  CJ=F(NX)
  L=L+1
  IF (L.GE.5.AND.K.EQ.0) GO TO 75
  IF (CJ.LT.0.0.OR.CJ.GT.CJOP) GO TO 70
  K=K+1
  IF ((CJOP-CJ).LT.DCJOP.OR.K.GE.KK) GO TO 40
  U=U+DW
  GO TO 10
40 DO 45 I=1,NX
45 F(I)=(EAL(I)+CJ*ALN(I))*R(I)
CALL INTGRT
DO 50 I=1,NX
CJP(I)=(CJ-F(I))/R(I)
50 F(I)=(EAL(I)+CJ*ALP(I))*R(I)
CALL INTGRT
CJNZ=CJ*R(NX)-F(NX)
DO 55 I=1,NX
55 F(I)=(EAL(I)+CJ*ALN(I)+CJP(I)*(ALP(I)-ALN(I)))*EM(I)**P
CALL INTGRT

C: NORMALIZED SPECTRAL DENSITY
FIN=F(NX)+CJP(NX)*EM(NX)**P+CJNZ*EM(I)**P

C: SIGNAL TO NOISE RATIO
STN=CJ*FIN
DWJ=(W-WJ)*1.E4
WRITE (3,94) VR,DWJ,CJ,STN
TYPE 94, VR,DWJ,CJ,STN
DO 60 I=1,NX
60 WRITE(2,101) EAL(I),EM(I),CJP(I),ALP(I),ALN(I),EF(I)
CALL CLOSE (2)
GO TO 80
70 DWJ=0.5*DWJ
W=W-DWJ
GO TO 10
75 WRITE (3,95)
TYPE 95
80 CONTINUE
CALL CLOSE (3)
STOP
90 FORMAT ('SAVE RESULTS IN FILE',$,S)
100 FORMAT ('FILE FOR G,M,JP,AN,E',$,S)
91 FORMAT ('LEVELS OF NO/1.E15 ARE: (MAX 12 IN A LINE)')
92 FORMAT (12F6.3)
93 FORMAT ('+',F5.2,1X,)$
94 FORMAT ('**CANNOT FIND SOLUTION**')
95 FORMAT ('**COULD NOT FIND SOLUTION**')
101 FORMAT(IX,6(E12.4,','),E12.4)
97 FORMAT (/$)
END

SUBROUTINE AXPTR (R,T1,T2,T3,T4)
REAL*8 T1,T2,T3,T4
WRITE (7,2) T1,T2,T3,T4
2 FORMAT (1X,4AH,$)
READ (5,3) R
3 FORMAT (G20,10)
RETURN
END
SUBROUTINE AXPTI (I,T1,T2,T3,T4)
REAL*8 T1,T2,T3,T4
WRITE (7,2) T1,T2,T3,T4
2 FORMAT (1X,4A8,5)
READ (5,3) I
3 FORMAT (14)
RETURN
END

SUBROUTINE INTGRT
DIMENSION F(I)
COMMON NX,DX,CRCT,F
S=0.
DO 10 I=2,NX
V=F(I-1)
F(I-1)=S
10 S=S+0.5*DX*V+F(I)
F(NX)=S+0.5*CRCT*(F(NX-1)+F(NX))
RETURN
END
LIST OF REFERENCES


Pearsall, T.P.; Nahory, R.E.; and Pollack, M.A. "Impact Ionization Coefficients for Electrons and Holes in In_{0.14}Ga_{0.86}As." Applied Physics Letters 27 (September 15, 1975):330-332.


