Dilute nitride-based photodetectors : fabrication, characterization and performance

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**DILUTE NITRIDE-BASED PHOTODETECTORS:
FABRICATION, CHARACTERIZATION AND
PERFORMANCE**

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A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

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Statement of originality

I hereby certify that the work embodied in this thesis is the result of original research and that it has not been submitted for a higher degree to any other university or institution.

Date

Xu Zhe

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List of Publications

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- waveguide photodetector with response up to 1.6 μm grown by molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 83, pp. 081102-1-3, 2008.
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Summary

Dilute nitride materials grown on GaAs substrate have shown the potential to act as new material candidates for the optical-fiber communication system. In particular, GaNAsSb has been found to be superior to its predecessor, GaInNAs, due to the possibility of suppressing In-induced N clustering and N-related defects in the material.

In this work, high performance photodetectors containing GaNAsSb as the active layer grown on GaAs substrate are demonstrated. The numerical studies show that a high quantum efficiency and a large bandwidth can be achieved by employing a waveguide structure. With a proper propagation distance ($\sim 10\ \mu\text{m}$), the light absorption is efficient and the GaNAsSb layer is applicable to be grown thin enough ($\sim 0.4\ \mu\text{m}$) for a short carrier transit-time. A thin GaNAsSb layer allows a further extension of the absorption edge (reduction of the bandgap) by increasing the N and Sb contents with the compromise of introducing more lattice strain. The use of additional AlGaAs cladding layers enhances the optical confinement and reduces the optical field mismatch between the waveguide and the fiber.

GaNAsSb on GaAs waveguide photodetectors (WGPDs) were successfully fabricated in this project. At the $1.3\ \mu\text{m}$ wavelength, high responsivity values of $0.72\ \text{A/W}$ and $0.55\ \text{A/W}$ were obtained for WGPDs with and without additional AlGaAs cladding layers, respectively. These values corresponded to the very

high internal quantum efficiencies of 96.7% and 73.9%, respectively. The optical performance agreed with the numerical studies. The best cut-off frequency was 16.5 GHz for the GaNAsSb/GaAs/AlGaAs WGPd.

At the 1.55 μm wavelength, the best responsivity was 0.6 A/W (0.1 mW optical power injection) at -4 V bias. Several GaNAsSb on GaAs WGPds with different dimensions showed bandwidths over 10 GHz with the best value being 14.3 GHz and a responsivity of ~ 0.2 A/W at the same time.

The combined performances achieved in this thesis are considered the best results for the dilute nitride-based photodetectors for the 1.3 μm and 1.55 μm wavelengths. Further analysis shows that the overall frequency responses were resistance-capacitance time limited. Based on the measurement setup, the small-signal equivalent circuits of the 2-port network are discussed. In this approach, the WGPd is represented by a lumped-element model with its bias dependent resistance and capacitance fitted from the reflection coefficient.

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List of Symbols

Symbols	Description
λ	Wavelength
ε	Permittivity
Ω	Ohm
q	Elemental electronic charge
e	Base of the natural logarithm
V_{bi}	Junction built-in voltage
V_R	Applied reverse bias voltage
N_a	Acceptor-impurity density
N_d	Donor-impurity density
W	Junction depletion width
R	Resistance
R_L	Load resistance
R_s	Series resistance
C_j	Junction capacitance
C_{pad}	Contact pad capacitance
$\emptyset$	Flux of incident light
α	Absorption coefficient
A	Illumination area
x	Position along the propagation direction

L	Propagation length
J	Current density
J_{ph}	Photocurrent density
I_{ph}	Photocurrent
η	Quantum efficiency
η_i	Internal Quantum efficiency
R_λ	Responsivity
A	Illumination area
x	Propagation distance
$h\nu$	Photon energy
P_{inc}	Incident optical power
t_{tr}	Carrier transit time
t_{RC}	Charge-discharge time of resistance-capacitance
v_d	Carrier drift velocity
v_s	Carrier saturation velocity
ω	Angular frequency ($2\pi\nu$)
f_{3dB}	3dB cutoff frequency
f_{tr}	Transit time limited 3dB cutoff frequency
f_{RC}	RC time limited 3dB cutoff frequency
n	Refractive index
n_{core}	Refractive index for core layer

n_{eff}	Effective refractive index
$n_{clad1,2}$	Refractive index for cladding layer 1, 2
k	Extinction coefficient
Γ	Optical confinement factor in waveguide
$\vec{E}$	Electric field
$E(x, y, z, t)$	Scalar electric field
$k(x, y, z)$	Spatially dependent wavenumber
$n(x, y, z)$	Spatially dependent refractive index
$d_{1,2}$	Thickness of the cladding layer 1, 2
S_{11}	Reflection coefficient of port-1
S_{21}	Forward transmission coefficient
Y_{11}	Admittance of port-1
g_m	Transconductance

Chapter 1: Introduction

First developed in the 1970s, fiber-optic communication has revolutionized the telecommunications industry and has played a major role in the advent of the information age. The importance of optical means of data transmission and processing has been accelerated by the advantages of optical means over electrical means. These advantages include increased transmission speed and distance, freedom from electromagnetic noise, reduced weight and size, and improved security [1].

The expansion of the Internet demands larger capacity and faster transmissions. In optical transmission systems, bit rates with terabits/s have been demonstrated by using wavelength division multiplexing (WDM) or optical time division multiplexing (OTDM) techniques [2]. Optoelectronic devices composed of III-V compound semiconductor materials have been essential in the practical realization of such optical transmission systems. Examples of these optoelectronic devices are photodetectors, lasers, and modulators. The research and development conducted on these optoelectronic devices continues to make them faster and more efficient in meeting the demand from optical fiber links.

1.1. Optical-fiber links

A basic optical communication system is shown in Figure 1.1. The transmitter sends the data information optically in the form of a modulated light signal. The light signal is then transmitted over some distance in a light guiding medium (i.e. an optical fiber). An optical amplifier may compensate for the loss of signal strength along the guiding distance. At the receiver part, this modulated light signal is detected by a photodetector and is converted into an electrical signal (i.e. a photocurrent). Finally, the external decision circuit extracts the data information.

Figure 1.1. Diagram of a basic optical communication system.

Light is attenuated during its propagation in the optical fiber. The attenuation characteristic when a silica fiber is used is shown in Figure 1.2 [3]. In the shorter wavelength, the attenuation is due to the Rayleigh scattering loss from the amorphous structure of the silica fiber. In the longer wavelength, the attenuation is due to the infrared absorption. Thus, to minimize the attenuation, the optical-fiber communication system has been designed to operate in one of the following three "telecom windows".

Figure 1.2. The measured attenuation in silica fibers (solid line) and theoretical limits (dashed lines) given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations (infrared absorption) in the infrared spectral region.

The first telecom window at the 800–900 nm was originally used. GaAs/AlGaAs laser diodes and light-emitting diodes (LEDs) served as transmitters and silicon photodiodes served as receivers. However, the fiber attenuations are still relatively high in this window and the fiber amplifiers are not developed well for this spectral region. Therefore, this telecom window is only suitable for short-distance transmission.

The second telecom window utilizes wavelengths around 1.3 μm where the attenuation of the silica fibers is much lower (<1 dB/km) and the fibers' chromatic dispersions are very weak. This window was used originally for long-haul transmission. However, the fiber amplifiers for 1.3 μm are not as good as the fiber amplifiers for the wavelength of 1.55 μm . In addition, low dispersion is not necessarily ideal for long-haul transmission since it increases the effects of optical nonlinearities.

The third telecom window utilizes the wavelengths around 1.55 μm and it is now widely used. The losses of the silica fibers attains the absolute minimum (<0.2 dB/km) in this spectral region and erbium-doped fiber amplifiers with very high performances are available. Fiber dispersion is usually anomalous but it can be tailored with flexibility.

1.2. The background of dilute-nitride materials and GaNAsSb

Figure 1.3 illustrates the bandgap energy and the lattice constant for the III-V compound alloy systems from these wavelengths [3]. In order to operate at the wavelengths of 1.3 μm and 1.55 μm , the optoelectronic devices require their active materials to have bandgaps of 0.95 and 0.8 eV. Previously, III-V material with a bandgap of less than 1.2 eV was not possible to be realized on other substrates but only on the InP substrate. This limitation was due to the lack of small bandgap materials that were lattice-matched to the other substrates (i.e. GaAs).

Figure 1.3. Graph of the bandgap energy and the lattice constant for the III-V compound alloy system.

The driving force for developments on the GaAs-based material system is to benefit from the advantages of this material system over other material systems. Compared with InP, GaAs has a lower substrate cost, a greater robustness, and is available in larger wafer sizes. To date, GaAs is the most important compound semiconductor material technologically and it is also the most studied one [4]. Many band structure parameters for GaAs are known with a greater precision than the band structure parameters for other compound semiconductors [5]. In addition, the availability of Ge-terminated Si substrate using a $\text{Si}_x\text{Ge}_{1-x}$ graded buffer has opened up the possibility of eventually growing GaAs-based III-V compound semiconductor devices on Si substrates due to the small lattice mismatch ($\sim 0.4\%$) between Ge and GaAs.

However, with the introduction of the GaNAs material in 1992 [6], researchers found that the incorporation of a small amount of nitrogen atoms (up to 4%) rapidly reduced the bandgap of GaAs. As shown in Figure 1.4, the interaction of the nitrogen state with the conduction band of GaAs splits the conduction band of GaNAs into two energy levels which reduce the minimum of the new conduction band [7]. In 1996, Kondow *et al.* reported the first material using the GaInNAs system that was lattice-matched to GaAs and had a small bandgap (1 eV) [8]. After continuous development in the past decade, compressively strained GaInNAs/GaAs quantum-wells appeared as challenging candidates to replace the GaInAsP/InP system for emission at the 1.3 μm wavelength. In

addition, edge-emitting lasers and vertical-cavity surface-emitting lasers (VCSEL) have been reported [9, 10]. GaInNAs has also been investigated for use in solar cells to improve their efficiency [11] and for use in heterojunction bipolar transistors (HBT) to improve their turn-on voltage [12].

Figure 1.4. Diagram of the splitting of the conduction band (E^C) into two energy levels (E_+ and E_-) for $\text{GaAs}_{0.99}\text{N}_{0.01}$ by the interaction of the nitrogen state (E^N).

In addition to GaInNAs, GaNAsSb has showed a tremendous potential over its predecessor since it was first reported by Ungaro *et al.* in 1999 [13]. Figure 1.5 shows the incorporation of a small percent of nitrogen (N) and antimony (Sb) atoms in GaAs to counter-balance the lattice strain and reduce the bandgap [14]. GaNAsSb is lattice-matched to GaAs by keeping the Sb and N concentration ratio at ~ 2.6 . Compared to the indium (In) used in GaInNAs, Sb induces a larger bandgap reduction in GaNAsSb [15]. Hence, less nitrogen composition is needed to reduce the bandgap energy necessary for 1.3 and 1.55 μm operations. In addition, by replacing In with Sb, the In-induced N clustering that leads to the formation of N-related defects in GaInNAs can be suppressed in GaNAsSb; thus resulting in a less defective material [16, 17].

Figure 1.5. The diagram showing the influence of incorporating nitrogen and antimony into GaAs on the bandgap energy and lattice constant.

1.3. Advantages of a waveguide photodetector

Conventional top-illuminated photodetectors rely on large illumination areas and thick absorption layers for sufficient photon absorption. Neither the transit time (governed by the transit time of carriers and the thickness of the absorption layer) nor the resistance-capacitance (RC) time (governed by the areas of the junction and contact pad) could be optimized without compromising the quantum efficiency/responsivity of the device. This type of structure exhibits the inherent trade-off between the responsivity and the bandwidth. Moreover, in order to extend the absorption wavelength of GaNAsSb to the 1.55 μm , the GaNAsSb has to be strained. Thus the growth of a thicker GaNAsSb absorption layer on GaAs for top-illuminated photodetectors is not applicable.

To overcome the above problems, edge-illuminated photodetectors, i.e. waveguide photodetectors (WGPDs), are employed to achieve a high responsivity and a high bandwidth performance in this project. In the WGPD structure, light is guided in the core layer and is absorbed during its propagation. The photogenerated carriers transit perpendicularly to the light propagating direction under the applied electric field. The quantum efficiency and the responsivity depend largely on the propagation length and are less sensitive to the thickness of the absorption layer. Since the core layer can be designed much thinner, the strained GaNAsSb layer for the 1.55 μm operating

wavelength is readily used in this structure. The propagation length, which is typically around 10 μm (depending on the absorption coefficient), is long enough for absorbing most of the light but is short enough for keeping the junction capacitance small. The bandwidth of the WGPd is determined by the carriers' transit time and the RC -time. Therefore, the responsivity and the bandwidth of the devices can be optimized almost separately. For example, in the InP material system, mushroom-mesa WGPds using InGaAs/InP have demonstrated a 110 GHz bandwidth with a 50% quantum efficiency at the 1.55 μm wavelength [18]. This 55 GHz bandwidth-efficiency product is much superior to the inherent top-illuminated single-pass limit of 30 GHz for InGaAs at the same wavelength.

1.4. Objectives

The first objective of this project is to realize high performance photodetector devices using GaNAsSb on GaAs substrate. The primary goal is the design and demonstration of 1.3 μm GaNAsSb photodetectors with improved electrical bandwidths and high responsivity. In order to attain this goal, a compact device structure with a strong light confinement capability is constructed.

The second objective of this project is to extend the detection wavelength of the photodetector to 1.55 μm with a high bandwidth-efficiency performance.

The third objective is to gain a better understanding of the properties of the material and the physics of the devices through the characterization process.

1.5. Major contribution of this thesis

In this thesis, detailed discussions on the structural optimization of a high quantum efficiency and high bandwidth GaNAsSb on GaAs WGPd for the 1.3 μm wavelength were presented. In the numerical simulation, a waveguide structure consisting of a 0.5 μm thick AlGaAs and a 0.5 μm thick GaAs double cladding layers on each side, and a 0.4 μm thick GaNAsSb core layer was shown to provide strong light confinement. Such WGPd with a 4 μm ridge width and a 10 μm ridge length showed a high internal quantum efficiency of 91.5% and a very high cut-off frequency of 80 GHz in calculation. This provided a general design guide for the growth and fabrication of a high speed and a high efficiency waveguide photodetector.

GaNAsSb/GaAs/AlGaAs and GaNAsSb/GaAs WGPds designed for the 1.3 μm wavelength were fabricated and characterized. A lower dark current density and a high reverse breakdown voltage were obtained. A very high internal quantum efficiency of 96.7% and a high responsivity of 0.71 A/W were obtained for the GaNAsSb/GaAs/AlGaAs WGPd with a 6 μm ridge width and a 25 μm ridge length. The bandwidth of the same device was 16.5 GHz at the -10 V bias condition. This is the best responsivity-bandwidth result to date for the

GaNAsSb based WGPd on GaAs for the 1.3 μm wavelength operation.

In addition, 1.55 μm GaNAsSb/GaAs WGPds using a 0.4 μm strained GaNAsSb layer, 1.0 μm *p*-GaAs, and ~ 0.3 μm *n*-GaAs cladding layers were demonstrated. Two best devices show a 0.44 A/W responsivity with an 11 GHz bandwidth and a 0.2 A/W responsivity with a 14.3 GHz bandwidth. This was the first report of using GaNAsSb/GaAs in high speed photodetectors for 1.55 μm wavelength operation. Based on the measurements, a small-signal equivalent circuit model was constructed to fit the experimental results.

1.6. Organization of the thesis

Chapter 1 provides an overview of the optical fiber communication, an introduction to dilute-nitride materials, and an outline of the benefits of employing a WGPd structure. The motivation for the work and the objectives of the work are also presented. This chapter also contains the major contributions of this work and an outline of the organization of this thesis.

Chapter 2 presents the *p-i-n* photodetector fundamentals in addition to the optics and the modeling of the WGPd. These are followed by a detailed discussion on the design considerations of GaNAsSb-based WGPds including the bandwidth estimation, the optical confinement, and the external coupling factors.

Chapter 3 discusses the process technology of the device fabrications. Chapters 4 and 5 present the experimental results and the analysis for the WGDs with different GaNAsSb compositions and epilayer structures designed for the 1.3 μm and 1.55 μm wavelengths, respectively.

Chapter 6 provides a small-signal equivalent circuit model for the 1.55 μm WGDs involving the intrinsic elements from the WGD and the parasitic elements from the measurement network. The last chapter, Chapter 7, contains an overall conclusion and some recommendations for future research.

Chapter 2: The Design and Optimization of a Waveguide Photodetector

2.1. Introduction

A WGPD is essentially a shorter form of an optical waveguide. The waveguide core layer absorbs the light energy, which, from the electrical point of view, represents the depletion layer of a $p-i-n$ junction. A very thin core layer leads to a short carrier transit-time at a given electric field. However, such thin layer may cause only a fraction of the optical mode to be confined in the core layer upon the fiber to the waveguide coupling. Therefore, the optical and electrical designs are interlocked. A detailed approach for the structural optimization of the GaNAsSb WGPD is presented in this chapter.

2.2. $p-i-n$ photodetector fundamentals

A photodetector is an optoelectronic device that absorbs optical energy and converts it to electrical energy, which usually manifests as a photocurrent. Three steps are usually involved in the photodetection process: (1) the absorption of optical energy and the generation of carriers, (2) the transportation of the photogenerated carriers across the absorption region, and (3) the carrier collection and the formation of a photocurrent that flows through an external circuit. The process of detection is sometimes associated with

demodulation, which occurs when a time-varying optical signal is converted into a time-varying electrical signal and is further processed and rectified. Photodetectors have a broad range of applications including infrared sensors in opt-isolators and detectors for optical-fiber communications. For these applications, photodetectors must have a high sensitivity at their operating wavelength, a low noise operation, wide bandwidths, a high reliability, and a low cost [19, 20].

Among the various types of photodetectors, the junction photodiode is the most common photodetection device. Junction photodiodes can be made with any semiconductor material in which a junction can be formed by joining *p*-type and *n*-type semiconductors together. This enables the photodiode to operate for a spectral range from visible to far infrared by using elemental and compound semiconductors. The bandgap and the lattice constants of these compound semiconductors can be tuned to meet the wavelength requirement.

In a *p-n* junction, the majority carriers (i.e. holes from the *p*-side and electrons from the *n*-side) diffuse into the other side of the junction and, thus, a built-in electric field (E_{bi}) is formed by the diffusion process, which opposes the further diffusion of carriers across the junction. In essence, the electric field generates drift currents of electrons and holes that match the corresponding diffusion currents in the thermal equilibrium exactly. This ionized region consisting of

immobile positive and negative charges on opposite sides forms the depletion region (W). This formation of p-n junction process is shown in Figure 2.1.

Figure 2.1. (a) p -type GaAs (C doped) layer and n -type GaAs (Si doped) layer before joining as junction and (b) formation of depletion region under thermal equilibrium.

Photodiodes operate under reverse bias conditions in which the applied electric field is in the same direction as the built-in electric field and in which the depletion region further expands. The depletion width is given in (2.1), where ε is the permittivity of the material, q is the elementary charge, V_{bi} and V_R are the built-in voltage of the photodiode and the applied reverse bias voltage across the junction, and N_a and N_d are the doping concentrations of the p -side and n -side.

$$W = \sqrt{\frac{2\varepsilon}{q} \cdot (V_{bi} + V_R) \cdot \left(\frac{1}{N_a} + \frac{1}{N_d}\right)} \quad (2.1)$$

The photoexcitation occurs when the incident photon energy is larger than the bandgap of the semiconductor material. The photons are absorbed mainly in the depletion region and in the neutral regions (particularly on the top when the light passes through). The photogenerated carriers are accelerated in the opposite directions by the electric field in the depletion region and they form a photocurrent. Photocurrent is detected, therefore, as an increase in the reverse-biased current. This process is shown schematically in Figure 2.2.

(a)

(b)

Figure 2.2. (a) A p - n photodiode showing carrier drift (depletion) and diffusion regions and (b) typical current-voltage relationship in the dark and under illumination.

For light propagation in bulk materials, Lambert's Law and Ray Optics apply. The power intensity (i.e. flux, Φ) of the incident light decays exponentially to the material's absorption coefficient (α) and propagation distance (x). Given an illumination area of A and a depletion width of W , the photocurrent generated can be obtained (see Eq. 2.4).

$$\Phi(x) = \Phi_0 \cdot e^{-\alpha x} \quad (2.2)$$

$$J_{ph} = q \cdot \int_0^W G_L dx = q \cdot \int_0^W \Phi_x dx = q \cdot \Phi_0 \cdot (1 - e^{-\alpha W}) \quad (2.3)$$

$$I_{ph} = J_{ph} \cdot A = q \cdot \Phi_0 \cdot A \cdot (1 - e^{-\alpha W}) \quad (2.4)$$

The two important figures of merit relating to the DC performance of the photodetector are quantum efficiency (η) and responsivity (R_λ) as given in (2.5) and (2.6). Quantum efficiency is defined as the number of electron-hole pairs collected to produce the photocurrent I_{ph} divided by the number of incident photons at a given incident optical power, P_{inc} . The internal quantum efficiency η_i is the number of electron-hole pairs generated divided by the number of photons absorbed and is usually very high. The absorption coefficient is a function of the wavelength and, therefore, for practical photodetectors, the long-wavelength cut-off of the spectral response is determined by the absorption edge or the bandgap of the semiconductor.

$$\eta = \frac{I_{ph}/q}{P_{inc}/h\nu} = 1 - e^{-\alpha W} \quad (2.5)$$

$$R_\lambda = \frac{I_{ph}}{P_{inc}} = \eta \cdot \frac{q}{h\nu} \quad (2.6)$$

From (2.5) and (2.6), it is obviously desirable to have a large depletion layer width (W) to obtain a higher quantum efficiency and responsivity. Aiming for this, a $p-i-n$ structure is usually used more commonly as shown in Figure 2.3. The $p-i-n$ photodiode has an intrinsic (non-intentionally doped) layer sandwiched between the p and n layers. Because of a very low density of free carriers in the intrinsic layer (high resistivity), any applied bias drops almost entirely across the intrinsic layer, which could be fully depleted at a very small reverse bias. Therefore, the $p-i-n$ photodiode has a "controlled" depletion width and a more uniform electrical field distribution in the depletion region. For vertically-illuminated $p-i-n$ structures, photoexcitation is usually provided through an etched opening in the top contact. Hence, the quantum efficiency and the responsivity for such type of structure are mainly determined by the thickness of the intrinsic layer.

Figure 2.3. The schematic of a $p-i-n$ photodiode.

However, the frequency response is determined by two factors: (1) the transit time (t_{tr}) for the carriers to cross the depletion region ((2.7) and (2.8)), and (2) the time to charge-discharge the junction capacitance plus any parasitic capacitance in the circuit (i.e. the RC time (t_{RC}), (2.9)). The approximated cut-off frequency is given in (2.10) [21, 22]. Therefore, the vertically-illuminated $p-i-n$ photodetector's cut-off frequency is determined by the thickness W of the intrinsic layer. The cut-off frequency could either be transit-time limited when W is large or RC -time limited when W is small. In order for this kind of photodetector to be efficient in detection, the depletion layer thickness W has to satisfy $\alpha \cdot W \geq 1$ (2.5) which exceeds the optimum W for a high cut-off frequency ($\alpha \cdot W \ll 1$) in most cases [22]. Hence, this trade-off between the cut-off frequency and the quantum efficiency is inherent with the vertically-illuminated $p-i-n$ photodetectors. The reported bandwidth-efficiency product is

40 GHz for GaAs and 30 GHz for InGaAs [22-24]. A bandwidth of 12 GHz has been obtained for a GaNAsSb/GaAs vertically-illuminated *p-i-n* photodetector with an illumination diameter of 30 μm at 1.3 μm [25].

$$t_{tr} = \frac{W}{v_d} = \frac{W}{\mu \cdot (V_{bi} + V_R)} \quad (2.7)$$

$$t_{tr} = \frac{W}{v_d} = \frac{W}{v_s} \quad (2.8)$$

$$t_{RC} = 2.2 \cdot R \cdot C_j = 2.2 \cdot R \cdot \frac{\varepsilon A}{W} \quad (2.9)$$

$$f_{3dB} = \left(\frac{1}{f_{tr}^2} + \frac{1}{f_{RC}^2} \right)^{-\frac{1}{2}} = \left[\left(\frac{W}{0.45 \cdot v_s} \right)^2 + (2\pi \cdot 2.2 \cdot R \cdot \frac{\varepsilon A}{W})^2 \right]^{-\frac{1}{2}} \quad (2.10)$$

One solution to overcome the trade-off between the quantum efficiency and the cut-off frequency is to use edge-illuminated structure (i.e. the waveguide photodetector (WGPD)) as shown in Figure 2.4. In this case, the light propagation is perpendicular to the photogenerated carriers' transit direction. The propagation length L (for photon absorption) and the absorbing layer thickness W (for carriers' transition) can be designed almost separately to achieve a high quantum efficiency and a high bandwidth.

Figure 2.4. The schematic of an edge-illuminated p - i - n photodetector.

Due to the small dimension of the waveguide structure, the microwave signal can be considered uniform along the whole waveguide if the modulation is not very high. For example, at a modulation frequency below 20 GHz, the microwave length is longer than 2 mm for the waveguide, which is more than 100 times longer than the length of a WGPD. The phase variation of the voltage/current along the waveguide can be ignored [26]. Hence, the WGPD is electrically modeled using lumped elements [27, 28] (the same as vertically-illuminated p - i - n photodetectors). Since the design of the intrinsic layer thickness W is almost independent of the quantum efficiency (although it affects the fiber to waveguide coupling efficiency), the WGPD gives a much higher fundamental limit of bandwidth. Optically, the light absorption follows the Lambert's Law with a position dependent confinement factor Γ being introduced as shown in (2.11) and (2.12) (which is assumed to be a constant of 1 in the vertically-illuminated structure). Due to that, the core dimension is

much smaller than the diameter of the input fiber, the light propagation in the waveguide photodetector involves a continuous energy transfer between the core layer and the cladding layers. Hence, waveguide optics have to be considered to analyze the optical propagation characteristics in this case.

$$R_\lambda = \frac{I_{ph}}{P_{inc}} = \frac{q \cdot \phi_0 \cdot A \cdot (1 - e^{-\Gamma \alpha L})}{\phi_0 \cdot h\nu \cdot A} = \frac{q}{h\nu} \cdot (1 - e^{-\Gamma \alpha L}) \quad (2.11)$$

$$\eta = \frac{I_{ph}/q}{P_{inc}/(h\nu)} = (1 - e^{-\Gamma \alpha L}) \quad (2.12)$$

2.3. Waveguide photodetector optical modelling

All waveguides consist of a region with a higher refractive index where the light is confined (*core*) surrounded by regions of a lower refractive index where the light is not guided (*cladding*). Optical fiber is the most commonly seen circular waveguide. This thesis used rectangular waveguides in which light is confined two-dimensionally. Figure 2.5 shows two commonly used rib and ridge types of waveguide. The vertical confinement is formed by the refractive index contrast between the core layer and cladding layer ($n_{core} > n_{clad}$). The horizontal confinement is formed by etching to form either a rib or a ridge in which the effective refractive index on the sides (consisting of air and the passivation layer) is lower than that of the center.

Figure 2.5. A cross-sectional view of (a) a rib waveguide and (b) a ridge waveguide.

A waveguide mode is a wave solution to the Helmholtz equations ((2.13), (2.14)). In this thesis, due to the complexity of solving the numerical equations and monitoring optical power distributions, the studies were based on the *BeamPROP* program using the beam propagation method (BPM). The main computation steps are described below [29]. Taking the example of solving the electrical field ($\vec{E}$) with its scalar electric field ($E(x, y, z, t)$) and the spatially dependent wavenumber ($k(x, y, z)$) expressed as (2.15) and (2.16), equation (2.13) is defined entirely by the refractive index distribution $n(x, y, z)$ (2.17).

$$\nabla^2 \vec{E} + k_0^2 \epsilon \vec{E} = 0 \quad (2.13)$$

$$\nabla^2 \vec{H} + k_0^2 \epsilon \vec{H} = 0 \quad (2.14)$$

$$E(x, y, z, t) = \phi(x, y, z) e^{-j\omega t} \quad (2.15)$$

$$k(x, y, z) = k_0 n(x, y, z) = \frac{2\pi}{\lambda_0} n(x, y, z) \quad (2.16)$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} + k(x, y, z)^2 \cdot \phi = 0 \quad (2.17)$$

The most rapid variation in the field ϕ is the phase variation due to propagation along the guiding axis (Z-axis). In the scalar assumption, a slowly varying field u and reference wavenumber $\bar{k}$ are introduced to factor out the rapid phase variation as:

$$\phi(x, y, z) = u(x, y, z) e^{j\bar{k}z} \quad (2.18)$$

Substituting (2.18) into (2.17) yields the Helmholtz equation expressed in terms of u :

$$\frac{\partial^2 u}{\partial z^2} + 2i\bar{k} \frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2) u = 0 \quad (2.19)$$

$$\frac{\partial u}{\partial z} = \frac{i}{2\bar{k}} \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - \bar{k}^2) u \right] \quad (2.20)$$

Equation (2.20) is a parabolic partial differential equation and is solved by a finite difference method based on the Crank-Nicholson scheme.

2.4. GaNAsSb WGPD design considerations

2.4.1. Bandwidth estimation

The bandwidths at different WGPD lengths are calculated according to (2.10). The electron and the hole are assumed to have the same drift velocity varying from 2.0×10^6 cm/s to 1.0×10^7 cm/s and the intrinsic layer is assumed to be fully depleted. The WGPD width is fixed at 4 μm . From the electrical point of view, it is equivalent to doubling the ridge width while halving the ridge length to maintain the same junction area. The effect of the ridge width will be discussed later.

As depicted in Figure 2.6, the RC time effect is dominant for a thinner core layer while the transit-time effect dominates for a thick core layer. The optimum core layer thickness is obtained when these two effects are balanced. By considering the ridge length of 10 μm , it is possible to achieve a theoretical bandwidth higher than 80 GHz with a core thickness of about 0.3–0.4 μm .

Figure 2.6. The bandwidth versus the core layer thickness at different WGPD lengths (L) and carrier velocities (v_s).

2.4.2. Optical confinement improvement

Figure 2.7 shows the $n - k$ plots for GaNAsSb which were obtained from the Prism Coupling Method. The real part (n) represents the refractive index while the imaginary part (k) represents the extinction coefficient from which the absorption coefficient (α) is calculated.

Figure 2.7. The $n - k$ plots for $\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}$ (solid lines) and $\text{GaN}_{0.035}\text{As}_{0.785}\text{Sb}_{0.18}$ (dotted lines).

$\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}$ is designed for operating at the $1.3 \mu\text{m}$ wavelength. At this wavelength, its refractive index is 3.537, which is higher than that of GaAs [30] and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ [31] (3.090 for $x = 0.7$; 2.927 for $x = 1.0$). This fact suggests that both GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ are suitable to be the cladding layers of the $\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}$ $p-i-n$ WGPD. However, there is a large geometrical mismatch between the optical fields of the input light and the core layer. This is because the fiber diameter is at least $2.0 \mu\text{m}$ and the thickness of the WGPD core layer is typically less than $1.0 \mu\text{m}$. Hence, this could reduce the light coupling efficiency into the core layer. To overcome this issue, a non-

absorptive material with an intermediate refractive index (and bandgap) between that of the core and cladding materials can be inserted as an inner cladding layer to enlarge the optical field distribution and enhance the optical confinement [27, 32, 33]. Therefore, in optimizing the design of WGPD, the effects of the structural and compositional parameters on the theoretical limits of the quantum efficiency of the 1.3 μm WGPDs consisting of a GaNAsSb core, a GaAs inner cladding, and an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ outer cladding layers (i.e. a GaNAsSb/GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ structure as shown in Figure 2.8) were investigated.

Figure 2.8. The cross-sectional view of a GaNAsSb/GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ WGPD.

Consequently, optimum structural and compositional parameters for high speed operation and high quantum efficiency were obtained for the GaNAsSb/GaAs/Al_xGa_{1-x}As WGPD. Light of the 1.3 μm wavelength with Gaussian profile and a spot size (i.e. half $1/e$ width) of 1 μm of normal incidence to the air/waveguide interface ($z = 0$) was used in this simulation. The absorption coefficient of GaN_{0.033}As_{0.887}Sb_{0.08} is 13550 cm^{-1} at 1.3 μm , which is derived from its extinction coefficient by $\alpha = \frac{4\pi k}{\lambda}$.

The quantum efficiencies for the above WGPD structure with a 0.5 μm GaAs inner cladding layer and a 0.5 μm Al_{0.7}Ga_{0.3}As at different GaNAsSb core layer thicknesses and WGPD widths were simulated. The results are shown in Figure 2.9. From each constant core layer thickness curve, the quantum efficiency experiences a saturation characteristic from the ridge width of 3 μm onwards. This saturation characteristic is because the Gaussian beam used in the simulation has a 1 μm spot size or, equivalently, a $1/e$ width of 2 μm . Hence, further increasing the WGPD width will only increase the junction area and deteriorate the frequency response without improving the quantum efficiency.

Figure 2.9. The quantum efficiency versus ridge width at different core layer thicknesses (ridge length = 10 μm).

A thicker core layer leads to a higher quantum efficiency due to the larger coupling factor at the fiber-to-waveguide input. However, it must be highlighted that increasing the core thickness to more than 0.4 μm will result in a corresponding decrease in the frequency response (Figure 2.6, Page 28). Therefore, a 4 μm WGPD width, which is the smallest dimension available from our photolithography mask, a 0.4 μm core thickness, and a 10 μm WGPD length were chosen to fulfill the considerations of high-speed and high coupling efficiency operation.

The quantum efficiency of the GaNAsSb/GaAs/Al_xGa_{1-x}As structure was calculated by considering the combinations of GaAs thickness (d_1) and Al_xGa_{1-x}As thickness (d_2) (each varies from 0 to 1.0 μm in a step size of 0.1 μm) with different Al compositions (from 0 to 100% in a step size of 10%). Therefore, the matrices of the quantum efficiency of the WGPD with different heights ($2d_1 + 2d_2 + 0.4$) and Al compositions (x value) were obtained. The results are depicted as contour plots in Figures 2.10–2.12 for ridge heights of 2.0, 2.4, and 2.6 μm , respectively. The highest quantum efficiency region (89–92%) for all three contour plots is always located around a GaAs thickness of 0.5 μm . This region spreads horizontally as the Al composition increases in each of the three cases of different ridge heights. For example, for the highest quantum efficiency region in Fig. 2.11, the GaAs layer thickness varies from 0.4 to 0.5 μm at a 40% Al composition and it varies from 0.3 to 0.7 μm at a 70% Al composition. This variation in thickness is because the refractive index of Al_xGa_{1-x}As decreases with an increase in the Al composition and, hence, gives rise to a stronger optical confinement. Therefore, if a higher Al composition in the Al_xGa_{1-x}As cladding layer is used, the range of the GaAs layer thickness to achieve a high quantum efficiency will be wider.

As the ridge height increases from 2.0 μm (Fig. 2.10) to 2.4 μm (Fig. 2.11), the Al composition range and the GaAs thickness range that allow a quantum

efficiency of more than 89% contour can be extended from 60–100% to 40–100% and from 0.4–0.6 μm to 0.4–0.7 μm , respectively. However, a further increase in the ridge height from 2.4 μm to 2.6 μm (Fig. 2.12) shows no significant extension of this region. Therefore, the WGPD with a ridge height of 2.4 μm was chosen as the optimized structure since a further increase in the cladding layer thickness increases the series resistance of the device without causing much improvement in the quantum efficiency.

Figure 2.10. Quantum efficiency for GaNAsSb/GaAs/Al_xGa_{1-x}As WGPD with a ridge height of 2.0 μm . Different values of quantum efficiency are displayed in color contours.

Figure 2.11. Quantum efficiency for GaNAsSb/GaAs/Al_xGa_{1-x}As WGPD with a ridge height of 2.4 μm. Different values of quantum efficiency are displayed in color contours.

Figure 2.12. Quantum efficiency for GaNAsSb/GaAs/Al_xGa_{1-x}As WGPD with a ridge height of 2.6 μm. Different values of quantum efficiency are displayed in color contours.

The highest quantum efficiency of 91.5% is given by a WGPD structure with a 0.5 μm GaAs inner cladding layer thickness and a 0.5 μm $\text{Al}_x\text{Ga}_{1-x}\text{As}$ outer cladding layer thickness. The Al composition of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ cladding layer should be 70%. This combination provides the best tolerance to growth fluctuation since a high quantum efficiency can be obtained from a wide range of compositions and dimensions (i.e. an Al composition from 40–100% and a $\text{Al}_x\text{Ga}_{1-x}\text{As}$ (GaAs) thickness from 0.3–0.7 μm (0.7–0.3 μm)). Normally, a high Al-containing epilayer requires a higher growth temperature to achieve good quality material [34]. However, if this condition cannot be satisfied in practice, the result in Fig. 2.11 shows that the Al composition of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ cladding layer can be reduced to 40% while maintaining a quantum efficiency that exceeds 89%.

The quantum efficiency of the two extreme cases (i.e. one with only AlGaAs cladding layer and the other with only GaAs cladding layer) are also shown in all of the contour plots in Fig. 2.10–2.12 above. In general, the quantum efficiency of the WGPD structure with only AlGaAs cladding layer is always lower than that of the WGPD with only GaAs cladding layer. To explain this, the optical field distributions and the propagation characteristics for three types of WGPD cladding layer configurations were simulated: (1) GaNAsSb/ $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$, (2) GaNAsSb/GaAs, and (3) GaNAsSb/GaAs/ $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$. Their structures and the corresponding

fundamental mode profiles are shown in Figures 2.13–2.15.

The large refractive index contrast in the GaNAsSb/Al_{0.7}Ga_{0.3}As configuration (Fig. 2.13(a)) leads to a narrow and horizontally distributed fundamental mode profile. The optical energy in the core layer (as shown in Fig. 2.13(b)) is almost entirely absorbed within the first 5 μm propagation distance. However, a significant amount of optical energy exists in the cladding layers (~30% with respect to the input) at the end of the WGPD and remains unabsorbed. In fact, in this configuration, the GaNAsSb core layer has to be 1.7 μm away from the GaAs substrate in order to reduce the amount of light being coupled to the substrate. This is because the bottom AlGaAs cladding layer and the GaAs substrate act as an adjacent waveguide that the light tends to couple into the substrate.

Figure 2.13. The fundamental mode profile and optical energy distribution for the GaNAsSb/ $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ WGPD.

In the GaNAsSb/GaAs configuration (Fig. 2.14), a larger fundamental mode profile is observed compared to the GaNAsSb/Al_{0.7}Ga_{0.3}As configuration (Fig. 2.13). Furthermore, the propagation distance (Fig. 2.14(b), ~9.5 μm) for all of the optical energy in the core layer to be fully absorbed is longer compared to the GaNAsSb/Al_{0.7}Ga_{0.3}As propagation distance configuration (~7.5 μm). The propagation distance is longer since a portion of light in the cladding layers is redistributed back to the core layer. However, this configuration suffers the problem of light escaping into the substrate. This can be seen in the more rapid reduction in the optical energy at the bottom cladding layer compared to the optical energy in the top cladding layer (Fig. 2.14(b)).

(a)

(b)

Figure 2.14. The fundamental mode profile and optical energy distribution for the GaNAsSb/GaAs WGPD.

The GaNAsSb/GaAs/Al_{0.7}Ga_{0.3}As configuration shown in Fig. 2.15 offers better light distribution and redistribution characteristics along the propagation length compared to the previous single cladding layer configurations. The GaAs inner cladding layer and the GaNAsSb core layer support most of the optical field distribution. The Al_{0.7}Ga_{0.3}As outer cladding layer reinforces the light confinement during propagation by total internal reflections at the Al_{0.7}Ga_{0.3}As/GaAs interface. Since the light propagation in a waveguide is a continuous distribution of optical energy amongst different layers, more optical energy in the GaAs inner cladding layer is redistributed back to the core layer for absorption. At the end of the WGPD ($Z = 10\mu\text{m}$), the remaining optical energy in the cladding layers (GaAs and Al_{0.7}Ga_{0.3}As) is less than 6% while the total unabsorbed optical energy is only 8.5%. Therefore, higher quantum efficiency can be achieved using this configuration compared to the single Al_{0.7}Ga_{0.3}As or GaAs cladding layer configuration with total unabsorbed optical energies of 37.9% and 21.6%, respectively.

(a)

(b)

Figure 2.15. The fundamental mode profile and optical energy distribution the GaNAsSb/GaAs/ $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ WGPD.

2.4.3. External injection related influences

The quantum efficiency for the WGPD itself is high due to its long interaction length and its external quantum efficiency depending on the coupling conditions. The simulation in the previous section considers an ideal injection condition (i.e. smallest spot size obtainable and perfect fiber alignments). However, the external injection conditions, dominated by the change of light spot size, axial offset, and tilt angles, contribute to the insertion loss of optical power [35, 36].

In this section, the effects of these external injection conditions on the WGPD's quantum efficiency are discussed briefly. Two WGPD configurations are considered for comparison: (1) the GaNAsSb (0.4 μm)/GaAs (0.5 μm)/Al_{0.7}Ga_{0.3}As (0.5 μm) configuration and (2) the GaNAsSb (0.4 μm)/GaAs (1.0 μm) configuration. Both configurations have a 4 μm ridge width and a 10 μm ridge length.

Spot size

The profile of light injected from optical fiber is Gaussian profile. A typical single-mode optical fiber has a diameter around 10 μm , which corresponds to a spot size around 5 μm . Using lensed-fiber and tapered-fiber can reduce the fiber diameter to as small as 2 μm . However, if a small spot size (1 μm) is not available, the mismatch of electromagnetic fields in a single-mode fiber (and in

WGPD) causes a serious coupling loss [37].

The quantum efficiencies at different spot sizes (1–5 μm) are shown in Figure 2.16. A larger geometrical shape mismatch of the light and waveguide cross-section results in a relatively smaller portion of the light being coupled directly into the core layer. Nevertheless, the GaNAsSb/GaAs/AlGaAs configuration has a higher quantum efficiency. The additional AlGaAs layers force more light in the cladding layers to redistribute back to the core layer. At larger spot sizes (2.5 μm onwards), the difference between the two configurations becomes smaller as the optical field distribution is much greater than the WGPD dimension.

Figure 2.16. The quantum efficiency versus spot size.

Axial offset

The axial offset effect occurs when the optical fiber is not aligned to the center of the core layer. The core layer is only $0.4\ \mu\text{m}$ thick and it requires a more accurate alignment in the vertical direction (Y direction) than the horizontal direction. Hence, the vertical offset effect is shown here. The offset is assigned positive when it is towards the air and negative when it is towards the substrate (Figure 2.17). Both configurations are more sensitive to the axial offset at a small spot size ($1\ \mu\text{m}$). When the spot size increases to $1.5\ \mu\text{m}$, the offset effect becomes less sensitive because, when the optical spot becomes larger, the alignment accuracy is less critical.

Figure 2.17. The quantum efficiency versus vertical axial offset.

Injection angle

Aligning the optical fiber normally to WGPD facet is difficult. The influence of the vertical angle (Y-Z plane) is the most critical aspect of this task [36]. The angle (θ) is assigned to be positive when it is tilted from the core to the substrate. The GaNAsSb/GaAs/AlGaAs structure is less sensitive to the tilt angle at both the 1.0 μm and the 1.5 μm spot sizes. When the tilt angle increases, the difference in quantum efficiency increases (Figure 2.18) since the GaNAsSb/GaAs/AlGaAs configuration has a shorter propagation distance for the light to be completely absorbed (7.5 μm) than the GaNAsSb/GaAs structure does (9.5 μm). The tilt angle effectively shortens the light propagation distance in the core layer. Hence, the loss becomes larger for the GaNAsSb/GaAs configuration at larger tilt angles.

For GaNAsSb/GaAs/AlGaAs configuration, the peak quantum efficiency values are 91.5% and 78.9% for the spotsizes of 1 μm and 1.5 μm , respectively. Both occurred at $\theta_{peak} = 0^\circ$. For GaNAsSb/GaAs configuration, for the spotsize of 1 μm , the peak quantum efficiency was 78.9% at $\theta_{peak} = 1^\circ$ (78.4% at $\theta = 0^\circ$). For the spotsize of 1.5 μm , the peak quantum efficiency was 65.5% at $\theta_{peak} = 2^\circ$ (64.2% at $\theta = 0^\circ$). There is noticeable shift in the peak position although difference of the quantum efficiency between the normal condition and peak condition is only about 0.5%–1.3%.

Figure 2.18. The quantum efficiency versus the tilt angle.

Moreover, all the curves are unsymmetrical with respect to $\theta = 0^\circ$. These observations are due to the unsymmetrical nature of the device structure. For simplicity, it could be explained by the difference in the effective refractive indices in the upper and lower regions with respect to the center of core layer as illustrated in Figure 2.19. Due to the presence of the substrate, the effective refractive index in the lower region is larger than that of the upper region (i.e. $n_{eff2} > n_{eff1}$). With the same tilt angle of θ , we have $\theta_2 = \frac{n_{air}}{n_{eff2}} \sin^{-1}(\theta) <$

$$\theta_1 = \frac{n_{air}}{n_{eff1}} \sin^{-1}(\theta).$$

Figure 2.19. The illustration of the tilted injection condition with incident beam and transmitted beam according to Snell's Law.

Whenever the injection is not normal (i.e. $\theta \neq 0^\circ$), the light is propagating away from the core and this is undesired. Tilting towards the air (i.e. $\theta < 0^\circ$) worsen the quantum efficiency faster than in the other direction. Therefore, the curves are unsymmetrical. In fact, the spotsize of the injected light is larger than the dimension of the WGPD's facet. When θ is positive and very small, the amount of light injected into the upper cladding layer is tilted towards the core and helps the absorption. This may even counter-balance the loss due to the amount of light injected into the lower cladding layer that is propagating away from the core. Therefore, the peak quantum efficiency may occur at a small tilt angle, if not exactly $\theta = 0^\circ$.

Through the above discussions (i.e. spotsize, axial offset, injection angle), the GaNAsSb/GaAs/AlGaAs configuration is found to be more robust to the external injection conditions and still provides higher quantum efficiency.

Chapter 3: The Growth and Fabrication of GaNAsSb Waveguide Photodetectors

3.1. Introduction

The working principles and design considerations of the WGPd were discussed in Chapter 2. In this chapter, GaNAsSb *p-i-n* WGPds were fabricated. Firstly, the epitaxial structures of the WGPds were grown by the molecular beam epitaxy technique. The fabrication used standard lithography processes, such as etching, dielectric passivation, and electron beam evaporation, etc. Secondly, the devices were mounted on a specially designed microwave submounts for radio-frequency measurements.

3.2. Material growth

All of the materials were grown by solid-source molecular beam epitaxy (MBE) utilizing a radio-frequency (RF) plasma-assisted nitrogen (N) source and a valved cracker antimony (Sb) source. MBE is a technique for growing crystalline materials via the interaction of one or several atomic beams on the surface of a heated crystalline substrate under an ultra-high vacuum condition. The solid-source materials are placed in evaporation cells to provide for an angular distribution of the atoms in the beam. There are several competitive advantages of MBE growth. The non-intentional doping (n.i.d.) and atom inter-

mixing are minimized since the growth temperature is relatively low. In addition, the precise control of doping is obtained from the completely physical evaporation process. The epitaxy layer thickness is controlled well from the low growth rate (typically less than 1.0 $\mu\text{m}/\text{hour}$). The detail of the growth and optimization of GaNAsSb material used in this work has been described in an earlier doctoral thesis by Tan Kian Hua [38].

For operation at the 1.3 μm wavelength, two epilayer structures were grown as shown in Figure 3.1. In both structures, the thickness of the GaNAsSb core layer was 0.4 μm . The doping concentrations for the p (C-doped) and the n (Si-doped) cladding layers were 4×10^{19} and $5 \times 10^{18} \text{ cm}^{-3}$, respectively. The GaAs buffer, the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer, and the GaAs layer were grown at 580 $^{\circ}\text{C}$ while the GaNAsSb layer with 3.3% of N and 8% of Sb was grown at 350 $^{\circ}\text{C}$. For operation at the 1.55 μm wavelength, the epilayer structure used a similar configuration as shown in Figure 3.2. GaNAsSb with 3.5% of N and 18% of Sb was grown at 400 $^{\circ}\text{C}$.

Figure. 3.1. The epilayer structures of (a) GaNAsSb/GaAs/AlGaAs WGPD and (b) GaNAsSb/GaAs WGPD for the 1.3 μm wavelength operation.

Figure 3.2. The epilayer structure of GaNAsSb/GaAs WGPD for the 1.55 μm wavelength operation.

3.3. WGPD fabrication

The samples were processed by different microfabrication processes in order to improve the fabrication yields and the device performance. These processes differed mainly in the planarization step in which (a) Si_3N_4 , (b) SU-8 2005, or (c) hydrogen silsesquioxane (HSQ) films were used. Thin Si_3N_4 film was deposited to avoid cracking. It resulted a higher leakage current and poor RF results. SU-8 had problems of being coated thin ($< 5 \mu\text{m}$). The device yield in later metallization step was restricted due to metal disconnection. The final use of HSQ film for planarization had good outcomes for both DC and RF performances. The HSQ (and SU-8) microfabrication processes are described and schematically shown below.

Steps for the WGPD microfabrication process:

1. A WGPD ridge was formed by etching the epilayer structure down to the bottom cladding layer or the substrate. An AZ1518 positive photoresist was spin-coated and soft-baked (105°C for 2 minutes). It was patterned according to the waveguide mask. After development, the sample was hard-baked at 110°C for over 30 minutes to harden the photoresist which served as the etch mask for etching. Reactive-ion etching (RIE) was used to etch the epitaxial layers. The active gases were BCl_3 (20 sccm) and Cl_2 (20 sccm) at RF power of 200W.

The etch depth was about 1.7–2 μm . Finally, the photoresist was removed by soaking the samples in hot acetone (Figure. 3.3).

Figure 3.3. Ridge formation process: (a) bare wafer, (b) photoresist spin coating and soft baking, (c) alignment and exposure, (d) development and hard baking, (e) ridge etching, and (f) photoresist strip.

2. A negative photoresist HSQ (or SU-8) film was spin-coated and patterned using the same waveguide mask. This dielectric layer's thickness (close to the WGPD ridge height) was essential for the following process of metallization. After development, the top surface of the ridge was exposed as shown in Figure. 3.4.

Figure 3.4. HSQ (or SU-8) planarization process, exposing the top ridge surface after development.

3. AZ5214 photoresist was used for the P-contact metallization process. The photoresist was spin-coated and soft-baked (105 °C for 2 minutes). The electrode mask was used. A 7.5 minutes' post exposure baking at 110 °C was required for its image reversal process. After development, the top surface of the ridge and a portion of the dielectric layer defining the size of the contact pad were exposed. Prior of loading into the metal evaporation chamber, the sample was dipped into diluted HCl solution to remove the surface oxide. The metal layer was deposited by electron beam evaporation. The metal on top of the photoresist was removed together with the photoresist in the lift-off process by soaking in acetone (Figure 3.5).

Remark: Two electrode masks have been used in this work. One had a contact pad size of 100 μm x 100 μm and the later one had a reduced contact pad size of 50 μm x 60 μm .

Figure 3.5. P-contact metallization process: (a) photoresist spin coating and soft baking, (b) alignment and exposure, (c) post exposure baking and flood exposure, (d) development, (e) metallization, and (f) lift-off.

4. The sample was mounted onto polishing holder by wax and the back of the substrate was lapped down gradually using 5 μm size lapping powder and 1 μm size lapping powder. The final substrate thickness was around 100 μm . A thinner substrate was desirable for easy cleaving and better high frequency performance. The N-metal layer consisting of Ni/Ge/Au was deposited on the backside by electron beam evaporation (Figure 3.6). The contacts were annealed at 380 $^{\circ}\text{C}$ for 1 minute.

Figure 3.6. Backside metallization on a thinned substrate.

5. The WGPD pairs were separated by cleaving. Mirror-like fiber coupling facets were created (Figure 3.7). The actual ridge length the WGPDs were determined in this step. The cross-sectional profile of a cleaved device is shown in Figure 3.8.

Figure 3.7. Sample cleaving to separate the WGPD pair.

Figure 3.8. Cross-sectional Scanning Electron Microscopy (SEM) image of the fabricated WGPD.

Chapter 4: Characterization of the 1.3 μm GaNAsSb Waveguide Photodetectors

4.1. Introduction

In this chapter, characterization results of the 1.3 μm GaNAsSb waveguide photodetectors are presented. Devices with two kinds of epilayer structures are characterized: (a) GaNAsSb/GaAs/AlGaAs and (b) GaNAsSb/GaAs. The use of the AlGaAs outer cladding layers showed an improved internal quantum efficiency of 96.7% and a high responsivity of 0.72 A/W. The device with a 6 μm ridge width and a 25 μm ridge length exhibited a record bandwidth of 16.5 GHz.

4.2. The epitaxy of the structure and device packaging

The two structures are shown in Figure 4.1. The thickness of each layer was grown according to the simulations discussed in Chapter 2. The ridge was formed by etching the epilayers down to the n^+ GaAs cladding layer. The thickness of the GaNAsSb core layer was 0.4 μm . The contact pad with a dimension of 50 μm x 60 μm was located at the end of the waveguide. Hydrogen silsesquioxane (HSQ) film was used for device planarization. The p and n electrodes were formed by the electron beam evaporation of 350 nm thick Pt/Ti/Pt/Au and 400 nm thick annealed Ni/Ge/Au. The WGPDs were available

in different ridge widths of 4, 6, 8, and 10 μm . The actual ridge length of each WGPD was determined by the cleaving condition when the waveguide coupling facet was made.

(a)

(b)

Figure 4.1. The epilayer structures for (a) the GaNAsSb/GaAs/AlGaAs WGPD and (b) the GaNAsSb/GaAs WGPD.

In order to reduce the parasitic capacitance from the packaging and to enable quick integration with the standard RF measurement setup, a Kovar substrate and a GSG probe pad were employed. The samples were cleaved further to make the devices closer to the edges. The cleaved sample, the GSG pad (150 μm pitch size), and a 50 ohm resistor were soldered on to the Kovar substrate (Figure 4.2). The length of the bonding wire was reduced to less than 1 mm. A standard RF probe can be placed on the GSG pad to extract the electrical signals. This method introduces minimum parasitic capacitance.

Figure 4.2. A WGPd soldered onto a Kovar plate and wire-bonded to a GSG probe pad.

4.3. Device characterization

4.3.1. Current-voltage characteristic

The current-voltage characteristic in the dark condition (see Figure 4.3) was measured by an Agilent 4156B Precision Semiconductor Parameter Analyzer. At a reverse bias voltage of 5 V, the current density was 0.54 A/cm². This value is more than one order smaller than the 13 A/cm² value reported previously in our *p-i-n* photodetectors [39]. The improvement on the leakage current is mainly attributed to the thinner GaNAsSb layer (0.4 μm versus 2 μm) and to the reduced growth temperature (350 °C versus 440 °C) which reduces the overall trap concentration [16, 40]. The device exhibited a turn-on voltage of 0.72 V ($J = 117$ A/cm²) and a breakdown voltage of -16.6 V ($J = 114$ A/cm²).

The inset of Fig. 4.3 showed the forward current of a WGPD with 6 μm ridge width and 25 μm ridge which was used for further characterizations in the following sections. The ideality factor was around 5 at low bias condition (below 1 V) indicating the presence of carrier recombination. The series resistance was estimated to be around 118 Ω.

Figure 4.3. The current-voltage characteristic of the WGPD. Inset: The forward current for a WGPD with a 6 μm ridge width and a 25 μm ridge length.

4.3.2. Spectral response

Figure 4.4 shows the setup of the spectral response measurement. This measurement was carried out using a 100 W Quartz Tungsten Halogen (QTH) lamp and a monochromator in conjunction with a lock-in amplifier. The wavelength range was varied from 1000 nm to 1600 nm with a step size of 20 nm. The light source was calibrated using a commercial InGaAs photodetector. A converging lens was used to reduce the spot size of the light beam focusing onto the WGPD facet. Due to the limitation of the optics geometry of the broad spectrum light source, the beam size was estimated to be at least three orders of magnitude larger than the WGPD facet of the largest device available (i.e. the 10 μm ridge width). This led to inefficient light coupling and thus compromised the actual responsivity (A/W).

Figure 4.4. The schematic for the measurement setup of spectral response.

Figure 4.5 shows the spectral response of the WGPD. The photodetector's absorption decreased beyond 1380 nm (indicating that the bandgap of GaNAsSb is around 0.89 eV). This agrees with previous work that measured a top-illuminated *p-i-n* photodetector which used the same GaNAsSb composition [39].

Figure 4.5. The normalized spectral response of the WGPD.

4.3.3. Responsivity and quantum efficiency

In the responsivity measurement, the broadband light source, chopper and monochromator system from the above setup were replaced by a 1.31 μm laser (Ortel 3541A). A single-mode lensed fiber with a fiber-end surface diameter of 4.5 μm was used. This greatly reduced the optical field mismatch between the fiber output and the waveguide core. The smallest device dimension available for the 1.3 μm WGPDs was a 6 μm ridge width and a 25 μm ridge length. At a 1 mW optical power injection, the maximum responsivity values measured were 0.72 A/W and 0.55 A/W at the -10 V bias condition for these devices of the two epilayer structures (Fig. 4.1, Page 60).

As shown in Figure 4.6, the responsivity from a WGPD with AlGaAs cladding layers is higher than that of a WGPD without AlGaAs cladding layers at all of the reverse bias conditions. As discussed in Chapter 2, for devices with similar cladding configurations, a considerable amount of light is also injected into the adjacent cladding layers during the coupling due to the fact the GaNAsSb core layer has a thin rectangular profile with only a 0.4 μm thickness. In the GaNAsSb/GaAs device, the light initially injected into the cladding layers will escape through the GaAs substrate underneath and, hence, will not be absorbed by the GaNAsSb core layer. In contrast, in the GaNAsSb/GaAs/AlGaAs device, the inner cladding GaAs layer effectively enlarged the optical mode profile. The

light injected in the GaAs cladding layers will be progressively redistributed back and absorbed by the GaNAsSb core layer.

For both devices, photocurrent (thus, the responsivity) increased with reverse bias voltage. This was mainly due to the expansion of the depletion width (See Figure 4.11, Page 73). As the depletion region expanded, carriers drifted more efficiently rather than diffused and were lost due to recombination.

Figure 4.6. A comparison of the responsivity in WGPDs with and without an AlGaAs cladding layer at a 1 mW optical power injection.

The responsivity values of 0.72 A/W for a GaNAsSb/GaAs/AlGaAs WGPD and of 0.55 A/W for a GaNAsSb/GaAs WGPD correspond to the external quantum efficiencies of 68.7% and 52.5%, respectively. Taking into account that approximately 29% of the incident light is reflected by the air/GaAs interface due to the difference in refractive index, the equivalent internal quantum efficiencies are 96.7% and 73.9%, respectively. Considering the slight variations of the geometries between the simulated and fabricated structures, the experimental values fall within the expected bounds as predicted in Chapter 2 (the internal quantum efficiencies of 91.5% and 77%, respectively).

As for the GaNAsSb/GaAs/AlGaAs WGPD, the photocurrents for various optical power levels ranging from 0.25 to 8 mW under different reverse bias conditions are shown in Figure 4.7. The photocurrent increased almost linearly with the optical power. The small volume of the active region resulted in the generation of a large photogenerated carrier concentration. The linear photoresponse indicates a fast transit of the carriers.

Figure 4.7. A diagram of the photocurrent versus the optical power for the GaNAsSb/GaAs/AlGaAs WGPD.

4.3.4. Bandwidth

In the frequency response measurement, the laser was modulated by an external modulator (EOSPACE) in order to extend the usable modulating frequency. However, the use of the external modulator introduced a slight signal attenuation into the measurement frequency span. Thus, the modulator's response was calibrated using a commercial high-speed InGaAs photodetector as a reference. The small-signals were provided and collected by the vector network analyzer (VNA). The VNA was calibrated using the standard electronic calibration (E-Cal) before measurement. The measurement setup is shown in Figure 4.8.

Figure 4.8. The measurement setup for high frequency measurement.

The relative frequency response of the GaNAsSb/GaAs/AlGaAs WGPD with a 6 μm ridge width and a 25 μm ridge length is shown in Figure 4.9 (the effect from the modulator has been removed). The signal level (S_{21}) raised at higher reverse biased conditions because additional photocurrent was generated when a large reverse bias voltage was applied to the detector. However, the noise levels also raised (tails of the curves, at 40 GHz).

Figure 4.9. The relative frequency response for a 1.3 μm wavelength WGPD.

As shown in Figure 4.10, the 3dB cut-off frequency was bias dependant. It increased from 6.2 GHz at the un-biased condition to 16.5 GHz at the -10 V bias condition. This was the result of the expansion of the depletion region and the increasing of the carriers' drift velocities at higher electric fields.

Figure 4.10. Comparison between the measured cutoff frequency and the calculated RC -time limited cutoff frequency, at different bias conditions.

The background doping concentration for the GaNAsSb layer was around $7 \times 10^{16} \text{ cm}^{-3}$ (*p* type) [41]. The capacitance measurement performed at 100 MHz frequency shows that the capacitance from the contact pad was around 0.04 pF. The calculated depletion width ($W_{\text{depletion}}$), junction capacitance (C_{junction}) and total device capacitance (C_{device}) versus bias voltage characteristics are shown in Figure 4.11.

Figure 4.11. The calculated depletion width and capacitances versus bias voltage.

Since the top p type GaAs layer is heavily doped, the depletion region is formed between the GaNAsSb layer and the bottom n type GaAs layer. The calculation results indicate that at least a -8 V bias is required to fully deplete the 0.4 μm GaNAsSb absorbing layer. The contact resistance of the tested device is around 118 Ω from the estimation of its forward current-voltage characteristic. In the small reverse bias condition, the bandwidth of the device is limited by both the capacitance effect and the carrier transit time. There is a larger discrepancy between the calculated RC -time-limited and the measured cut-off frequencies since the diffusion of carriers in the partially depleted GaNAsSb layer further degrades the frequency response. In the high reverse bias condition, the measured cut-off frequency of 16.5 GHz at -10 V is close to the calculated RC -time-limited cut-off frequency of 17.4 GHz at -10 V ($f_{RC} \sim 1/(2\pi RC)$).

4.4. Summary

In this chapter, we characterized the DC and RF performance of the 1.3 μm GaNAsSb WGPLDs with two types of layer configurations: (a) the GaNAsSb/GaAs/AlGaAs configuration and (b) the GaNAsSb/GaAs configuration. High responsivity values of 0.72 A/W and 0.55 A/W were obtained for WGPLDs with and without AlGaAs cladding layers, respectively. These high responsivity values correspond to the very high internal quantum efficiencies of 96.7% and 73.9%, which are within the simulation expectations

discussed in Chapter 2. A 16.5 GHz cut-off frequency is obtained for the GaNAsSb/GaAs/AlGaAs WGPD above. Further analysis indicates that the frequency response of the tested device is limited by the RC -time-effect.

Chapter 5: Characterization of the 1.55 μm GaNAsSb Waveguide Photodetectors

5.1. Introduction

In this chapter, experimental results of the 1.55 μm waveguide photodetectors are presented. The antimony content of the GaNAsSb layer in the WGPD was increased to 18% while the nitrogen content was slightly increased to 3.5% (8% Sb and 3.3% N for the 1.3 μm wavelength operation). This resulted in a slightly strained GaNAsSb layer on GaAs substrate and the amount of light that can be absorbed was constrained by its critical thickness. Nevertheless, this constraint was overcome by using the waveguide structure that uses a long propagation distance to compensate for the thin absorbing layer thickness. From the two attempts for the experiments, improvements were made by applying *in-situ* thermal annealing of the grown epilayer structure and by refining the fabrication processes.

5.2. Early demonstration of WGPDs up to 1.6 μm photon detection

5.2.1. Introducing lattice-strain to extend the absorption edge

Increasing the nitrogen and antimony contents is necessary to extend the operation wavelength of the WGPDs. However, due to the presence of nitrogen-related defects which degrade the crystal quality [16, 17], further increasing the nitrogen content is not desirable. Thus, the antimony composition was increased to 18% while the nitrogen composition was slightly increased to 3.5%. This led to a slightly strained GaNAsSb layer on GaAs substrate.

Figure 5.1 shows the (224) x-ray reciprocal space map of the sample. The measurement comprised of a series of ω - 2θ scans, each offset in the sample x-ray incident angle by $\pm\delta\omega$ with respect to its neighbouring scan. The result shows that the parallel (along the Q_x axis) d-spacing difference between the GaAs substrate and the GaNAsSb layer peaks in a reciprocal lattice unit (Q_x direction) was 0.062×10^{-3} and the perpendicular (along the Q_y axis) d-spacing difference (Q_y direction) was 6.651×10^{-3} . This indicated that the GaNAsSb layer (labelled L) had an approximately 1% relaxation.

Figure 5.1. An (224) x-ray reciprocal space map of the GaNAsSb/GaAs *p-i-n* WGPD. *S* and *L* denote the GaAs substrate peak and the GaNAsSb layer peak, respectively.

5.2.2. Epilayer structure and device packaging

The very first 1.55 μm wavelength WGPD consisted of a 0.4 μm GaNAsSb (non-intentionally doped), a 1 μm *p* type GaAs (C-doped) top cladding layer, and a 0.5 μm *n* type GaAs (Si-doped) bottom cladding layer (Figure 5.2). The devices were mounted onto half dual in-line package (DIP) for characterization (Figure 5.3). This method only worked for DC measurements and was not suitable for RF measurements in GHz range. First, the frequency limitation of the DIP is about a few MHz. Second, due to the geometry constraint (devices must be placed at the edge to allow fiber coupling movement), the bonding wire from each device to the pin was too long. This excessive length resulted in a

huge additional inductance that downgraded the device's frequency performance.

Figure 5.2. The epilayer structures for GaN_{0.035}As_{0.785}Sb_{0.18}/GaAs WGPd.

Figure 5.3. WGPds mounted onto the dual in-line package in the early approach.

5.2.3. Current-voltage characteristic

The current-voltage characteristic is shown in Figure 5.4. At the bias voltage of -1.5 V, the dark current density of the device was 22.2 A/cm². The strained GaNAsSb/GaAs WGPD exhibited a higher leakage current than that of the lattice-matched GaNAsSb/GaAs *p-i-n* device with a reported dark current density of 13 A/cm² at -5 V [39]. This was because the strained GaNAsSb layer in WGPD had a 1% lattice relaxation which might have given rise to threading dislocation and, hence, resulted in a higher device leakage current.

Figure 5.4. The current-voltage characteristics of a WGPD with a 6.5 μm ridge width and a 500 μm ridge length.

5.2.4. Spectral response

Figure 5.5 shows the spectral response of the WGPD (with a 6.5 μm ridge width and a 500 μm ridge length) using the same setup discussed in Section 4.3.2. The result shows that the WGPD had a longer absorption edge (up to 1.6 μm) compared to that of a previous vertically-illuminated 1.3 μm $\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}/\text{GaAs}$ photodetector [39].

Figure 5.5. The spectral response of the $\text{GaN}_{0.035}\text{As}_{0.785}\text{Sb}_{0.18}/\text{GaAs}$ WGPD for the 1.55 μm wavelength operation compared to the spectral response of the previous 1.3 μm wavelength photodetector.

Due to the limitation of the light source used in this measurement, the measurement was limited to 1600 nm. However, the calculation using the band-anticrossing model [42, 43] shows that the $\text{GaN}_{0.035}\text{As}_{0.785}\text{Sb}_{0.18}$ has an energy bandgap of 0.77 eV (or $\lambda = 1.61 \mu\text{m}$).

5.2.5. Responsivity

In the responsivity measurement, a tuneable laser source (1510–1640 nm) was coupled to the waveguide facet of the WGPD through a stripped flat-end single-mode fiber ($\sim 10 \mu\text{m}$ core diameter). All of the tested WGPDs were biased at -1.5 V under an incident laser power of 100 μW at 1.55 μm . The results for the WGPDs with the 6.5 and 10 μm ridge widths are shown in Figure 5.6. The WGPD with the longer ridge length gave a higher responsivity. However, the responsivity saturated at 0.25 A/W for the WGPDs with a 6.5 μm ridge width while it saturated at 0.29 A/W for the WGPDs with a 10 μm ridge width. The larger ridge width has less coupling loss since the optical fiber used had a core diameter of $\sim 10 \mu\text{m}$.

Figure 5.6. The responsivity characteristics of GaNAsSb/GaAs WGDs with different ridge widths and lengths at the 1.55 μm wavelength under a 100 μW optical power and the -1.5 V bias condition.

Figure 5.7 shows the influence of the reverse bias voltage and the optical power on the responsivity. The responsivity was larger at a higher reverse-bias voltage. The absorption layer might not be depleted completely until the reverse-bias voltage was high enough. However, a large reverse-bias condition is not desirable as it causes a high dark current at the same time. The responsivity dropped when the laser power further increased due to the fact that, within certain volumes, only finite numbers of electron and hole carriers are generated. Further increasing the optical power causes screening effects [44, 45].

Figure 5.7. The responsivity versus the optical power under different bias conditions for WGPD with a 4 μm ridge width and a 200 μm ridge length.

5.3. High performance 1.55 μm wavelength WGPD

With the experience of demonstrating the GaNAsSb/GaAs WGPD capable of 1.55 μm wavelength detection, the next objective was to improve the device performance by reducing the reverse leakage current, improving the responsivity, and pursuing a high electrical bandwidth.

5.3.1. Diagram of the epilayer structure and the device packaging

The GaNAsSb/GaAs WGPD epilayer structure is shown in Figure 5.8(a). The

GaNAsSb active layer consisted of the same N (3.5%) and Sb (18%) contents as those from the previous approach. The nonintentionally doped GaNAsSb layer was grown at 400 °C at RF plasma power of 450 W. The *p* and *n* GaAs-cladding layers were grown at 580 °C with doping concentrations of $1 \times 10^{19} \text{ cm}^{-3}$ (C doped) and $5 \times 10^{18} \text{ cm}^{-3}$ (Si doped), respectively. After growth, the whole structure was treated with *in-situ* thermal annealing at 660°C for 15 minutes.

Hydrogen silsesquioxane (HSQ) film was used for planarization [46] after the waveguide ridge was formed by etching the epilayers down to the GaAs substrate. The *p* and *n* electrodes were formed by 350 nm thick Pt/Ti/Pt/Au and 400 nm thick annealed Ni/Ge/Au, respectively. The metal contact pad was located at one end of the WGPD with a dimension of 50 μm x 60 μm . The ridge widths of WGPD were 4, 6, 8, and 10 μm . A microwave submount with a 2.92 mm K-connector on a microstrip line was used to connect the WGPD to the microwave lines (Fig. 5.8(b)). The sample was soldered close to the microstrip line to which the single WGPD was wire-bonded from its contact pad. This setup ensured that a minimum electrical length was introduced in the packaging (a bonding wire shorter than 1 mm). Throughout the measurements, a single-mode lensed fiber with a fiber-end diameter of 2.7 μm was used for the optical coupling.

(a)

(b)

Figure 5.8. (a) The epilayer structure of the GaNAsSb/GaAs WGPD. (b) the top view of the device mounted onto a microwave carrier with a 2.92 mm connector.

5.3.2. Current-voltage characteristic

The device exhibited a similar soft breakdown behavior as shown in Figure 5.9 but it was less severe compared with the earlier approach. The reverse breakdown started from the bias voltage of -2 V onwards. This was also attributed to the slight lattice relaxation that gave rise to the threading dislocations. The dark current density was 2.95 A/cm² at -1.5 V, which was reduced more than seven times than that of the device with the same GaNAsSb composition discussed earlier (22.2 A/cm² at -1.5 V). Under the 1.55 μ m optical power ($P_{inc} = 5$ mW) illumination condition, the total current increased due to the generation of the photocurrent.

Figure 5.9. The current-voltage characteristic for a WGPD with 8 μ m ridge width and 15 μ m ridge length.

5.3.3. Responsivity and quantum efficiency

As shown in Figure 5.10, the photocurrent (I_{ph}) increased with the optical power (P_{inc}). The larger photocurrent at the higher reverse bias voltage was due to the expansion of the depletion region in the active layer. The lensed fiber had a much smaller diameter than the ridge width of the WGPDs, high coupling efficiencies were obtained for both WGPDs (8 μm and 6 μm ridge width). Most of the light was expected to be absorbed within the first 10–20 μm propagation distance due to the large absorption coefficient ($\alpha \sim 2 \times 10^4 \text{ cm}^{-1}$ at the 1.55 μm wavelength). Therefore, at the same applied bias voltage, the photocurrents from the two WGPDs with different lengths (15 μm and 49 μm) were very close.

Figure 5.10. The photocurrent for the WGPDs with ridge dimensions of 8 μm x 15 μm (solid lines) and 6 μm x 49 μm (dotted lines).

At higher reverse bias conditions, the responsivity (I_{ph}/P_{inc}) decreased noticeably with the increase of optical power (Figure 5.11). A high responsivity of 0.6 A/W was observed at 0.1 mW optical injection at -4 V bias. A responsivity of 0.18 A/W was observed at 5 mW optical injection at -4 V. The decrease of the responsivity at the higher optical injection power was caused by the screening effect of the electric field due to the high density of photo-generated carriers [47-49]. Higher nonlinearity at -4 V was due to the presence of a slight avalanche effect at the higher reverse bias for this material [41].

Figure 5.11. The responsivity versus the optical power under different reverse bias voltages for the WGPDs with ridge sizes of 8 μm x 15 μm (solid lines) and 6 μm x 49 μm (dotted lines).

5.3.4. Bandwidth

In the frequency measurement, the 1.55 μm laser (from NETTEST module with erbium-doped fiber amplifier) was modulated externally through a 40 Gbit/s intensity modulator (from Sumitomo Osaka). The optical power available at the input of the WGPD was fixed at 5 mW. The S-parameters were measured by an Agilent N8364B Vector Network Analyzer (VNA). Standard calibration was performed using an Agilent electronic calibration (ECal module 4692A) for the frequency range of 10 MHz–40 GHz. The RF power was fixed at -5 dBm.

The forward transmission coefficient (S_{21}) indicates the frequency response of the photocurrent as a function of the modulated light signal (i.e. AC responsivity, $\Delta I_{ph}/\Delta P_{inc}$). The relative frequency responses for the various WGPDs are shown in Figure 5.12 in which the effects of the modulator were removed. For the WGPD with a junction area of 4 μm x 17 μm , the cut-off frequency was 14.3 GHz at the -1 V bias condition (Fig. 5.12(a)). This was the highest value obtained among all the tested devices with different dimensions. However, it had a lower DC responsivity (~ 0.2 A/W) regardless of the bias voltage, due to the poor light coupling in the experiment. An 11 GHz cut-off frequency and a 0.44 A/W DC responsivity were obtained for the WGPD with a junction area of 8 μm x 15 μm at the -5 V bias condition.

Since the devices had a soft reverse breakdown characteristic beginning from -2 V, dark current increased faster than the photocurrent with reverse bias voltage. This has led to the raising of the noise floor for each frequency response curve which was effectively the value of the last data point (See Fig. 5.12). As the reverse bias voltage increased, the frequency response became noisier. A 5dB reduction of the dynamic range (the ratio of the strongest signal to the minimum detectable signal) was found for the WGPD with junction area of $6\ \mu\text{m} \times 24\ \mu\text{m}$ (0 V to -3 V) and $6\ \mu\text{m} \times 49\ \mu\text{m}$ (from -1 V to -4 V).

(a)

(b)

Figure 5.12. The relative frequency responses of the WGDs under different bias conditions: (a) WGDs with the junction areas of $4\ \mu\text{m} \times 17\ \mu\text{m}$ and $6\ \mu\text{m} \times 24\ \mu\text{m}$ and (b) WGD with the junction areas of $6\ \mu\text{m} \times 49\ \mu\text{m}$ and $8\ \mu\text{m} \times 15\ \mu\text{m}$.

The frequency response from the measured devices showed a bias dependent characteristic. Figure 5.13 shows the measured cutoff frequencies for the different WGDs at different bias conditions. The cutoff frequency increased as a higher reverse bias voltage was applied due to the expansion of the depletion region and the reduction of junction capacitance at higher reverse bias voltages.

A linear scaling trend was present for the four WGPDs with larger junction areas for reverse bias voltage up to -4 V. Assuming that the WGPDs have the same series resistance value at the same reverse bias voltage, the increment of the cut-off frequency was proportional to the reduction of the junction area (thus the junction capacitance). This implies that the bandwidths of these devices were limited by the resistance-capacitance (RC) time constant. In addition, the junction capacitance was dominant over the contact pad capacitance. As the junction area was reduced further, the effect of the capacitance from the contact pad (~ 0.04 pF) became comparable to the junction capacitance from the WGPD.

Figure 5.13. The cutoff frequency versus the WGPD junction area at different reverse bias voltages.

5.4. Summary

We have presented the characterization results from two generations of GaNAsSb/GaAs WGPDs for a 1.55 μm wavelength operation. The use of a strained GaNAsSb layer in the waveguide structure successfully achieved the detection wavelength over 1.55 μm . These devices exhibited soft reverse breakdown behavior. The dark current density was reduced by employing *in-situ* thermal annealing. Thus, a higher reverse bias voltage can be applied to the devices during operation to achieve a higher performance.

At the 1.55 μm wavelength, devices with a 14.3 GHz (~ 0.2 A/W) and 11 GHz (0.44 A/W) bandwidth were demonstrated. To our knowledge, this is the first demonstration of high speed and high responsivity GaNAsSb/GaAs photodetectors at the 1.55 μm wavelength.

Chapter 6: The Small-signal Equivalent Circuit of the Waveguide Photodetector

6.1. Introduction

One way of analysing the microwave properties of a waveguide photodetector is to use a lumped-element equivalent circuit model. A concise RF equivalent circuit model facilitates device analysis, optimization, and design of matching circuit for maximum power transfer. A valid model should consist of parameters that carry physical meaning from the device structure. Since the WGPD is inherently an optoelectronic device, its equivalent circuit model should incorporate the optical effect, which is presented as a current source. In this chapter, the approach of constructing the equivalent circuit is presented.

6.2. Small-signal equivalent circuit of WGPD

6.2.1. Microwave submount modelling

The 1-port reflection coefficient measurement (S_{11}) was performed first to extract the equivalent circuit for the microwave submount and the WGPD RC time related elements. With and without mounting of the WGPD onto the submount, the reflection coefficient showed periodical resonances. Therefore, the submount was modeled first. From the construction of the submount, the simple model contained: a lossy transmission line component representing the K-connector, a microstrip line component with open-end effect representing the

open circuit condition without mounting of the WGPD, and a resistance (R_1) and an inductance (L_1) in series representing the interconnection between the K-connector and the microstrip line (Figure 6.1(a)).

The fitting was based on Random and Gradient Optimizers in Agilent Advanced Design System (ADS) in which the least square of the error function (i.e. residual between simulated and measured data) is minimized for the frequency span. The fitting result of S_{11} is plotted in the form of Y_{11} (admittance of the network). The admittance is deduced directly from the reflection coefficient and is also the inverse of impedance as expressed in (6.1) and (6.2). The real part of Y_{11} reveals the presence of resistance and imaginary part of Y_{11} reveals the presence of inductance or capacitance. The fitting results are shown in Figure 6.1(b) and the fitting parameters are shown in Table I.

$$Y_{11} = \frac{1}{Z_0} \cdot \frac{1-S_{11}}{1+S_{11}} \quad (6.1)$$

$$Y_{11} = Z_{11}^{-1} = \frac{R}{R^2+X^2} + j \frac{-X}{R^2+X^2} \quad (6.2)$$

(a)

Figure 6.1. (a) The equivalent circuit for the microwave submount used in the measurement, (b) measured and simulated admittance (Y_{11}).

TABLE I: FITTING PARAMETERS FOR THE SUBMOUNT

Parameter	Value
Characteristic impedance, Z_0	50 Ω
Resistance, R_1	1.12482 Ω
Inductance, L_1	0.0215779 nH
Component: Microstrip line (TL2) and substrate (MSub1)	
Line width	229.834 μm
Line length	1511.09 μm
Substrate thickness	200.013 μm
Relative dielectric constant	11.0251
Conductor conductivity	6.49259×10^7 S/m
Conductor thickness	0.402144 μm
Dielectric loss tangent	0.0464687
Conductor surface roughness	4.24247 μm
Component: K-connector (TL1)	
Length	8995.31 μm
Effective dielectric constant	4.72416
Attenuation	4.21176×10^{-5} dB/m
Frequency for scaling attenuation	0.790668 GHz
Dielectric loss tangent	0.000249787

6.2.2. WGPD model in the dark condition

With the fitted equivalent circuit of the microwave submount, the lumped-element model for the WGPD was determined by fitting the measured S_{11} of the microwave submount with the WGPD mounted. Since these measurements were carried out in the 1-port reflection configuration and without fiber coupling of the light source, the fitted parameters contained only the resistance-capacitance (RC) time related elements.

The proposed equivalent circuit for the WGPD (mounted on the submount) in dark condition is shown in Figure 6.2. The junction resistance (R_j) and the junction capacitance (C_j) are in parallel. A small resistance (R_s) from the p -GaAs cladding layer is in series with the junction impedance. A small capacitance of the contact pad is in parallel with the above impedance. The bonding wire between the WGPD and the microstrip line (~ 0.6 mm length) is represented by a wire component. The fitting values of the lumped-element model for a WGPD ($6\text{ }\mu\text{m}$ ridge width and $49\text{ }\mu\text{m}$ ridge length) at different bias conditions are shown in Table II. The fitting results are selectively shown for the WGPD at the -2 V bias condition in Figure 6.3.

Figure 6.2. The equivalent circuit for the WGPD package in the dark condition.

TABLE II: FITTING PARAMETERS FOR THE WGPD ($6 \mu\text{m} \times 49 \mu\text{m}$) UNDER THE DARK CONDITION

Bias voltage	0 V	-1 V	-2 V	-3 V	-4 V
C_j (pF)	1.09	0.78	0.68	0.63	0.59
R_j (Ω)	2579	4976	3531	570	131
R_s (Ω)	6.1	4.9	4.3	3.9	3.7
C_{pad} (pF)	0.03	0.035	0.035	0.032	0.035

Figure 6.3. Measured and simulated admittance (Y_{11}) of the WGPD ($6\text{ }\mu\text{m} \times 49\text{ }\mu\text{m}$) at the -2 V bias in the dark condition.

Based on the fitted values in Table II, the simulated intrinsic 1-port reflection coefficient is shown in Figure 6.4. At low reverse bias conditions, the WGPD behaved close to an ideal capacitor. The junction capacitance (C_j) decreased with the increase of the reverse bias voltage due to the expansion of the depletion region. The junction resistance (R_j) decreased at the higher reverse bias voltages and took into account the faster increase of the dark current.

Figure 6.4. The intrinsic reflection coefficient (S_{11}) from the WGPD ($6\ \mu\text{m} \times 49\ \mu\text{m}$) in the dark condition.

The background doping concentration of $\text{GaN}_{0.035}\text{As}_{0.785}\text{Sb}_{0.18}$ layer could be estimated from the fitted junction capacitance values (C_j). From previous experience of the growth and characterizations of GaNAsSb, its background doping was *p*-type. Thus, in the operation, the depletion region was formed between the GaNAsSb layer and the bottom *n*-GaAs cladding layer ($N_d = 5 \times 10^{18} \text{ cm}^{-3}$). From Eq. (2.1) and (2.9) (Page 17 and Page 22), we have

$$W = \frac{\varepsilon A}{C_j} = \frac{\varepsilon_0 \varepsilon_r}{C_j} = \sqrt{\frac{2 \cdot (\varepsilon_0 \varepsilon_r)}{q}} (V_{bi} + V_R) \cdot \left(\frac{1}{N_a} + \frac{1}{N_d} \right) \quad (6.3)$$

With $\varepsilon_r = 13$ and assuming a built-in potential of $\sim 0.5 \text{ V}$, the background doping for GaNAsSb is $\sim 8 \times 10^{17} \text{ cm}^{-3}$ (*p*-type). This value was one order higher than that of the $\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}$ ($7 \times 10^{16} \text{ cm}^{-3}$) used in this work. The background doping was induced by the defect states, especially the nitrogen-related defects. It has been reported for $\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}$ that when its growth temperature varied from $350 \text{ }^\circ\text{C}$ to $480 \text{ }^\circ\text{C}$, the background doping increased from $2 \times 10^{16} \text{ cm}^{-3}$ to $1.5 \times 10^{18} \text{ cm}^{-3}$ [41]. The further deterioration of the background doping at the similar growth temperature could be due to the involvement of lattice strain.

6.2.3. Full WGPD model

When the photodetector was under an optical illumination and reverse biased, a photocurrent was generated from the active layer (depletion region). Hence, electrically, it behaved as a current source. In the equivalent circuit, this current source was in parallel with the junction capacitance (C_j). Since the bandwidth of the WGPD was also affected by the transit-time of the carriers across the active layer, this current source could be further represented as a voltage-controlled-current-source (VCCS) [50] as shown in Figure 6.5.

Figure 6.5. The WGPD small-signal equivalent circuit including the transit-time effect.

The transit-time limited frequency response (f_{tr}) was determined by the fitting parameter R_t and C_t and g_m . The transconductance g_m took into account for the optical-to-RF conversion efficiency and nonlinearities of the photoresponse under different optical power. R_t was fixed at 50 Ω while the values of C_t and g_m were determined by fitting the measured forward transmission coefficient (S_{21}). In this approach, the R_tC_t was a lump sum for all the timing factors in generating the photocurrent, including the carrier drift time in the depleted region and diffusion time in other regions.

A modulator was used to modulate the optical signal in the measurement. However, due to the complexity of inserting a model for the modulator in the equivalent circuit, its effect was not taken into account in this full WGPD model. Thus, the fitted transit time limited frequency response (f_{tr}) was underestimated.

The fitting results are shown in Figure 6.6. For the WGPD with a 4 μm ridge width and a 17 μm ridge length, the transit-time (R_tC_t) was about 3.0 ps ($g_m = 4.5 \times 10^{-6}$ S) while, for the WGPD with a 6 μm ridge width and a 49 μm ridge length, the transit-time was about 2.8 ps ($g_m = 7.24 \times 10^{-6}$ S).

There two tested devices had the identical epilayer structure. The larger device (with 6 μm ridge width and a 49 μm ridge length) was biased at a higher voltage (-4 V). Its slightly shorter transit-time could be due to the expansion of

the depletion region so the diffusion time was reduced. Moreover, due to the high background doping concentration of the GaNAsSb absorption layer, both devices were obviously not fully depleted at the testing conditions (-1 V and -4 V, respectively). Thus the fitted transit-time was limited by the carriers' diffusion time. These fitted transit-time values corresponded to a transit-time limited bandwidth of over 53 GHz for both devices. This also agreed with the conclusion in Section 5.3.4 that the measured bandwidths are limited by the RC time constant.

Figure 6.6. The measured and fitted forward relative frequency response (S_{21}) for the WGPDs with: (a) 4 μm ridge width and 17 μm ridge length (-1 V biased) and (b) 6 μm ridge width and 49 μm ridge length (-4 V biased), under the illumination condition.

6.3. Summary

In conclusion, we have presented the extraction of the small-signal equivalent circuit of the 2-port network based on the RF measurement setup for the 1.55 μm WGPDs. This equivalent circuit included the sub-network that is attributed to the microwave submount, the lumped elements from the WGPD device physical structure, and a transit-time equivalent RC circuit. From the fitting results, the intrinsic reflection coefficients were obtained which consisted of bias dependent resistors and a capacitor. The fitting parameters suggested that the overall frequency responses of the tested devices are limited by the RC -time constant.

Chapter 7: Conclusions and Recommendations

7.1. Conclusions

In this thesis, we have presented the design, fabrication, characterization, and analysis of the high responsivity and high speed GaNAsSb photodetectors on GaAs platforms. These devices used a novel dilute nitride material, GaNAsSb, as the active layer. By controlling the N and Sb contents, the GaNAsSb photodetectors have been tailored to operate at the 1.3 μm and the 1.55 μm wavelengths with promising performances towards high responsivity and high bandwidth. Figure 7.1 summaries the responsivity-bandwidth performance of the reported dilute nitride-based photodetectors operating at 1.3 μm and 1.55 μm wavelengths [51-62].

Figure 7.1. Summary of the reported dilute nitride-based photodetectors for the 1.3 μm (solid circles) and 1.55 μm (open circles) wavelengths operation (red color circles are the results from this work).

The structural design of the 1.3 μm wavelength WGPDs was discussed as in Chapter 2. Adopting a thin active layer in the waveguide structure was found to achieve a high responsivity and high speed at the same time. Adopting this thin active layer also enabled the achievement of a high responsivity for the 1.55 μm wavelength since the thickness of the GaNAsSb absorption layer was constrained by the critical thickness due to the lattice strain. From the simulation of the optical characteristics, the coupling efficiency was improved

by using additional AlGaAs cladding layers. These additional cladding layers enlarged the optical field distribution and, therefore, reduced the optical field mismatch. This also enhanced the optical confinement. Finally, further analysis showed that the GaNAsSb/GaAs/AlGaAs configuration is more resistant to the imperfections of the fiber-to-WGPD alignment conditions.

Chapter 3 introduced the device fabrication technique. As the experiments cycled, practical issues have been identified. Different dielectric layers such as Si_3N_4 , SU-8 and HSQ have been used. The mask has been re-defined to reduce the area of the contact pad. In the later batches of fabrications, the substrate was thinned down such that a more precise cleaving process was made possible. The effects of these changes were reflected in the device performance in the subsequent chapters.

In Chapter 4, 1.3 μm wavelength WGPDs using GaNAsSb (3.3% N and 8% Sb) were characterized. The results showed a good consistency with the simulation expectations. For the GaNAsSb/GaAs/AlGaAs WGPD, a very high responsivity of 0.72 A/W (corresponding to 96.7% internal quantum efficiency) was obtained. Meanwhile, a lower dark current density and high reverse breakdown voltage were obtained. The bandwidth of the device was 16.5 GHz at the -10 V bias condition. These results are comparable to the existing InP-based photodetectors of a similar design.

In Chapter 5, 1.55 μm wavelength WGPDs using GaNAsSb (3.5% N and 18% Sb) were characterized. The absorption wavelength was extended to 1.6 μm by adopting a slightly strained GaNAsSb layer on GaAs. The dark current density was still higher than that of the lattice-matched GaNAsSb on GaAs devices in the previous chapter. However, the *in-situ* thermal annealing showed a reduction of the dark current density. A high responsivity of 0.6 A/W was observed at 0.1 mW optical injection at -4 V bias and 0.18 A/W was observed at 5 mW optical injection at -4 V bias. Several devices with different dimensions showed the bandwidths over 10 GHz. The highest bandwidth of 14.3 GHz was obtained from the smallest device available.

Based on the experimental results presented in Chapter 5, the small-signal equivalent circuits of the 1.55 μm wavelength WGPDs were discussed in Chapter 6. The construction of the small-signal equivalent circuits was based on the S-parameter measurements. The analysis confirmed that the bandwidths of the devices were limited by the resistance-capacitance effect.

7.2. Recommendations for future research

In this work, the GaNAsSb/GaAs photodetectors suffered a background doping in the GaNAsSb layer. This makes the devices require a higher reverse bias voltage to deplete the active layer and lead to a higher dark current. Due to the faster increasing of dark current than the photocurrent, the dynamic range of the devices was degraded at higher reverse bias conditions where a higher bandwidth was desired.

Higher responsivities and bandwidths of the devices can be achieved at a higher reverse bias condition. However, these are usually difficult to achieve with a high background doping concentration in the active layer. The background doping concentration could be due to the nitrogen-related defects and to arsenic-antisite defects that are formed during the growth of the GaNAsSb material. Therefore, an improved material growth condition such as growth temperature, is needed in future to minimize these defects.

From the extraction of the small-signal equivalent circuits of the 2-port network presented in Chapter 6, we found that the overall bandwidth of the devices is limited by the RC time constant. The capacitance includes the WGPd's junction capacitance and a finite parasitic capacitance from the contact pad. This pad capacitance becomes comparable to the junction capacitance when the device dimension scales down or the junction is fully depleted. In fact, the

contact pad area could be further reduced (areas of $100\ \mu\text{m} \times 100\ \mu\text{m}$ and $50\ \mu\text{m} \times 60\ \mu\text{m}$ were used in this research) since the bonding wire only covers a small area on the contact pad. This will improve the RC time constant limited bandwidth.

The above consideration is based on the top-and-bottom contacts configuration. Changing to a top-and-top contact configuration (i.e. planar design) will enable the integration of Ground-Signal-Ground (GSG) probe pad with the WGPD device in the fabrication stage. This is illustrated in Figure 7.2. The WGPD can be grown on a semi-insulating (S.I.) GaAs substrate. The signal pad can be connected to the top of the ridge using an air-bridge metallization technique [39]. The symmetrical ground pads connect to the bottom portion of the ridge. In this structure, both DC and RF measurements can be directly performed and devices are expected to suffer minimum parasitic effects.

Figure 7.2. Diagram of a planar WGPD structure.

As an optical-to-electrical conversion device, the input network is usually a commercialized high speed laser or a modulator. Their impedances are well-matched to a standard transmission line. However, the output network (i.e. WGPD and its packaging) is not matched. One way to improve the matching is by applying a $50\ \Omega$ resistor in parallel with the WGPD. From the derived equivalent circuit, an output matching network could be constructed to improve the matching condition at a broader frequency range.

In this thesis, the GaNAsSb photodetector was tailored to operate at the $1.3\ \mu\text{m}$ ($n=3.537$) and $1.55\ \mu\text{m}$ ($n=3.46$) wavelengths. This shows the possibility of demonstrating some integrated structures. At $1.55\ \mu\text{m}$ wavelength operation, a $\text{GaN}_{0.033}\text{As}_{0.887}\text{Sb}_{0.08}/\text{GaAs}$ WGPD becomes a passive waveguide. It could be integrated with a $\text{GaN}_{0.035}\text{As}_{0.785}\text{Sb}_{0.18}/\text{GaAs}$ WGPD through a tapered design (Figure 7.3). In this case, a $1.55\ \mu\text{m}$ light source could be coupled into the passive waveguide and then coupled into the WGPD. Achieving such enhancements will require more complicated growth procedures (i.e. selective area re-growth) and fabrication techniques. However, the same tapered design could be achieved with one round of growth of GaNAsSb. The bandgap can be tuned by post annealing the wafer at the selective areas. The difference of the annealing temperatures on the wafer allows the engineering of bandgap to certain extend [63].

Figure 7.3. The integration of a GaNAsSb/GaAs passive waveguide and a GaNAsSb/GaAs WGPD for the 1.55 μm wavelength detection.

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