**NANYANG
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UNIVERSITY**

**HIGH-SPEED AND HIGH-PHOTOCURRENT INP-
BASED UNI-TRAVELING-CARRIER PHOTODIODE**

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HIGH-SPEED AND HIGH-PHOTOCURRENT INP-BASED UNI-TRAVELING-CARRIER PHOTODIODE

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Abstract

With the rapid development of modern optical communication technology, photodiodes (PDs) with high performance have attracted intensive research interests for the application of CATV network, photonic analog-to-digital converter and optical links to phased array antenna and so on. To meet the requirements of high speed, high responsivity and high photocurrent (power) operation, various types of PDs have been investigated. Uni-traveling-carrier photodiode (UTC-PD) has attracted much attention since it was proposed in 1997. Compared to conventional PIN-PD, UTC-PD has a unique mode of operation where only faster electrons serve as the active carriers, which can reduce the space charge effect and lead to much higher current, and higher speed operations.

In this thesis, a top-illuminated InGaAs/InP UTC-PD which is able to achieve high speed, high photocurrent and high responsivity simultaneously at 1.55 μm has been realized. In general, InP-based UTC-PD consists of a p-type narrow-bandgap InGaAs light absorption layer and an n-type wide-bandgap InP carrier collection layer. The abrupt energy barrier at InGaAs/InP absorption/collection interface results in the blocking of electron flow, causing a buildup of stored charge, degrade DC performance at high current densities. It also limits the high-speed, high-photocurrent performance. To overcome this problem, compositional graded InGaAsP layers were normally inserted between the InGaAs absorption and InP collection layers. However, the insertion of the InGaAsP layers often results in the difficulty in growth process as well as results in the complexity of device fabrication. In our UTC-PD structure, a novel dipole-doped structure, in combination with a setback layer were employed at the interface between InGaAs/InP absorption and

collection layers to suppress the current blocking effect. The new structure eases epilayer growth and device fabrication. The design of layer thickness and layer structure has been optimized to maximize the 3-dB bandwidth of UTC-PD with dipole-doped structure without compromising the responsivity. The UTC-PD has been fabricated and characterized with DC and RF performances at 1.55 μm wavelength. The devices show a low dark current of nA range with highest photocurrent of 160 mA and high responsivity of 0.6A/W. 3-dB bandwidth of over 40 GHz, which is due to the limitation of equipment, has been obtained. Clear eye opening at 30 Gbit/s (limitation of equipment) with output RF power of 13.2 dBm have also been realized. A semi-analytical approach has been developed to model the dipole-doped UTC-PD. A 3-dB bandwidth of 103 GHz is predicted for the top-illumination UTC-PD with diameter of 18 μm .

Table of Contents

Acknowledgements	i
Abstract.....	iii
Table of Contents	v
List of Figures.....	viii
List of Tables... ..	xiv
Chapter 1 Introduction	1
1.1 Fiber-optic communication	1
1.2 Motivations	5
1.3 Objective	8
1.4 Organization of the Thesis and Major Contributions	8
Chapter 2 Literature Review.....	12
2.1 Fundamentals and Principles of a Photodiode	12
2.2 Commonly Used Semiconductor Photodiodes	15
2.2.1 Positive-Intrinsic-Negative Photodiode (PIN-PD)	15
2.2.2 Uni-Traveling-Carrier Photodiode (UTC-PD).....	17
2.3 Performance Parameters of Photodiode.....	20
2.3.1 Dark Current	20
2.3.2 Responsivity.....	22
2.3.3 Bandwidth	23
2.3.4 Output Photocurrent and Output RF Power.....	27
2.3.5 Eye Diagrams	28

Chapter 3	Design and Fabrication of UTC-PDs.....	31
3.1	Device Structure with Dipole-doped Layers.....	31
3.2	Design Considerations for 3-dB Bandwidth of UTC-PD	35
3.3	Fabrication of UTC-PD.....	39
Chapter 4	DC and RF Characterization and Analysis of UTC-PDs	44
4.1	DC Measurement	44
4.1.1	Dark Current Measurement At Room Temperature	44
4.1.2	Temperature-dependent Dark Current Measurement	45
4.1.3	Photocurrent and Responsivity	50
4.2	RF measurement	53
4.2.1	3-dB Bandwidth	53
4.2.2	Large Signal Output RF power	62
4.2.3	Eye Diagram	68
4.3	Figure of Merit.....	71
Chapter 5	Modeling of UTC-PDs with a Semi-analytical Approach.....	74
5.1	Introduction.....	74
5.2	Microwave Modelling Techniques for Photodiodes.....	75
5.3	A Semi-analytical Modeling method of Dipole-doped UTC-PD	77
5.3.1	Equivalent Circuit Model.....	77
5.3.2	Parameter Extraction.....	82
5.4	Results and Discussion	90

Chapter 6	Conclusions and Future Work.....	98
6.1	Conclusions.....	98
6.2	Future Work.....	99
6.2.1	Linearity Characterization	99
6.2.2	Balanced Photodiode	101
Appendix.....		103
Bibliography....		107
Publications....		114

List of Figures

Figure 1-1 Schematic of an optical link [5].	2
Figure 1-2 A receiver module including (a) an optical pre-amplifier and a photodiode and (b) a photodiode with electrical post-amplifiers [8].....	4
Figure 2-1 Reverse-biased p-n junction photodiode with an external load [42].....	13
Figure 2-2 Generation of an electron-hole pair by means of a photon [42].	13
Figure 2-3 Photocurrent versus reverse-bias voltage for different incident light power [42].	14
Figure 2-4 Top (a) and back (b) illuminated PIN-PD [43].	15
Figure 2-5 Operation and band diagram of a PIN-PD [44].	16
Figure 2-6 Comparison of energy band diagrams between the PIN-PD (left) and UTC-PD (right) [21] with the illustration of carrier transports.	18
Figure 2-7 Effect of high density photo-generated carriers on band diagrams for : (a) UTC-PD; (b) PIN-PD [21].	20
Figure 2-8 (a) Typical I-V Curves of a PD. (b) Dark I-V relation around origin point [52].	21
Figure 2-9 Basic concept of photocurrent [42].	22
Figure 2-10 Relationship of responsivity vs. wavelength [44].	23
Figure 2-11 Carrier trapping at the heterojunction structure.	26
Figure 2-12 (a) Electron pill-up at the heterojunction (b) Compositional graded layer inserted at the interface to realise current blocking.	27
Figure 2-13 Eye pattern formed by superposition of the random pulse pattern. (a) Ideal transmission- eye is open [62]. (b) Attenuation and dispersion- eye closure [63].	30
Figure 3-1 Schematic energy band diagram of dipole-doped UTC-PD.	34

Figure 3-2 Comparison between energy band profiles of a UTC-PD with (solid line) and without (dashed line) dipole-doped structure. Inset: Conduction band discontinuity at the InGaAs/InP (absorption/collection) interface.	35
Figure 3-3 Prediction of O-E 3-dB bandwidth considering both the carrier-transit-time limited bandwidth and RC limited bandwidth.	37
Figure 3-4: Key fabrication & testing steps for the UTC-PD	39
Figure 3-5: Fabrication steps of UTC-PD using wet mesa etching and conventional lithography.....	41
Figure 3-6 Layout of single UTC-PD.	42
Figure 3-7 Layout of one square array of UTC-PDs with different dimensions. ...	43
Figure 3-8 Left: full processed wafer; right: Single top illuminated UTC-PD with CPW pad design.....	43
Figure 4-1 Dark I-V characteristics of the fabricated devices with 18, 21 and 44 μm diameter.....	45
Figure 4-2 Series resistance of 36 and 80- μm -diameter UTC-PD.....	45
Figure 4-3 Dark $\ln I$ - V Characteristics of a 30- μm -diameter UTC-PD under different temperature conditions (25°C-125°C).	46
Figure 4-4 Forward dark $\ln I$ - V characteristics of a 30 μm -diameter UTC-PD under different temperature conditions (25°C-125°C).	47
Figure 4-5 Ideality factor n and product of n and T and under different T conditions.	49
Figure 4-6 Modified Arrhenius plot of UTC-PD.....	50
Figure 4-7 Photocurrent versus bias voltages of devices with 18, 36 and 70- μm -diameter when the optical input power is 150 mW.	51

Figure 4-8 Measured output photocurrent versus input optical power of devices with a 36 μm diameter at different reverse bias from -1 V to -5 V.	52
Figure 4-9 Measured output photocurrent of a 70- μm -diameter dipole-doped UTC-PD at reverse bias of -5, -6 and -6.5 V under different optical input power.....	53
Figure 4-10 Experiment setup for RF measurement of UTC-PD.	54
Figure 4-11 (a) Measurement setup using 3-axis motion platform and a vertical camera(b) wafer with multiple dies and devices under testing on the sample holder, and (c) a closed-loop UTC-PD device under testing, with an optical fiber at the left-hand side of the CPW probe.	56
Figure 4-12 Measured S_{22} of 18, 44 and 70- μm -diameter UTC-PD under -5 V reverse bias voltage.....	57
Figure 4-13 Measured S_{21} magnitude for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.	58
Figure 4-14 Measured S_{21} phase for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.	58
Figure 4-15 Measured S_{21} magnitude for 18- μm -diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.....	59
Figure 4-16 Measured S_{21} phase for 18- μm -diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.	59
Figure 4-17 Measurement frequency response of a 18- μm -diameter UTC-PD at various optical power conditions at -4 V.	61
Figure 4-18 Measured frequency responses of a 18- μm -diameter UTC-PD with dipole-doped structure under -1 V to -4 V bias when the optical input power is 100 mW.....	61
Figure 4-19 Experimental setup for testing the output RF power of UTC-PD.....	63

Figure 4-20 Output RF power of an 18- μm -diameter UTC-PD measured under various optical input power of 10dBm to 20 dBm, in the frequency range of 2 GHz to 30 GHz.	64
Figure 4-21 Output RF power of a 18- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 30 GHz.	65
Figure 4-22 Large signal output RF power of a 18- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 2 GHz.	66
Figure 4-23 Large signal output RF power of a 36- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 2 GHz.	67
Figure 4-24 Large signal output RF power of a 70- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 2 GHz.	67
Figure 4-25 Output waveform of a 18- μm -diameter UTC-PD at -5 V for 20 Gbit/s signals.	68
Figure 4-26 Output waveform of a 18- μm -diameter UTC-PD at -5 V for 25 Gbit/s signals.	69
Figure 4-27 Output waveform of a 18- μm -diameter UTC-PD at -5 V for 30 Gbit/s signals.	69
Figure 4-28 Waveform and spectrum of a 18- μm -diameter UTC-PD for 30GHz 15dBm Sinewave input at -5 V.	70
Figure 4-29 High photocurrents reported for various PDs.	71
Figure 5-1 A flowchart for an ideal circuit simulator [42].	75
Figure 5-2 Modeling methods for photodiode.	76
Figure 5-3 Equivalent circuit model of PIN-PD.	79
Figure 5-4 Fabricated device and cross section view of InP-based UTC-PD with dipole-doped structure.	80

Figure 5-5 Cross-sectional schematic of InP-based UTC-PD with dipole-doped structure. The equivalent circuit elements are related to the UTC-PD parameters as shown.	80
Figure 5-6 Equivalent circuit model of InP-based UTC-PD with dipole-doped structure.....	81
Figure 5-7 Illustration of test structure: (a) pad with UTC-PD (b) open and (c) short.	82
Figure 5-8 Flowchart of parameter extraction procedure used in this work.....	85
Figure 5-9 Modeling of dipole-doped UTC-PD in ADS.	86
Figure 5-10 Extracted pad capacitance C_p and inductance L_p versus the frequency.	87
Figure 5-11 Extracted series resistance R_s (R_c and $R_c + R_{dd}$) as a function of frequency for UTC-PD with diameter of 18 μm under different bias voltages.	87
Figure 5-12 Extracted series resistance R_s (R_c and $R_c + R_{dd}$) as a function of frequency for UTC-PD with diameter of 18, 44 and 70 μm under -5V bias voltages.	88
Figure 5-13 Extracted junction capacitance C_j of UTC-PD with 18 μm diameter with different bias voltages.	88
Figure 5-14 Extracted junction capacitance C_j of UTC-PD with 18, 44 and 70 μm diameter under -5V bias voltages.	89
Figure 5-15 Comparison of measured (symbols) and modeled (line) S_{22} of 18, 44 and 70- μm -diameter UTC-PD under -5 V reverse bias voltage.	91
Figure 5-16 Comparison of measured (solid line) and modeled (symbols) S_{21} magnitude for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.	92

Figure 5-17 Comparison of measured (solid line) and modeled (symbols) S_{21} phase for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.	92
Figure 5-18 Comparison of measured (solid line) and modeled (symbols) S_{21} magnitude for 18- μm -diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.....	93
Figure 5-19 Comparison of measured (solid line) and modeled (symbols) S_{21} phase for 18- μm -diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.	93
Figure 5-20 Measurement (symbols) and modeling (solid lines) S_{21} magnitude results of a 18- μm -diameter UTC-PD at -1, -3 and -5 V bias when the optical power is 75 mW.....	94
Figure 5-21 Measurement (symbols) and modeling (solid lines) S_{21} phase results of a 18- μm -diameter UTC-PD at -1, -3 and -5 V bias when the optical power is 75 mW.	94
Figure 5-22 Measurement (symbols) and modeling (solid lines) results of a 18- μm -diameter UTC-PD at various optical power conditions at -4 V.....	95
Figure 5-23 Measurement (symbols) and modeling (solid lines) results of a 18- μm -diameter UTC-PD at various dc bias conditions and 100 mW optical input.....	96
Figure 6-1 RF output representation of optical signal components for a two-tone input to photodiode, showing fundamentals, harmonic distortions and intermodulation distortion [76].	100
Figure 6-2 Fundamental and IMD3 as a function of input RF power.	100
Figure 6-3 Two laser two-tone MZM nonlinearity setup [79].....	101
Figure 6-4 Basic design example of the BPD [80].	102

List of Tables

Table 2-1 Bandgap energies and operation wavelength at 300K for representative photodiode materials.	14
Table 3-1 Structure comparison of conventional UTC-PD and dipole-doped UTC-PD	33
Table 3-2 Optimized layer structure of UTC-PD with dipole-doped structure.	38
Table 4-1 Extracted n , I_0 and q/nkT at different temperatures.	48
Table 4-2 Comparison with UTC-type PDs from other literatures.....	73
Table 5-1 Comparison of microwave modelling techniques for photodiodes [42]	77
Table 5-2 Extracted model parameters.	90

Chapter 1 Introduction

1.1 Fiber-optic communication

The method that signals transmit over a distance for communication is called telecommunication, the history of which may date back to 5000 years ago, when the use of smoke or flag as visual signals by our ancestors established one of the oldest forms of communication in recorded history. With the development of human society, science and technology, the demand for high capacity, high speed data transition has been stimulated by the rapid growth of information traffic. Typically, there are four possible methods to transmit data [1, 2, 3, 4]:

1. Free-space radio-frequency (RF) transmission
2. Free-space optical transmission
3. RF propagation over a fixed transmission line
4. Optical propagation over a fixed fibre-optic transmission line.

The first approach is low cost, but it typically has lower speed and requires relatively large power over long distances. The advantage of the second method is its flexibility; however, the signal quality and transition range are strongly restricted by the environmental conditions [1]. The third approach has been primarily used since their invention in 1880. It is simple to integrate with standard electronics and is ideal for relatively short distances and low data rates [1]. The forth approach based on fiber optics - also known as RF optoelectronics, are becoming the main technology for low-haul communication since its invention.

The most basic transmission unit in RF optoelectronics is an analog fiber optic link as shown in Figure 1-1. A basic optical link is comprised of three basic components: a laser for the signal source, a modulator that imposes the radio frequency (RF) or high speed digital signals onto the optical carrier to carry information, optical fibers as signal transmission medium, and optical receivers with photodetector for signal detection and converts optical signal into electrical signal. Optical communication systems have been the mainstream information transmission systems in past decades and are still dominant today thanks to the invention and development of broadband semiconductor lasers, low-loss fibers, fast photodetectors (PDs), and other high quality optoelectronic components [1]. Fiber-optical signal transmission has many advantages: high speed transmission, large bandwidth, low transmission loss over long distances, immunity to electrical disturbance, low material cost and so on.

Figure 1-1 Schematic of an optical link [5].

The optical fibre makes the main difference between optical communication and other data transmission methods. A fiber is made of two types of glass: the inner tube maintains the flow of the light, which is kept in the core by total internal reflection, while the outside cladding prevents the light from escaping [6]. At present,

we have many variants of optical fibre optimized for different rates of transmission and distance. Comparing with conventional coaxial cables, the most remarkable advantage of optical fiber is its low loss. For example, a typical commercial coaxial cable exhibits loss of 56 dB/km at 2.4 GHz. In contrast, the transmission loss in typical optical fibers is lower than 0.2 dB/km at 1.55 μm wavelength and this loss is independent of the frequency of the microwave signals being transmitted. Fibers have replaced conventional coaxial cables, revolutionized the telecommunications industry.

The vast demand of higher standard data transmission requires intense research on developing fiber-optic technology. These requirements largely depend on newly developed optical and electronic semiconductor devices. The PD in the receiver module of the optic link in Figure 1-2 is a key component, which determines the performance of the whole system. In the optical communication system, the photodiode in the front end of receiver plays a crucial role of absorbing the optical signal and converting it to electrical signal at high modulation frequencies. In the ultra-high-speed optical communication system with large capacity, there are three key parameters need to consider carefully when design the photodiode: wide bandwidth, high efficiency and high output power: (1) The wide-bandwidth photodiode can respond the high-bit-rate modulated optical signal fast; (2) Photodiode with high efficiency can fully convert the optical signal into photocurrent. Due to the limitation of the receiver's sensitivity, photodiode with high efficiency is indispensable for the system; (3) Loss is one of the most important considerations for an analog optical link. The loss of an analog optical link relies heavily on the RF/optical conversion efficiencies at the transmitter and receiver ends. At the receiver module, the capability of photodiode to handle very high

photocurrent levels while maintaining the corresponding output RF power is essential to improve the loss and dynamic range of the analog optical link [5]. These high-output photodiodes are used to perform optical-to-electrical conversion, and are typically followed by RF amplifiers to obtain sufficiently powerful RF signals for radar or digital logic applications. If these photodiodes possess sufficiently high saturation current levels and good linearity at RF frequencies, their outputs can be used directly without the need for post-amplification. Hence, high-performance photodiodes have attracted intensive research interests for the application of CATV network, photonic analog-to-digital converter and optical links to phased array antenna [7].

Figure 1-2 A receiver module including (a) an optical pre-amplifier and a photodiode and (b) a photodiode with electrical post-amplifiers [8].

1.2 Motivations

The development of RF optical communications and high-speed high-capacity data transmission has been one of the primary driving forces for research on photodiodes. The evolution of telecommunication systems toward higher capacity, advances in microwave photonics, and the emergence of multiple-component all-optical functions has pushed photodiodes to higher and higher performance. Achieving high speed without sacrificing other performance parameters such as responsivity and noise has presented challenges in the areas of materials, device design, packaging issues, and testing methods [9].

To meet the requirements for both high output and high speed operation, various types of photodiodes have been investigated. Commonly used conventional positive-intrinsic-negative photodiode (PIN-PD) [10] is one of the simplest PD structures, which is used for a wide range of applications. In a conventional PIN-PD structure, both electrons and holes are photo-generated in the depletion layer. The holes with much lower drift mobility and velocity, contribute dominantly to the space charge and can result in the degradation of device performance, especially under high power illumination [7, 11]. Hence, Ishibashi *et al.* [11] proposed a new type of photodiode - uni-traveling-carrier photodiode (UTC-PD) which could achieve high speed and high photocurrent operation simultaneously [7]. Compared to PIN-PD, the UTC-PD has a unique mode of operation which is that only faster electrons serve as the active carriers. This feature can reduce the space charge effect and lead to much higher current and higher speed operations [12]. Due to this advantage, UTC-PD has attracted a great research attention for very promising high-output and high-speed devices.

In order to achieve higher device performance, different types of UTC-PDs [8-20] designed to achieve high-output, high responsivity and large bandwidth have been reported. One of the key structure designs to optimize the performance of UTC-PD is to suppress the current blocking at the interface between the absorption and collection layer [21]. Usually, InGaAsP compositional graded quaternary structures are employed between the small-bandgap light absorber and wide-bandgap carrier collector to reduce the energy barrier, facilitate carriers traveling and relieve the carrier accumulation [22]. However, the presence of compositional graded InGaAsP layers at InGaAs/InP interface could result in the complexity and difficulty in the material growth and subsequent device fabrication.

Another design aspect to realize the ultimate high frequency 3-dB response is that the device is typically designed with a thin absorption and collection layer and a smaller active area than for PIN structures to reduce the carrier transit and junction capacitance [11]. However, the responsivity is normally compromised in such devices. In order to maintain a reasonable responsivity, the devices with small active area require a more complicated device structures such as backside illumination or waveguide design, which result in high costs for design, fabrication and assembly. As an example, when the device active area of UTC-PD is downscaled to $5 \mu\text{m}^2$, ultra-high speed performance (f_{3dB} of 310 GHz) has been achieved at the $1.55 \mu\text{m}$ wavelength operation [12]. However, such a high f_{3dB} can only occur in a very small range of dc reverse bias conditions (0.5 to 0.7 V), and under a small load resistance (12.5Ω) for sustaining a high RC-limited bandwidth [12]. This small load resistance would reduce the output power as compared to that of PD under a standard 50Ω load and the same operation current [12, 13]. Furthermore, a thinner absorption layer would largely affect the responsivity performance of device with a limited

responsivity as low as 0.07 A/W [12, 13]. Thus, optimization of device layer structure design which could enable UTC-PD to achieve high-speed performance without compromising the responsivity is still of research interest.

On the other hand, the design of integrated circuits with computer-aided design (CAD) tools depends greatly on the models of actual devices. Modeling of photodiodes is very important for a careful analysis of their performance and design issues. For high-output and high-speed photodiodes, various modeling methods, such as physics-driven modeling, analytical modeling, empirical modeling and equivalent circuit modeling, have been investigated (especially for PIN-PDs) [25-32]. Wang *et al.* [25, 26] and Wu *et al.* [27] both proposed their analytical equivalent circuit models for high-performance photodiodes.

The accuracy of the results depends greatly on the parameters of the equivalent circuit model; thus a good equivalent circuit model is not merely helpful for prediction of the performances of devices but also important for extracting model parameters conveniently and accurately [23-37]. Numerical optimization techniques are usually used to determine the optimal values of model parameters [35, 38]. However, the accuracy of the optimization methods can vary largely up to the optimization method used and the initial values of model parameters selected [23-41]. Nonphysical and nonunique results of the extracted parameter could be generated. Analytical methods usually allow extracting a unique and physically meaningful set of parameters from a set of closed-form expressions based on the measurement results of devices [33-39]. However, some parameters may be difficult to be extracted directly using analytical methods.

Motivated by above mentioned existing issues, thus, research work has been conducted on UTC-PDs for design, fabrication, measurement, modeling and analysis in this thesis.

1.3 Objective

The main objective of the research work in this thesis is to achieve a InP-based UTC-PD device which could attain high-speed, high-responsivity and high-output performance simultaneously at 1.55 μm wavelength. To overcome the issues on other reported UTC-PDs, a novel transition layer structure at the InGaAs absorption layer and InP collection layer interface, without using InGaAsP quaternary material to suppress the current blocking needs to be proposed. Then, layer structure needs to be carefully designed to further optimize the UTC-PD's performance. With optimised UTC-PD layer structure design and fabrication process, UTC-PD will be able to achieve high-speed performance without compromising the responsivity and output performance. Furthermore, in order to have a better prediction of device bandwidth and a careful analysis of device performance, a semi-analytical model based on the actual device structure and physics of our proposed UTC-PD needs to be developed.

1.4 Organization of the Thesis and Major Contributions

Thesis is organized into six chapters.

Chapter 1 presents the background of the current research work: the development of fiber-optic communication and the role of photodiodes, the motivation, objective of current research work, the overview of this thesis and my major contribution.

In Chapter 2, the literature background of topics related to this research work are reviewed. Beginning from the fundamentals and principles of photodiode, several types of commonly used photodiodes, including their structures, operation mechanism performances and common applications, are studied. The operation principles of our main research object – UTC-PD is studied in comparison with conventional PIN-PD. Lastly, several key UTC-PD performance parameters, which will be characterized, were introduced.

Chapter 3 introduces the design and fabrication of UTC-PD. A UTC-PD structure with novel dipole-doped layers are proposed. The effectiveness of using dipole-doped structure and setback layer to replace conventionally used compositional InGaAsP layer to reduce the current blocking effect were validated by simulation. Layer structure and layer thickness are optimized to maximize the high-speed performance of dipole-doped UTC-PD, without compromising the photocurrent and responsivity. A high 3-dB bandwidth of 100 GHz is predicted for 18- μ m-diameter UTC-PD based on a semi-analytical equivalent circuit model. UTC-PDs with different dimensions are fabricated using standard micro-fabrication techniques. The major fabrication processes are described in this chapter.

In Chapter 4, the DC performances including temperature dependent dark current, photocurrent and responsivity, RF performances such as 3-dB bandwidth, output RF power, and output eye diagram are characterized for UTC-PDs with different diameters under various conditions. Measurement results have been presented and analyzed. The devices show a low dark current of nA range with highest photocurrent of 160 mA and high responsivity of 0.6A/W. 3-dB bandwidth of over 40 GHz, which is due to the limitation of equipment, has been obtained.

Clear eye opening at 30 Gbit/s (limitation of equipment) with output RF power of 13.2 dBm have also been realized.

A semi-analytical equivalent circuit and model parameter extraction methods to predict the 3-dB bandwidth of UTC-PD is developed in Chapter 5. The equivalent circuit model is proposed uniquely based on the actual structure of physics of our proposed UTC-PD. The semi-analytical method combines the advantages of using analytical method and numerical optimization method for extracting the small-signal model parameters of UTC-PD. With this semi-analytical modelling method, a 103 GHz 3-dB bandwidth can be achieved from an 18- μ m-diameter UTC-PD.

Finally, chapter 6 reviews what we have achieved in this research work and recommends the future work focusing on nonlinearity measurement on UTC-PDs and balanced PD.

The major contributions of this thesis is on the development of high performance InP UTC-PDs for high current and high frequency applications. In particular, InP-based UTC-PDs with novel dipole-doped layers were designed and layer structures were optimized to achieve high speed, high photocurrent and high responsivity simultaneously at 1.55 μ m. UTC-PDs with different dimensions were fabricated and characterized. DC and RF measurement results were demonstrated and analyzed. A semi-analytical modelling approach were developed to predict the 3-dB bandwidth of UTC-PDs. InP UTC-PDs with state-of-the-art performance have been demonstrated. The devices show the highest photocurrent of 160 mA and high responsivity of 0.6A/W with low dark current of nA range. 3-dB bandwidth of over 40 GHz, which is due to the limitation of equipment, has been obtained. 3-dB bandwidth over 100 GHz is predicted for top-illuminated UTC-PD with a 18- μ m of

diameter. Clear eye opening at 30 Gbit/s (limitation of equipment) with output RF power of 13.2 dBm have also been realized.

Chapter 2 Literature Review

2.1 Fundamentals and Principles of a Photodiode

As we discussed in chapter 1, in an optical communication system, the semiconductor laser diodes convert an electrical signal into light and launch it into the optical fiber which serves as a communication channel. The receiver module at the end of the optical transmission line (fiber) interprets the information carried on the light signal which is transmitted in the fiber. The first element in this receiver is the photodiode. Thus, the principle of operation of a photodiode can be explained simply as the opposite manner of a laser's operation. Actually, a p–n junction in reverse-biased condition can be taken as the simplest photodiode. Figure 2-1 shows the p–n junction photodiode with an external load and Figure 2-2 shows the generation of an electron–hole pair with the help of a photon. When the incident light penetrates into the depletion region of the p and n material, the free carriers are removed. If the incident light energy is greater or equal to the bandgap energy of the semiconductor material (E_g), the photons will release their energy and excite electrons from the valence band to the conduction band, leaving holes in their places in the valence band (see Figure 2-2). If the incident light energy is hc/λ (where h is Plank's constant, c is light velocity, and λ is light wavelength), the maximum optical wavelength requires can be expressed as [42]:

$$\lambda_{max}[\mu m] = \frac{hc}{E_g} = \frac{1.24}{E_g[eV]} \quad (2-1)$$

Figure 2-1 Reverse-biased p-n junction photodiode with an external load [42].

Figure 2-2 Generation of an electron-hole pair by means of a photon [42].

Therefore, in order to generate electron-hole pairs, the incident light wavelength must be less than a threshold $\lambda_{\max}$. Table 2-1 gives summary of the bandgap energies and operation wavelength at 300 K for some representative photodiode materials.

The electron-hole pairs generated with the help of photon will be separated and swept to the opposite sides of the depletion region (space-charge region) by the electric field existing across this region. If an external circuit is connected to the p and n regions, electrons will flow away from the n region and holes will flow away from the p region toward opposite electrodes. These electrons and holes generate current flow in semiconductor. Figure 2-3 shows the relationship between output

photocurrent and reverse bias voltage for different optical input powers, and it can be seen that the output photocurrent increases with the increase of the optical input power.

Table 2-1 Bandgap energies and operation wavelength at 300K for representative photodiode materials.

Materials	Bandgap energies eV	Short wavelengths less than 1.31 μm	Long wavelengths 1.31-1.55 μm
GaAs	1.43	√	×
InP	1.35	√	×
GaAs _{0.88} Sb _{0.12}	1.15	√	×
In _{0.14} Ga _{0.86} As	1.15	√	×
Si	1.14	√	×
In _{0.53} Ga _{0.47} As	0.75	√	√
GaSb	0.73	√	√
Ge	0.67	√	√
InAs	0.35	√	√

Figure 2-3 Photocurrent versus reverse-bias voltage for different incident light power [42].

2.2 Commonly Used Semiconductor Photodiodes

2.2.1 Positive-Intrinsic-Negative Photodiode (PIN-PD)

To meet the needs for modern optical communication system, there are three basic requirements, responsivity, speed and output performance, that need to be taken into consideration when designing a PD. Unfortunately, there are usually some trade-offs between these three targets. In the early stages, the vertical type photodiode (VPD) was the most popular, commercial product used in an optical communication system. PIN-PD [10], which represents one of the simplest VPD structures, has been used for a wide range of applications. As shown in Figure 2-4 and 2-5, a PIN-PD is formed by inserting an intrinsic layer as the light absorption region between the P⁺ and N⁺ region. The intrinsic region is wider than the depletion region of a normal PN junction's contact interface. When a PIN-PD is working under reverse bias condition, light is illuminated on the PD's topside or backside, penetrates into and is absorbed by the intrinsic layer, electron-hole pairs are generated in this depleted absorption layer and travel independently in opposite directions. Thus both electron and hole current components contribute to the total output response in a PIN-PD. On the other hand, due to the significant difference in electron and hole carrier velocities, the total performance is determined by the holes with low velocity.

Figure 2-4 Top (a) and back (b) illuminated PIN-PD [43].

Figure 2-5 Operation and band diagram of a PIN-PD [44].

PIN-PD has been widely used in various areas since its invention due to its simple structure and relatively high responsivity. However, there are some limitations of using PIN-PD when high speed and high output devices are required in modern optical communications. PIN-PD cannot sustain high photocurrent levels due to two major reasons. First, PIN-PD is very susceptible to thermal failure because the electric field in the intrinsic InGaAs absorption region needs to be high enough to ensure that the electrons and holes travel at the saturation drift velocity [45]. On the other hand, the electric field in the intrinsic InGaAs absorption region is responsible for most of the heat generation in PIN-PD. Since InGaAs is a narrow-bandgap semiconductor, its critical temperature for thermal runaway is relatively low. This will result in thermal failure at relatively small photocurrent levels. Second, PIN-PD is particularly susceptible to the current saturation induced by space-charge effect [45]. In a photodiode, as the photocurrent increases, first the non-linearity sets in, gradually increasing with increasing photocurrent, and finally at some level, the

photocurrent remains constant with increasing input optical power, this is called saturation. At high optical input powers the detection capability is restricted by saturation effects in the photodiode. In analog applications, high output photocurrent help to minimize the noise figure and hence increase the dynamic range. In a PIN-PD the electron velocity is higher than that of hole. Balance is broken in the spatial profile of the photo-generated carriers with fewer electrons than holes in the depleted intrinsic absorption region. As the optical input power increases and the photo-generated carriers accumulate, the electric field in this depleted region is screened by these charges and due to the unbalanced carrier density distribution, the electric field collapses near the n side [45]. When the electric field drops to the point that carriers no longer maintain saturation velocity, the bandwidth decreases and the RF output power saturates. This situation is the so-called space-charge effect.

Many researchers have reported various ways to improve the device speed performance based on the PIN structure, such as the partial-depleted-absorption photodiode (PDA-PD) [46], dual-absorption photodiode (DA-PD) [47], dual-depletion layer PIN-PD [48], and partial p-doped PIN-PD [49]. These structures are designed to release the carrier transit time without sacrificing the responsivity.

2.2.2 *Uni-Traveling-Carrier Photodiode (UTC-PD)*

In 1997, Ishibashi *et al.* [11] proposed a new type of photodiode, the so-called uni-traveling-carrier photodiode (UTC-PD), which could achieve high speed and high output operation simultaneously. Figure 2-6 shows the comparison of energy band diagrams between the conventional PIN-PD and UTC-PD with the illustration of carrier transports. The active part of the UTC-PD consists of a neutral (p-type) narrow-bandgap light absorption layer and an undoped (or a lightly n-type doped)

wide-bandgap carrier collection layer. The photo-generated minority electrons in the neutral absorption layer travel by diffusion (and/or drift) into the depleted collection layer. Here, a quasi-field is introduced into the absorption layer by means of the bandgap grading and/or doping grading, which is very effective at reducing electron traveling time [21]. On the other hand, because the absorption layer is quasi-neutral, photo-generated majority holes respond very fast within the dielectric relaxation time [21]. Therefore, in UTC-PD only the electron transport determines the photoresponse. This characteristic is an essential difference between the UTC-PD and the conventional PIN-PD, in which both electrons and holes contribute to the response current, and the total performance is determined by low-velocity holes [50].

Figure 2-6 Comparison of energy band diagrams between the PIN-PD (left) and UTC-PD (right) [21] with the illustration of carrier transports.

The difference of operation mode provides UTC-PD several advantages over PIN-PD. First, UTC-PD has higher operation speed [21]. The velocity of electrons in the depletion layer is an order of magnitude higher than that of the holes. In addition, the thicknesses of the carrier collection layer and the absorption layer can be designed independently. There is a trade-off between the thickness of the InGaAs and the diffusion of carriers. Thus, we can calculate and design the layers with

certain thickness to achieve a low carrier transit time without sacrificing the RC charging time to improve the photodiode's speed performance [51]. Another advantage is the higher output photocurrent which is due to the much lower space charge effect in the depletion region [23]. This is also result of the high electron velocity in the depletion layer. As shown in Figure 2-7, the energy band of PD is modified under high optical input conditions, due to the stored photo-generated carriers in the absorption layer. Saturation of output can occur due to reduced carrier velocity induced by decreased electric field [21]. However, in UTC-PD the space charge includes only high-velocity electrons, which will not become slow until the electric field is reduced to a fairly low level. Therefore, the output saturation does not occur until the current density becomes an order of magnitude higher than that for PIN-PD [21]. This explains the reason that UTC-PD has a much wider linear range than PIN-PD. Furthermore, because even at relatively low electric field UTC-PD can still maintain high speed and non-saturated operation, low bias voltage or even zero bias voltage operation is possible. A smaller operation voltage has many advantages on reducing power consumption, simplifying heat sinking, and improving reliability. Due to these features, UTC-PDs have attracted a great deal of attention as promising high-speed, high-responsivity and high-output devices.

Figure 2-7 Effect of high density photo-generated carriers on band diagrams for : (a) UTC-PD; (b) PIN-PD [21].

2.3 Performance Parameters of Photodiode

2.3.1 Dark Current

The dark current is the leakage current that flows when the photodiode is in the absence of any optical signal and originates from thermally generated electron–hole pairs while a reverse voltage is applied across the junction. The current–voltage (I - V) characteristics of a photodiode with no incident light are similar in nature to that of a normal p–n junction. The dark current can be expressed as follows [42]:

$$I_d = I_s \left[e^{\frac{qV}{kT}} - 1 \right] \quad (2-2)$$

where I_d is the photodiode dark current, I_s is the reverse saturation current, e is the electron charge, V is the applied bias voltage, k is the Boltzmann constant, and T is the absolute temperature. This relationship is shown in Figure 2-8, which is also the transfer function of a typical photodiode. In Figure 2-8 (b), dark current presents around the origin point with no light. Typically, three states can be defined for a

PD's operation: $V = 0$, I is reverse saturation current; $V > 0$ (forward bias), I increases exponentially; $V < 0$ (reverse bias), I is the sum of dark current and photocurrent.

Figure 2-8 (a) Typical I - V Curves of a PD. (b) Dark I - V relation around origin point [52].

Thus, the photodiode device produces a total current I_t that is a sum of the photocurrent I_p and a dark current I_d , and can be expressed by [42]:

$$I_t = I_s \left[e^{\frac{qV}{kT}} - 1 \right] + I_p \quad (2-3)$$

As the applied reverse bias increases, there is a sharp increase in the photodiode current.

In order to reduce the dark current, in fabrication process of a photodiode, after mesa formation, passivation step is necessary to terminate the dangling bonds at the mesa edge and to protect the sidewall of the photodiode to reduce the surface leakage current.

2.3.2 Responsivity

The responsivity shows the efficiency of a photodiode converting light signal into an electrical signal (photocurrent) (see Figure 2-9); in other words, this characteristic is a measure of a PD's sensitivity to light. It is defined as the ratio of the photocurrent I_p to the optical input power illuminating on the PD P_{in} at a given wavelength [42]:

$$R = \frac{I_p}{P_{in}} \quad (2-4)$$

Figure 2-9 Basic concept of photocurrent [42].

For example, a responsivity of 0.5 A/W means when the photodiode is illuminated by 1 mW of light, a current of 0.5 mA will be produced. Responsivity varies with light wavelength (Figure 2-10) and applied reverse bias. As shown in Figure 2-10, responsivity increases with increasing of wavelength until the cut-off wavelength is reached for each material. Thus, maximum responsivity can be anticipated for InGaAs at 1.55 μm wavelength.

Figure 2-10 Relationship of responsivity vs. wavelength [44].

2.3.3 Bandwidth

Bandwidth is a very important parameter which demonstrates the operation speed of PDs. In general, the optical-to-electrical (O-E) 3-dB bandwidth (f_{3dB}) of a PD is mainly determined by the carrier transit time ($1/f_t$) and the external parasitic RC charging time ($1/f_{RC}$) [27]:

$$\frac{1}{f_{3dB}^2} = \frac{1}{f_T^2} + \frac{1}{f_{RC}^2} \quad (2-5)$$

In addition to carrier transit and RC charging, the carrier trapping at the energy barrier of heterojunction, which is also called current blocking, also influences the operation speed of PDs. These influencing factors will be discussed in the following.

2.3.3.1 RC Time Constant

The RC time constant is the charging time of external parasitic RC network in a PD. The RC-limited bandwidth can be estimated as [43]:

$$f_{RC} = \frac{1}{2\pi R_L C_T} \quad (2-6)$$

where R_L is load resistance, C_T is the total capacitance through the depletion layer and can be derived from [53]:

$$C_T = \frac{\epsilon_0 \epsilon_{req} A}{d} \quad (2-7)$$

where A is the area of UTC-PD's active part, ϵ_0 is the dielectric constant of vacuum, ϵ_{req} is the relative equivalent dielectric constant of the total depletion layer and d is the total thickness of the depletion layer. Thus, for high frequency characterization, smaller junction area and thicker depletion layer can be used to minimize the RC time constant and increase the bandwidth of UTC-PD.

For the junction capacitor of UTC-PD which is made using different materials including InGaAs and InP with dielectric constant values of ϵ_{r1} and ϵ_{r2} and thickness d_1 and d_2 , the equivalent dielectric constant ϵ_{req} can be expressed as [53]:

$$\epsilon_{req} = \frac{(d_1 + d_2)\epsilon_{r1}\epsilon_{r2}}{d_1\epsilon_{r2} + d_2\epsilon_{r1}} \quad (2-8)$$

2.3.3.2 Carriers Transit Time

In a PD, the electrodes will collect photo-generated carriers, which transport across the high-electrical field region after being produced in the active region, after the light was illuminated to the material. Under an electric field, the electrons will transport to the right and the holes transport oppositely. This distribution generates an internal current which decrease the inside electrical field. This process leads to saturation in the device in the end. In a PIN-PD, when electrons and holes travel independently, the output response is sum of both current components. Due to the low velocity of holes compared to electrons, hence, the transit time of holes

determine the speed of PIN-PD. The transit-time-limited bandwidth in a P-I-N photodiode can be expressed as [54, 55]:

$$f_T = \frac{3.5v_{e+h}}{2\pi d} \quad (2-9)$$

where $v_{e+h} = \sqrt[4]{2(1/v_e^4 + 1/v_h^4)}$ is the average drift velocity of electrons and holes in the depletion layer.

One of the advantages of the UTC-PD is that it can take advantage of the electron velocity overshoot to boost operation speed and output current. When the average electron velocity is much larger than reported electron drift velocity in undoped InP at a similar electric field, this indicates that the electron velocity overshoot is actually taking place in the depletion layer of the UTC-PD [55]. Similar phenomena have also been observed in the collector layer of HBTs [56, 57, 58]. In the case of a short traveling distance, such as in the depletion layer of the UTC-PD, the optimum electric field providing the shortest average electron traveling time becomes higher due to the nonequilibrium transport of electrons, which results in the velocity overshoot [59, 60, 61]. Thus, in a UTC-PD, when the active region - the absorption layer (and transition layer) and carrier collection layer - is completely depleted, the electron will drift through the whole active region with an average electron drift velocity, thus the carrier-transit-time limited bandwidth of UTC-PD can be estimated based on [27, 55]:

$$f_T = \frac{0.55v_e}{d} \quad (2-10)$$

where v_e is the average drift velocity of electrons and d is the total drift distance of electrons through the active region- depletion layers.

2.3.3.3 Carrier Trapping

The trapping of holes at valance band and that of electrons at conduction band are discontinuous due to the heterojunction structure in PDs (Figure 2-11). For a typical UTC-PD which has an p-type doped InGaAs absorption layer and a wide InP collector (Figure 2-12 (a)), the band discontinuity results from the different energy gaps of small-bandgap InGaAs and wide-bandgap InP that forming the heterojunction. The abrupt energy barrier of the conduction band at InGaAs/InP absorption/collection interface can block electron flow, cause a buildup of stored charge, degrade DC performance at high current densities and also limit the high-speed performance. One of the key structure designs to optimize the performance of UTC-PD is to suppress the current blocking (carrier trapping) at the interface between the absorption and collection layer. To overcome this problem, compositional graded InGaAsP layers were normally inserted between the InGaAs absorption and InP collection layers (Figure 2-12 (b)) [20, 21]. However, the insertion of the InGaAsP layers often results in the difficulty in growth process as well as results in the complexity of device fabrication.

Figure 2-11 Carrier trapping at the heterojunction structure.

Figure 2-12 (a) Electron pill-up at the heterojunction (b) Compositional graded layer inserted at the interface to realise current blocking.

In this work, novel dipole-doped InGaAs/InP structure in combination with a setback layer are employed to replace conventionally used InGaAsP. The use of dipole-doped interface may ease the material growth and device fabrication without compromising the device performance [7]. The details of the dipole-doped structure will be introduced in next Chapter.

2.3.4 Output Photocurrent and Output RF Power

According to the Equation (2-4) the photocurrent should increase with the increase of optical input power. However, at high illumination levels the photocurrent is no longer proportional to the input and tends to saturate due to the reduction of electric field induced by the space charge effect. The output power refers to the RF power delivered to a 50Ω load resistor [5]. Photodiodes as the optical to electrical converters in the optic links must be able to operate at very high photocurrent level and generate high RF output power. A number of efforts [14-21] have been done to increase the maximum photocurrent that a single PD can sustain and the power handling ability without device failure [54].

The UTC-PD tends to have higher output due to the high-velocity electrons, which results in much less space charge effect compared to PIN-PD. What's more, in a UTC-PD, similar to the discussion of factors influencing the speed performance of PD, the conduction band discontinuity at the absorption/collection layer interface will cause carrier trapping, which will also limit the output photocurrent. Proper design of materials and structures at this interface should be considered to reduce the carrier trapping and current blocking. What's more, increasing the absorption area and reducing the carrier collection layer thickness can result in a high output, however this will increase the RC time constant [21].

In Chapter 4, we will demonstrate high output photocurrent and RF power achieved from our fabricated UTC-PDs.

2.3.5 Eye Diagrams

High-speed optical transmission systems often suffer serious signal loss and quality degradation in every process of modulation, transmission and detection due to low probability phenomena such as modulation fluctuation and spectrum fluctuation of lasers. The eye pattern of the receiving module output contains all the information concerning the degradation of quality. An eye diagram is an indicator of the quality of signals in high-speed digital transmissions. It is a critical and commonly used measure of optical-link performance in optical networks. The eye diagram of the photodiode, in particular, is a key element in determining the link budget. The eye diagram can be applied to many types of investigation, for example modulation characteristics and transmission characteristics of laser diodes, analysis of noise, jitter, inter-symbol interference, and estimation of eye margin [62].

The eye diagram is formed by superposition of 2-3 bit-long electrical sequences in the bit stream on each other [62]. The resulting pattern looks like an eye shape so we call it eye diagram. Eye patterns can be observed using an oscilloscope. If we consider a 4-bit pattern as shown in following:

0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111,
1000, 1001, 1010, 1011, 1100, 1101, 1110, 1111

Since 0 represents no light signal and 1 represents the presence of a light signal, the superposition of all the pattern results the eye diagram shown in Figure 2-13. An eye diagram is a very convenient method of visualizing the quality of digital data transmission. An open eye implies that the signal has been ideally transmitted and are easily resolvable (Figure 2-13 (a)). If the data have suffered loss, dispersion and jitter during transmission, in this case the detected eye is not open (Figure 2-13 (b)). Thus we can obtain a quick estimate of system performance from the opening of the eye.

Figure 2-13 Eye pattern formed by superposition of the random pulse pattern. (a) Ideal transmission- eye is open [62]. (b) Attenuation and dispersion- eye closure [63].

Chapter 3 Design and Fabrication of UTC-PDs

3.1 Device Structure with Dipole-doped Layers

In Chapter 2, we have discussed the fundamentals and principles of UTC-PD. Several types of UTC-type PDs [6-20] designed to achieve high responsivity, high photocurrent and large bandwidth have been reported.

For a typical UTC-PD which has a p-type doped InGaAs absorption layer and a wide InP collector, to suppress the current blocking and improve the device bandwidth and power/current handling capability, InGaAsP compositional graded quaternary structures are employed at the InGaAs/InP heterostructure interface to smooth the bandgap discontinuity. However, the presence of compositional graded InGaAsP layers at InGaAs/InP interface could result in the complexity and difficulty in the material growth and subsequent device fabrication. In this work, UTC-PDs with novel dipole-doped InGaAs/InP structure without using InGaAsP quaternary material are reported. The use of dipole-doped interface may ease the material growth and device fabrication without compromising the device performance. Besides, optimization of structure layers has been made to further optimize the high-speed performance of UTC-PD. The dipole-doped UTC-PDs have demonstrated good figure-of-merit (FOM) with high speed as well as high photocurrent and high responsivity performance.

Table 3-1 shows the detailed layer structure comparison between the conventional UTC-PDs with InGaAsP quaternary structure [20] (left column) and the UTC-PDs with novel dipole-doped structure developed in this work (right

column) [7]. Both structures are similar, a 450 nm InGaAs absorption layer graded in three steps, to form a quasi-neutral electric field to aid carrier transport, and a 200 nm InP carrier collection layer, with the exception at the InGaAs/InP interface, where it has been highlighted. Generally, InP-based UTC-PD consists of a p-type narrow-bandgap InGaAs light absorption layer and an n-type wide-bandgap InP carrier collection layer. The abrupt energy barrier at InGaAs/InP absorption/collection interface can block electron flow, cause a buildup of stored charge, degrade DC performance at high current densities and also limit the high-speed performance. To overcome this problem, compositional graded InGaAsP layers were normally inserted between the InGaAs absorption and InP collection layers [20, 21]. However, the insertion of the InGaAsP layers often results in the difficulty in growth process as well as results in the complexity of device fabrication.

In our UTC-PD structure, dipole-doped layers, in combination with a 22-nm-thick undoped InGaAs setback layer were employed at the InGaAs/InP absorption and collection interface to reduce the current blocking effect. The dipole-doped layers consist of an 8-nm-thick InGaAs layer and an 8-nm-thick InP layer, both of which have been p- and n-type doped with the concentration of $1 \times 10^{18} \text{ cm}^{-3}$. The dipole-doped UTC-PD structures used in this work were grown by molecular beam epitaxy (MBE). Beryllium was used for the p-type dopant and Silicon for the n-type.

Table 3-1 Structure comparison of conventional UTC-PD and dipole-doped UTC-PD

Conventional InGaAs/InP UTC-PD with InGaAsP quaternary structure			InGaAs/InP UTC-PD with novel dipole-doped structure		
Layer	Thickness (nm)	Doping (cm ⁻³)	Layer	Thickness (nm)	Doping (cm ⁻³)
InGaAs	30	p:1×10 ¹⁹	InGaAs	30	p:1×10 ¹⁹
InP	200	p:1×10 ¹⁹	InP	200	p:1×10 ¹⁹
InGaAs	50	p:2×10 ¹⁸	InGaAs	50	p:2×10 ¹⁸
InGaAs	100	p:1×10 ¹⁸	InGaAs	100	p:1×10 ¹⁸
InGaAs	300	p:5×10 ¹⁷	InGaAs	300	p:5×10 ¹⁷
InGaAs	15	undoped	InGaAs	22	undoped
InGaAsP	15	n:5×10 ¹⁶	InGaAs	8	p:1×10 ¹⁸
InGaAsP	15	n:5×10 ¹⁶	InP	8	n:1×10 ¹⁸
InP	5	n:5×10 ¹⁷	InP	13	n:1×10 ¹⁷
InP	200	n:5×10 ¹⁶	InP	200	n:5×10 ¹⁶
InP	600	n:5×10 ¹⁸	InGaAs	30	n:5×10 ¹⁸
S. I. – InP substrate			InP	600	n:5×10 ¹⁸
			S. I. – InP substrate

Figure 3-1 Schematic energy band diagram of dipole-doped UTC-PD.

Figure 3-1 illustrated the schematic energy band diagram of the whole structure of a UTC-PD with a dipole-doped interface the band diagram simulation of a UTC-PD with and without dipole-doped structure, which has been obtained by using a 1-D simulator, is shown in Figure 3-2 [64]. The solid line and dashed line represent the band profiles with and without dipole-doped structure, respectively. The inset also presents the enlarged conduction band diagram near the InGaAs/InP heterointerface. It is noted that, by incorporating a dipole-doped structure, the effective energy barrier at the InGaAs/InP interface can be reduced by ~ 0.2 eV. Not only the energy barrier is reduced, which facilitates the electrons easily thermionic emission across, but also the thickness of the triangular well is reduced, which could enhance electrons tunnel through the junction barrier. Therefore, the reductions on the barrier height and thickness may substantially suppress the current blocking.

Figure 3-2 Comparison between energy band profiles of a UTC-PD with (solid line) and without (dashed line) dipole-doped structure. Inset: Conduction band discontinuity at the InGaAs/InP (absorption/collection) interface.

3.2 Design Considerations for 3-dB Bandwidth of UTC-PD

As we discussed in last chapter, the speed of a PD is mainly limited by two factors: the carrier transit time and the RC delay time. And the overall O-E 3-dB bandwidth can be predicted by [27]:

$$\frac{1}{f_{3dB}^2} = \frac{1}{f_T^2} + \frac{1}{f_{RC}^2} \quad (3-1)$$

The carrier-transit-time limited bandwidth of UTC-PD can be estimated based on [27]:

$$f_T = \frac{0.55v_e}{d} \quad (3-2)$$

where v_e is the average drift velocity of electron and d is the total drift distance of

electron through the depletion layers. Here, we assume that the active region of UTC-PD is completely depleted, which is valid for the UTC-PDs at high reverse bias (> 2 V for our case). For the UTC-PDs using InP and InGaAs, an average drift velocity of 2×10^7 cm/s for electrons drift through the dipole-doped structure, setback layer and carrier collection layer can be expected.

As to the RC-limited bandwidth, it can be calculated by [43]:

$$f_{RC} = \frac{1}{2\pi R_L C_T} \quad (3-3)$$

where R_L is load resistance, which is 50Ω in our work and C_T is the total capacitance through the depletion layer with thickness of d . C_T can be determined by [53]:

$$C_T = \frac{\epsilon_0 \epsilon_{req} A}{d} \quad (3-4)$$

where A is the area of UTC-PD's active part, ϵ_0 is the dielectric constant of vacuum, ϵ_{req} is the relative equivalent dielectric constant of the total depletion layer and d is the total thickness of the depletion layer.

As we know, when a capacitor is made using different dielectric layers with dielectric constant values of $\epsilon_{r1}, \epsilon_{r2}, \dots, \epsilon_{rn}$ and thickness $d_1, d_2, \dots, d_n$, the equivalent dielectric constant ϵ_{req} is given by [53]:

$$\epsilon_{req} = \sum_{m=1}^n \frac{d_m}{d \epsilon_{rm}} \quad (3-5)$$

where d_m is the thickness and ϵ_{rm} is the dielectric constant of the m th layer, and d is the total thickness, that is,

$$d = d_1 + d_2 + \dots + d_n \quad (3-6)$$

In this work, for the junction capacitor of UTC-PD which is made using different materials including InGaAs and InP with dielectric constant values of ϵ_{r1} and ϵ_{r2}

and thickness d_1 and d_2 , the equivalent dielectric constant ϵ_{req} can be expressed as [53]:

$$\epsilon_{req} = \frac{(d_1 + d_2)\epsilon_{r1}\epsilon_{r2}}{d_1\epsilon_{r2} + d_2\epsilon_{r1}} \quad (3-7)$$

The total thickness of depleted region is $d = d_1 + d_2$.

Figure 3-3 shows the theoretical f_{3dB} (solid lines) for UTC-PD with diameter of 12 μm , 18 μm , and 21 μm based on the structure given in Figure 3-1. It can be seen that, for different junction areas (diameters), proper optimization of the thickness for InP layer is needed to achieve a maximum f_{3dB} . For example, compared to the device with a diameter of 12 μm , a thicker InP layer is required for the UTC-PD with a diameter of 18 μm to achieve the maximum bandwidth. In this work, according to the calculation, the thickness of InP layer is set to be around 0.371 μm , which is optimized for the top-illuminated UTC-PD with 18- μm diameter, while the performance for other device sizes is compromised.

Figure 3-3 Prediction of O-E 3-dB bandwidth considering both the carrier-transit-time limited bandwidth and RC limited bandwidth.

Thus, structure of dipole-doping UTC-PD has been optimized. Compared to our initial design shown in Table 3-2, the thickness of carrier collection layer has been increased from 200 nm to 350 nm, in order to further reduce the junction capacitance and thus increase the RC-limited component of the bandwidth, to increase the total O-E 3-dB bandwidth. Plus 8-nm-thick $1 \times 10^{18} \text{ cm}^{-3}$ and 13-nm-thick $1 \times 10^{17} \text{ cm}^{-3}$ InP transitional layers, the total thickness of InP layer is set to be around 371nm. In addition, a PECVD Si_3N_4 anti-reflection coating has also been deposited. The thickness of the Si_3N_4 is optimized to be 150 nm to ensure a lowest reflection at wavelength of 1.55 μm .

Table 3-2 Optimized layer structure of UTC-PD with dipole-doped structure.

Layer	Thickness (nm)	Doping (cm^{-3})
$\text{In}_{0.6}\text{Ga}_{0.4}\text{As}$	30	p: 1×10^{19}
InP	200	p: 1×10^{19}
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	50	p: 2×10^{18}
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	100	p: 1×10^{18}
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	300	p: 5×10^{17}
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	22	undoped
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	8	p: 1×10^{18}
InP	8	n: 1×10^{18}
InP	13	n: 1×10^{17}
InP	350	n: 5×10^{16}
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	30	n: 5×10^{18}
InP	600	n: 5×10^{18}
S. I. – InP substrate		

3.3 Fabrication of UTC-PD

By using conventional photolithography, wet chemical etching and benzocyclobutene (BCB) passivation, double-mesa structure UTC-PDs have been fabricated with different dimensions aiming for high 3-dB bandwidth and high responsivity. Top-illuminated configuration is employed to ease the device measurement and packaging. In order to improve the device responsivity, the highly doped InGaAs cap layer is selectively etched by using the P-type electrode as the etch mask. In addition to the anti-reflection coating, the BCB at the top window region is removed to further improve the absorption. To facilitate the discussion and analysis of the device measurement results, the key fabrication process and test steps are summarized in Figure 3-4.

Figure 3-4: Key fabrication & testing steps for the UTC-PD

Figure 3-5 shows the cross-sectional schematics of the device at different major fabrication steps.

1) Step 01: P-Metal (non-alloy ohmic contact, Ti/Au/Ni=50/250/50nm).

2) Step 02: P-Iso (wet etching, InGaAs=30nm, InP=200nm, InGaAs=480nm, InGaAs=221nm).

3) Step 03: N-Iso (wet etching, InGaAs=30nm, InP=600nm).

4) Step 04: N-Metal (non-alloy ohmic, Ti/Au/Ni=50/300/50nm).

5) Step 05: Via 1 (BCB Dry Etch).

6) Step 06: Via 2 (BCB Dry Etch).

7) Step 07: Metal 1 (Ti/Au=50/50nm seed metal + 1.5um Au Plating).

Figure 3-5: Fabrication steps of UTC-PD using wet mesa etching and conventional lithography.

The optimized main UTC-PD process steps will be described in detail in Appendix.

Figure 3-6 shows the layout of a typical UTC-PD with dimensions of 0.4×0.45 mm². It is based on the coplanar waveguide (CPW) transmission line consisting of ground-signal-ground (GSG) conductors for RF probing [7].

Figure 3-6 Layout of single UTC-PD.

A critical dimension of the PD is the diameter of the PD's P-mesa. Thus, several variations of the PD diameters have been included in the mask layout as shown in Figure 3-7. Smaller dimensions (eg. 18- μ m-diameter) are for high speed performance and larger dimensions (eg. 70- μ m-diameter) are for high output performance, medium dimensions (eg. 44- μ m-diameter) are for high speed and high output performance. Thus, one square array consists of 35 structures including complete UTC-PDs, open and short test structures. Seven layers of photo-masks were taped out for device fabrication.

Figure 3-7 Layout of one square array of UTC-PDs with different dimensions.

Figure 3-8 shows the UTC-PD wafer and UTC-PD device ready for DC and RF characterization. The left figure is the top view of the full processed wafer, and the right side is a single UTC-PD with CPW probing pads.

Figure 3-8 Left: full processed wafer; right: Single top illuminated UTC-PD with CPW pad design.

Chapter 4 DC and RF Characterization and Analysis of UTC-PDs

4.1 DC Measurement

4.1.1 Dark Current Measurement At Room Temperature

All the DC current-voltage (I - V) measurements were conducted using semiconductor characteristic measurement system (PM5+Keithley 4200 SCS). Figure 4-1 shows a typical I - V characteristic of UPC-PDs with various diameters without illumination. All the devices have a reasonable reverse leakage current of nA range. The dark current tends to increase with the increase in device area. The 18- μ m-diameter dipole-doped UTC-PD demonstrated a dark current of 7×10^{-8} A at -3 V suggesting the effective $\text{Si}_3\text{N}_4/\text{BCB}$ surface passivation is important for device to achieve high photocurrent (power) performance under high reverse bias.

The series resistance of a photodiode arises from the resistance of the contacts, and the resistance from the p-contact is the major part. Therefore, in order to achieve a low-resistance ohmic contact, a very highly-doped (10^{19} cm^{-3}) thin layer of InGaAs has been used as p-contact layer in our UTC-PD. The series resistance of a photodiode is a nonlinear differential resistance, and can be obtained from the derivative of the voltage with respect to the current; the ratio of a small change in voltage to the corresponding change in current, i.e. the inverse slope of the I - V curve at a point. Figure 4-2 shows the series resistance of the fabricated UTC-PD with diameter of 36 and 80 μ m. The series resistance is estimated to be $\sim 48 \Omega$ and 9.63

Ω , respectively. The lower series resistance could contribute to the high-speed performance.

Figure 4-1 Dark I - V characteristics of the fabricated devices with 18, 21 and 44 μm diameter.

Figure 4-2 Series resistance of 36 and 80- μm -diameter UTC-PD.

4.1.2 Temperature-dependent Dark Current Measurement

What's more, I - V measurement of UTC-PD under different temperature conditions have also been conducted to investigate the temperature-dependent (T -

dependent) characteristics of UTC-PD, in order to study the possible current conduction mechanism. Figure 4-3 shows the dark ($\ln I$ vs V) of a 30 μm -diameter UTC-PD measured from -5 V to 2 V at different temperatures (25°C-125°C).

Figure 4-3 Dark $\ln I$ - V Characteristics of a 30- μm -diameter UTC-PD under different temperature conditions (25°C-125°C).

As shown in Figure 4-4, the conduction mechanism can be analyzed by dividing the forward $\ln I$ vs V curves into three distinct voltage regions [65]. Region I is linear region. The merging and leveling of forward I - V data in region III shows current saturation which is probably induced by the space charge effect.

Figure 4-4 Forward dark $\ln I$ - V characteristics of a 30 μm -diameter UTC-PD under different temperature conditions (25°C-125°C).

As introduced in Chapter 2, in region I (0.05-0.5 V) and region II (0.5-0.8V) the forward current can be expressed by:

$$I = I_0 \exp\left(\frac{qV}{nkT}\right) = I_0 \exp\left[\frac{qV}{E_{00} \coth\left(\frac{E_{00}}{kT}\right)}\right] \quad (4-1)$$

with $E_{00} = \frac{qh}{4\pi} \left(\frac{N_D}{\epsilon m^*}\right)^{\frac{1}{2}}$, where n is the ideality factor, I_0 is the reverse saturation current, E_a is the activation energy of predominant mechanism of current, N_D is the doping concentration in InP, ϵ and m^* are the permittivity and electron effective mass of InP.

The reverse saturation current I_0 can be expressed as

$$I_0 = I_{00} \exp\left(\frac{-E_a}{nkT}\right) \quad (4-2)$$

where I_{00} is a factor parameter which depends on the transport mechanism.

After fitting with equation above to region I and region II, n , I_0 and q/nkT at different temperatures are extracted, given in Table 4-1.

Table 4-1 Extracted n , I_0 and q/nkT at different temperatures.

$T(^{\circ}\text{C})$	Region I			Region II		
	$I_{01}(\text{A})$	q/n_1kT (V^{-1})	n_1	$I_{02}(\text{A})$	q/n_2kT (V^{-1})	n_2
25	5×10^{-9}	21.847	1.78	2×10^{-5}	7.625	5.1
50	1.3×10^{-8}	21.745	1.65	2.70×10^{-5}	7.634	4.72
75	4.8×10^{-8}	20.431	1.63	3.7×10^{-5}	7.401	4.51
100	1.5×10^{-7}	19.299	1.61	4.3×10^{-5}	7.363	4.22
125	4.2×10^{-7}	18.43	1.58	5.7×10^{-5}	7.28	4

In both regions, n , I_0 and q/nkT are sensitive to the temperature. I_0 increase with increasing temperature, while q/nkT and n decrease. With increasing temperature, the slope of I - V curves (q/nkT) still changes slightly, indicating that the thermionic current is increasing more significantly at high temperatures. In both regions $n(T) > 1$, which suggests tunneling may possibly contribute to the recombination. In Region II the ideality factor $n > 2$, which is not between 1 and 2, could result from the recombination at the surface or at the edge that relates to the defects. Sometimes, it could also be from the metal contact.

The n versus T plot is shown in Figure 4-5.

Figure 4-5 Ideality factor n and product of n and T and under different T conditions.

It is found that the experimental data of ideality factor n fits very well to its theoretical expression given for the tunneling enhanced recombination mechanism from Equation (4-1):

$$n = \frac{E_{00}}{kT} \coth \frac{E_{00}}{kT} \quad (4-3)$$

where E_{00} is the characteristic tunneling energy. After fitting, $E_{00}=44$ meV and 133 meV for region I and region II can be extracted, respectively.

Based on equation 4-2:

$$n \ln I_0 = \frac{-E_a}{kT} + n \ln I_{00} \quad (4-4)$$

modified Arrhenius plots of $n \ln I_0$ vs $1000/T$, which is shown in Figure 4-6, yields a straight line with a slope corresponding to the activation energy E_a , from which the carrier transport mechanism can be analyzed.

Figure 4-6 Modified Arrhenius plot of UTC-PD.

The activation energy E_a shows different constant at different regions. However, in both regions, E_a is larger than the sum of InGaAs bandgap (0.75 eV at 300K) and the conduction band discontinuity ($\Delta E_c=0.22$ eV) indicates at temperature above room temperature (25°C) the electron injection is dominated by thermionic emission.

4.1.3 Photocurrent and Responsivity

Dipole-doped UTC-PDs with different diameters were measured for photocurrent and responsivity under different reverse bias and optical pumping power conditions at 1.55 μm wavelength. The measurement results of 18, 36 and 70- μm -diameter UTC-PDs are demonstrated below. Figure 4-7 shows the relationship of photocurrent versus bias voltages of devices with 18, 36 and 70 μm diameter when the optical input power is 150 mW. For UTC-PD with 18 and 36 μm diameter, the photocurrent is insensitive to reverse bias in the range from -1 V to -5 V. This may due to the smaller size of UTC-PD, light absorption efficiency is relatively low and the collection region is almost completely depleted. Device

already tends to saturate when the high optical power and reverse bias were added. The photocurrent and responsivity is relatively low. For the 70- μm -diameter UTC-PD, photocurrent increases obviously with the increasing of reverse bias. This suggests that the device could only be depleted at higher reverse bias.

Figure 4-7 Photocurrent versus bias voltages of devices with 18, 36 and 70- μm -diameter when the optical input power is 150 mW.

Figure 4-8 shows the relationship of photocurrent versus optical input power at -1 to -5 V reverse bias for a 36- μm -diameter UTC-PD. Generally, the photocurrent increases with the increase of the input optical power, which follows roughly a linear relation in the low optical input power range. However, for device biased at -1 V, the photocurrent starts to saturate when the input power is higher than 100 mW. Increase in the reverse biasing voltage delays the saturation. When the reverse bias is higher than -2 V, the photocurrent increases almost linearly without obvious saturation under 200 mW optical input power.

Figure 4-8 Measured output photocurrent versus input optical power of devices with a 36 μ m diameter at different reverse bias from -1 V to -5 V.

Similarly, photocurrent of a 70- μ m-diameter dipole-doped UTC-PD as a function of optical power under different reverse-bias voltages is shown in Figure 4-9. The device was tested using an on-wafer probe station. No thermal management such as heat sink and device cooling was employed. The device starts to show saturation at input power higher than 100 mW. The responsivity around 0.6 A/W can be obtained when the optical input power is below 100mW. When the optical power is higher than 100 mW, the responsivity starts to degrade; this could be attributed to the onset of space-charge effect under high injection. Nevertheless, the highest photocurrent of 160 mA is obtained under 6.5 V reverse bias voltage. This is one of the highest values for the photocurrent reported for PDs operating at 1.5 μ m. It is worth noting that, the device has not fully saturated under 1000 mW input power. The measurement was limited by the maximum power (1000 mW of our

EDFA). By increasing optical pumping power and improving heat dissipation, even higher photocurrent can be anticipated.

Figure 4-9 Measured output photocurrent of a 70- μm -diameter dipole-doped UTC-PD at reverse bias of -5, -6 and -6.5 V under different optical input power.

4.2 RF measurement

4.2.1 3-dB Bandwidth

Since photodiode is a two-port device converting optical signal into electrical signal, scattering (S) parameters of two-port network can be used to characterize photodiode in frequency domain. S_{22} and S_{21} are used to characterize the reflection coefficient (electrical properties) of electrical (E) port, and the optical-to-electrical (O-E) transmission coefficient (electrical response relative to optical input signal), respectively. In this section, the S parameters of fabricated UTC-PD with different

diameters under different operation conditions such as optical power, bias voltage, etc, have been measured and studied.

The S parameters and high-speed response characteristics of the fabricated dipole-doped UTC-PDs have been tested by an Agilent PNA-X Network Analyzer N5244A, using an Agilent Lightwave Component Analyzer (LCA) N4373D as the light source in the frequency range from 10 MHz to 40 GHz, incorporated with an Erbium Doped Fiber Amplifier (EDFA). The setup is shown in Figure 4-10, the modulated light coming out from the LCA is amplified by the EDFA and coupled into the devices under testing. And the whole wafer is mounted on a three-dimensional platform, as shown in Figure 4-11 (a) (b). And Figure 4-11 (c) demonstrates a device under testing. The right port the device pad is connected with Cascade ground-signal-ground (GSG) probe and the optical fiber shown on the left is used to couple the pumping light into the device. All the RF measurements were carried out on wafer after full 2-port calibrations on a standard impedance substrate, to the probe tips.

Figure 4-10 Experiment setup for RF measurement of UTC-PD.

(a)

(b)

(c)

Figure 4-11 (a) Measurement setup using 3-axis motion platform and a vertical camera(b) wafer with multiple dies and devices under testing on the sample holder, and (c) a closed-loop UTC-PD device under testing, with an optical fiber at the left-hand side of the CPW probe.

For the RF characterization, first, S_{22} (E port reflection coefficient) parameters were measured for the 18, 44 and 70- μm -diameter UTC-PDs under -5 V reverse bias voltage, as shown in Figure 4-12. The measured S_{22} data will be used for parameter extraction in the semi-analytical modelling method. The modelling and parameter extraction method will be discussed in next Chapter. Figure 4-13 and 4-14 shows measured S_{21} for 18, 44 and 70- μm -diameter UTC-PDs under various bias voltages and optical input powers in magnitude and phase. And measured S_{21} for 18- μm -diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input in magnitude and phase are given in Figure 4-15 and 4-16. Increase in input optical

power results in a drastic increase in devices 3-dB bandwidth, which is similar to the earlier reports for UTC-PDs by other research teams [15]. The 18- μm -diameter UTC-PD with dipole-doped structure shows large 3-dB bandwidth beyond 40 GHz (limitation of LCA) when injecting 75 mW optical power at -5 V reverse bias.

Figure 4-12 Measured S_{22} of 18, 44 and 70- μm -diameter UTC-PD under -5 V reverse bias voltage.

Figure 4-13 Measured S_{21} magnitude for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.

Figure 4-14 Measured S_{21} phase for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.

Figure 4-15 Measured S_{21} magnitude for 18-μm-diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.

Figure 4-16 Measured S_{21} phase for 18-μm-diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.

Figure 4-17 shows the frequency response of an 18- μm -diameter UTC-PD GHz biased at -4 V at different optical input power levels from 25 mW to 100 mW. Increase in input optical power results in a drastic increase in device bandwidth. The device exhibits a large 3-dB bandwidth for every curve, which is 20 GHz or even higher, suggesting that the small current blocking effect in the devices. For the measurements at high optical power, the 3-dB bandwidth is far beyond 40 GHz. The influence of device bias on f_{3dB} measured for an 18- μm -diameter UTC-PD is shown in Figure 4-18. The optical input power is set at its highest level (100 mW) to ensure the largest bandwidth. A drastic increase in f_{3dB} can be seen when the reverse bias voltage is increased from -1 V to -2 V. This could be attributed to the widening of the depletion region as carrier collection layer may not be fully depleted at the reverse bias voltages below -2 V. The 3-dB bandwidth beyond 40 GHz will be modeled by the semi-analytical model. The 3-dB bandwidth, which is beyond 40 GHz, will be determined by using a semi-analytical model develop in this work in later chapter. It is worth mentioning that, under the test condition of optical input power 100 mW and -4 V bias, 3-dB bandwidth over 100 GHz from the 18- μm -diameter UTC-PD is predicted. The modeling method and procedure will be presented in next Chapter.

Figure 4-17 Measurement frequency response of a 18- μm -diameter UTC-PD at various optical power conditions at -4 V.

Figure 4-18 Measured frequency responses of a 18- μm -diameter UTC-PD with dipole-doped structure under -1 V to -4 V bias when the optical input power is 100 mW..

4.2.2 Large Signal Output RF power

As we have discussed in Chapter 2, compared with PIN-PD, UTC-PD tends to have much higher output power at high frequencies. Besides the small signal RF measurement carried out in the earlier part of this chapter, large signal output RF power results from our dipole-doped UTC-PD with different diameters will be shown here.

The experimental setup for testing the output RF power of UTC-PD can be found in Figure 4-19 below. The source light signal was generated by a Keysight compact tunable laser source 81989A at 1.55 μm wavelength. The RF signal was generated by a Keysight analog signal generator N5173B and amplified by a broadband Keysight N4985A amplifier. Then the light signal and RF signal was fed into a Mach-Zehnder modulator (MZM). The modulation depth is controlled by the RF input to the MZM. The MZM was biased at the quadrature point to minimize the distortion to the main signal. After external modulation, the modulated light signal was amplified by an erbium-doped fiber amplifier (EDFA), and launched into the UTC-PD utilizing a lensed fiber after passing through an attenuator. The output RF signal of UTC-PD was detected by a Keysight N8487A power sensor and displayed on a Keysight N1913A power meter.

Figure 4-19 Experimental setup for testing the output RF power of UTC-PD.

Figure 4-20 shows the large signal RF output power of UTC-PDs with diameter $18\ \mu\text{m}$ was measured under different optical input powers from 10 dBm to 20 dBm, at -3 and -5 V bias voltages in the frequency range from 2 GHz to 30 GHz. For low-level excitation, with the increasing of frequency the RF output power of device decreases as the modulation frequency approaches the 3-dB bandwidth of the photodiode [5]. When the photodiode is operated under extremely high intensity illumination, the output decreases more rapidly owing to the space-charge effect. Devices with larger size suffer from these two factors more seriously than smaller devices as large size devices tend to have smaller bandwidth.

Figure 4-20 Output RF power of an 18- μm -diameter UTC-PD measured under various optical input power of 10dBm to 20 dBm, in the frequency range of 2 GHz to 30 GHz.

The large signal output RF power of the 18- μm -diameter UTC-PD at 30 GHz under -3 V and -5 V reverse bias are demonstrated in Figure 4-21. The ideal relation between the RF power and current on a 50 Ω load is plotted as the straight line for reference. The output RF power shows very linear increasing when the photocurrent increases and no saturation is observed. The curve trend is consistent with the ideal line. However, the overall RF output power is relatively low due to the smaller device dimension. At higher bias voltage and higher photocurrent (optical input power), even higher output RF power can be expected. However, thermal issue become the main problem for our test setup and needs to be solved by implementing a heat sink for future study.

Figure 4-21 Output RF power of a 18- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 30 GHz.

Measurement results of output RF power of 18, 36 and 70- μm -diameter UTC-PD at different photocurrent under bias voltages -3 V and -5 V at 2 GHz are shown in Figure 4-22, 4-23 and 4-24, respectively. The ideal relation between the RF power and current on a 50 Ω load is also plotted as the straight line for reference. Generally, output RF power increases with the increasing of photocurrent and reverse bias voltage. For 18- μm -diameter UTC-PD at -3 V and -5 V, and for 36- μm -diameter UTC-PD at -3 V, output RF power increases linearly with increasing of photocurrent without saturation., which is consistent with the ideal curve. For 36- μm -diameter UTC-PD at -5 V, similar to other UTC-type PDs, the measured RF power experiences a linear increase with the increasing of photocurrent before saturation occurs. This phenomenon can also be observed from Figure 4-24 the output performance of a 70- μm -diameter UTC-PD under -3 V and -5 V at 2 GHz. From Figure 4-24, a wide linearity is maintained up to output power of 12 dBm at a bias

voltage of -5 V and it reaches highest RF power of 13.2 dBm when the optical input power is 20 dBm. This is caused by the bandwidth improvement due to the self-induced electric field in the graded-doped absorber [19-21]. Such a wide linearity range is important for analog applications [21]. However when the photocurrent reaches 30 mA, the UTC-PD begins to saturate. This may due to the decrease of the electric field in the depletion region at higher photocurrent, which is mainly caused by the space charge effects, voltage drop, swing effect and the thermal heating.

Figure 4-22 Large signal output RF power of a 18- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 2 GHz.

Figure 4-23 Large signal output RF power of a 36- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 2 GHz.

Figure 4-24 Large signal output RF power of a 70- μm -diameter UTC-PD versus photocurrent under -3 V and -5 V at 2 GHz.

4.2.3 Eye Diagram

The UTC-PD could be also used as a photoreceiver for ultra-high-bit-rate communication systems [21]. Eye diagram analysis is the easiest and most intuitive method for viewing waveforms in high-speed communication systems. In order to evaluate the signal transmission quality of our dipole-doped UTC-PD, output eye diagrams have been investigated using an Agilent Oscilloscope. Figures 4-25, 4-26 and 4-27 shows output eye diagram of a 18- μm -diameter UTC-PD at -5 V for 20 Gbit/s, 25 Gbit/s and 30 Gbit/s input.

Figure 4-25 Output waveform of a 18- μm -diameter UTC-PD at -5 V for 20 Gbit/s signals.

Figure 4-26 Output waveform of a 18- μ m-diameter UTC-PD at -5 V for 25 Gbit/s signals.

Figure 4-27 Output waveform of a 18- μ m-diameter UTC-PD at -5 V for 30 Gbit/s signals.

All these eye diagrams show clearer eye openings, sufficient fast rise/fall time and quite low jitter. This proves our UTC-PD definitely work well at 30 Gbit/s and potentially up to higher speed. However, due to the limitation of the testing equipment we cannot get results higher than 30 Gbit/s.

Large signal Sinewave measurement was also conducted using a 32 GHz Analog Signal Generator (Keysight N5173B). The output waveform and spectrum were observed. Figure 4-28 shows a typical output waveform and spectrum from a high-speed UTC-PDs with 18- μm diameter for large signal Sinewave input at -5 V at 30 GHz. Good Sine waveform and strong signal (low noise) is recovered from the UTC-PD. The peaks at low frequencies observed on spectrum could be due to the nonlinear behavior of the devices.

Figure 4-28 Waveform and spectrum of a 18- μm -diameter UTC-PD for 30GHz 15dBm Sinewave input at -5 V.

4.3 Figure of Merit

In order to evaluate the performance of high photocurrent and high-speed photodiode, several figure-of-merits (FOMs) can be defined. One is defined as the product of output photocurrent and bandwidth. The comparison of the FOM of our proposed dipole-doped UTC-PDs with other high-photocurrent and high-speed PDs reported in the literature [17, 19, 20,66-68] is shown in Figure 4-29. It can be seen that the UTC-PDs with a dipole-doped InGaAs/InP interface are on par with other high-current PDs, in which InGaAsP quaternary layers are used to smooth the conduction band discontinuity. The result suggests the effectiveness of using dipole doping to minimize the current blocking and space charge effects. This has been confirmed by the measurement of 3-dB bandwidth for the dipole-doped UTC-PDs. If the presence of conduction band discontinuity at InGaAs/InP interface resulted in a significant electron pile-up and current blocking at the InGaAs/InP interface, the carrier transport from InGaAs absorption region to InP collector would be slowed down. Poor frequency response of the device should be expected.

Figure 4-29 High photocurrents reported for various PDs.

Another FOM can be defined as the product of responsivity and bandwidth. A comparison of this FOM between our work and UTC-type PDs in other literatures is listed in Table 4-2. So far, most UTC-PDs with large bandwidth or high responsivity were reported on the devices using backside illumination or other complicated designs. It can be seen, the ultra-high 3-dB bandwidth of 325 GHz was obtained from a backside-illuminated $12\text{-}\mu\text{m}^2$ near-ballistic UTC-PD (NBUTC-PD) by scaling down the area with the sacrifice of the responsivity (0.015 A/W) [69]. The record FOM (product of bandwidth and responsivity) of $50\text{ A/W}\cdot\text{GHz}$ was obtained from a polarization-independent edge-illuminated refracting-facet uni-traveling-carrier photodiode (RF-UTC-PD) by use of refracting facet structure [70]. For NBUTC-PD incorporated with evanescently coupled optical waveguide in reference [15] and backside-illuminated modified UTC-PD (MUTC-PD) in reference [17], although the relatively high responsivity (both 1.14 A/W) has been achieved with incorporating a waveguide (NBUTC-PD) or thick absorption layer design (MUTC-PD), the bandwidth of the device is compromised. In our work, for the top-illuminated dipole-doped UTC-PD, the 3-dB bandwidth of 103 GHz and the responsivity of 0.6 A/W yield a high FOM of $61.8\text{ A/W}\cdot\text{GHz}$ among the reported UTC-type PDs.

Table 4-2 Comparison with UTC-type PDs from other literatures

Type	Illumination	Size	Max Bandwidth (GHz)	Max Responsivity (A/W)	FOM (A/W·GHz)	Reference
NBUTC-PD	BI	12 μm^2 (Area)	325	0.015	4.875	[69]
UTC-PD	BI	5 μm^2 (Area)	310	0.07	21.7	[12]
MUTC-PD	BI	14 μm (Diameter)	65	0.45	29.25	[14]
RF-UTC-PD	EI	128 μm^2 (Area)	50	1	50	[63]
NBUTC-PD	WG	320 μm^2 (Area)	40	1.14	45.6	[15]
UTC-PD	BI	20 μm (Diameter)	29	1	29	[16]
MUTC-PD	BI	25 μm (Diameter)	26	1.14	29.64	[17]
MUTC-PD	BI	40 μm^2 (Area)	24	0.69	16.56	[18]
MUTC-PD	BI	28 μm (Diameter)	23	0.82	18.86	[19]
Dipole-doped UTC-PD	TI	18 μm (Diameter)	103	0.6	61.8	This work

BI=Backside illuminated; WG=Waveguide; TI=Top illuminated.

Chapter 5 Modeling of UTC-PDs with a Semi-Analytical Approach

5.1 Introduction

The rapid development of optical communications has created a demand for efficient and accurate CAD tools for the design, simulation, and analysis of almost every process of optoelectronic devices, integrated circuits and systems. The CAD tools are in need of continuous improvement until the simulation results are in good agreement with actual measurement performance of the object being simulated. On the other hand, the simulation results using the CAD tools depend greatly on the models of actual devices. Typically, the commercial optoelectronic CAD software can be divided into two kinds: physics-based and equivalent-circuit-based. The physics-based CAD software, considers fundamental equations of operation mechanism in semiconductors. The equivalent-circuit-based CAD software addresses the issue of what needs to be known about the device in addition to its equivalent circuit to predict the performance [42]. The equivalent-circuit-based models are built basing on the accurate parameter extraction from experimental data. Thus the simulation results are derived from the process data of devices. Figure 5-1 shows the flowchart for an ideal circuit simulator in which the device model plays an important role.

Figure 5-1 A flowchart for an ideal circuit simulator [42].

5.2 Microwave Modelling Techniques for Photodiodes

CAD methods for optoelectronic integrated circuits depend greatly on models of real devices. Modeling of photodiodes is very important for analysis of their performance and solving design issues. Figure 5-2 shows the commonly used modeling methods for photodiodes [42]. There are three kinds of modeling methods for various photodiodes, that is the physics-based model (1 in Figure 5-2), the equivalent circuit model (2 in Figure 5-2), and semi-analytical model (3 in Figure 5-2).

Figure 5-2 Modeling methods for photodiode.

The physics-based models are based on the behavior of photo-generated carriers and electric fields in photodiodes, and are obtained by numerically solving basic semiconductor device physical equations. The physical simulation of the photodiode device is based on the Poisson equation, current continuity equation, and rate equations for charged traps in two or three dimensions [71]. The physical model relates to the parameters about process (geometry dimension, material parameters, doping profile, and so on), surface effects, substrate conduction, contact resistivity, and so on [72]. However, due to large volume of parameters and terms that need to consider, applying physics-based models are usually time-consuming.

Equivalent circuit models use basic circuit components (resistance, capacitance, and control sources) to represent devices. However, equivalent circuit models require extensive characterization of the device after fabrication, as well as some knowledge of process variation statistics. And curve-fitting errors and discontinuous or inaccurate high-order derivatives in current and voltage expressions, always lead to inaccurate predictions of intermodulation distortion (IMD). Different equivalent

circuit model included in each commercial software uses different expressions to characterize the operation mechanism of device.

The semi-analytical models are based on the combination of physical equations and the equivalent circuit and overcome the drawbacks of the physics-based models and equivalent-circuit-based models, while retaining their advantages. The circuit simulators are used to solve the physical equations and parasitic elements can be taken into account. Table 5-1 gives a comparison of the three kinds of microwave modelling techniques for photodiodes [42].

Table 5-1 Comparison of microwave modelling techniques for photodiodes [42]

Parameters	Physical-based models	Equivalent circuit models	Semi-analytical models
Speed	Slow	Fast	Fast
Accuracy	High	Medium	High
Physical meaning	Excellent	Medium	Good

5.3 A Semi-analytical Modeling method of Dipole-doped UTC-PD

5.3.1 Equivalent Circuit Model

Just as mentioned above, an accurate model parameter extraction technique of UTC-PD is important for understanding of the device physical mechanisms and improving the device performances [33-36]. Development of the equivalent circuit models of UTC-PDs is also essential as it allows the existing well-developed circuit simulation software to be utilized in the design and analysis of optoelectronic circuits [34, 40]. For high-speed photodiodes, although various modeling methods,

such as physics-driven modeling, analytical modeling, empirical modeling and equivalent circuit modeling, have been investigated (especially for PIN-PDs), an accurate equivalent circuit model, which accounts for the unique device structure and operation mechanism of UTC-PD with dipole-doped structure is still lacking [24-26]. Wu *et al.* [27] proposed an analytical equivalent circuit model for near-ballistic UTC-PD. In this model, an artificial resistance-capacitance (R-C) network is used in the optical input part to simulate the bandwidth limitation from the carrier transit time. However, this R-C network is of certain level of difficulty to directly relate to the physical structure of the device. Furthermore, due to the structural differences between the NBUTC-PD and the UTC-PD with dipole-doped structures in this work, development of a new equivalent model for UTC-PD by taking the additional p⁺-n⁺ dipole-doped layers into consideration is necessary.

The accuracy of the results depends greatly on the parameters of the equivalent circuit model, thus a good equivalent circuit model is not merely helpful for prediction of the performances of devices but also important for extracting model parameters conveniently and accurately [33-37]. Numerical optimization techniques are usually used to determine the optimal values of model parameters [35, 38]. However, the accuracy of the optimization methods can vary largely up to the optimization method used and the initial values of model parameters selected [33-35, 37-39, 41]. Nonphysical and nonunique results of the extracted parameters could be generated. Analytical methods usually allow extracting a unique and physically meaningful set of parameters from a set of closed-form expressions based on the measurement results of devices [33, 35, 37-39]. However, some parameters may be difficult to be extracted directly using analytical methods.

Since the semi-analytical modelling of UTC-PD is based on the equivalent circuit model of PIN-PD, first we introduce the equivalent circuit model of a normal PIN-PD. Figure 5-3 shows a typical equivalent circuit model for a PIN-PD. In this diagram, the photocurrent has been modelled as a current source i_p , whose magnitude depends on the incident optical power. The shunt resistance R_j , represents the resistance across the junction. The series resistance R_s is that of the bulk semiconductor and the contact resistance. The load resistor R_L , shunts the total diode capacitance C_d , and this time constant usually limits the speed of PIN-PD response.

Figure 5-3 Equivalent circuit model of PIN-PD.

On the basis of this PIN-PD model, an equivalent circuit model, which is more suitable for our proposed UTC-PD with dipole-doped structure, as shown in Figure 5-4, has been proposed. Figure 5-5 shows the cross-sectional schematic of dipole-doped UTC-PD and indicates how the equivalent circuit components are associated with the physical parameters of the device, where R_c represents the contact resistance; C_j is the junction capacitance; L_p and C_p are the CPW pad inductance and capacitance. R_{dd} and C_{dd} represent the resistance and capacitance of the additional p^+-n^+ dipole-doped layers in the device structure [24].

Figure 5-4 Fabricated device and cross section view of InP-based UTC-PD with dipole-doped structure.

Figure 5-5 Cross-sectional schematic of InP-based UTC-PD with dipole-doped structure.

The equivalent circuit elements are related to the UTC-PD parameters as shown.

Rearranging the equivalent circuit components shown in Figure 5-5 gives an equivalent circuit model of the InP-based UTC-PD with dipole-doped structure in Figure 5-6. The 3-dB bandwidth of UTC-PD is limited by both the internal carrier transit time ($1/f_T$) and the external parasitic RC time ($1/f_{RC}$), which can be expressed as [27]:

$$\frac{1}{f_{3dB}^2} = \frac{1}{f_T^2} + \frac{1}{f_{RC}^2} \quad (5-1)$$

where $f_T = 1/(2\pi\tau_T)$, and the carrier transit-induced time delay is represented with a linear resistance-capacitance circuit ($\tau_T = 2\pi R_t C_t$), which is combined to a voltage-controlled current source (VCCS). g_m represents the transconductance, which can be expressed as:

$$g_m(f) = \frac{g_{m0} e^{-j2\pi f \tau_T}}{1 + j \frac{f}{f_T}} \quad (5-2)$$

g_{m0} is the transconductance in the low frequency range.

Figure 5-6 Equivalent circuit model of InP-based UTC-PD with dipole-doped structure.

The values of parasitic elements can be determined by measuring reflection coefficient (S_{22}) of open and short structures, which only consists of coplanar waveguide (CPW) pad patterned on the same substrate with UTC-PD devices. Figure 5-7 shows the CPW pad with UTC-PD device, open and short test structures.

Figure 5-7 Illustration of test structure: (a) pad with UTC-PD (b) open and (c) short.

5.3.2 Parameter Extraction

The Y-parameter of port 2 Y_{22} can be expressed as follows:

$$Y_{22} = j\omega C_p + \frac{j\omega C_j}{1 + j\omega Z' C_j} \quad (5-3)$$

where

$$Z' = j\omega L_p + R_c + \frac{R_{dd}}{1 + j\omega R_{dd} C_{dd}} \quad (5-4)$$

The Z-parameter of port 2 Z_{22} can be expressed as follows:

$$Z_{22} = \frac{1}{Y_{22}} \quad (5-5)$$

The pad capacitance C_p can be determined by measuring an open structure shown in Figure 5-7 (b). C_p is expressed as follows:

$$C_p = C_{open} = \frac{\text{Im}(Y_{22})}{\omega} \quad (5-6)$$

The pad inductance L_p can be determined by measuring an short structure shown in Figure 5-7 (c). L_p is expressed as follows:

$$L_p = L_{short} = \frac{\text{Im}(Z_{22})}{\omega} \quad (5-7)$$

when

$$YY = Y_{22} - j\omega C_p \quad (5-8)$$

$$ZZ = \frac{1}{YY} \quad (5-9)$$

$$ZZ_1 = ZZ - j\omega L_p \quad (5-10)$$

After de-embedding the parasitic parameters (capacitance C_p and inductance L_p), the series resistance can be expressed as follows:

$$R_s = \text{Re}(ZZ_1). \quad (5-11)$$

At high frequency ranges, R_c can be expressed as follows:

$$R_c = R_s \text{ (at high frequency)} \quad (5-12)$$

while the resistance of the dipole-doped structure can be determined by R_s at low frequency range and R_c given above as:

$$R_s(\text{at low frequency}) = R_{dd} + R_c \quad (5-13)$$

$$R_{dd} = R_s(\text{at low frequency}) - R_c \quad (5-14)$$

The junction capacitance C_j can be expressed as follows:

$$C_j = \frac{-1}{\text{Im}(ZZ_1)\omega} \quad (5-15)$$

Also, we have

$$C_j = \varepsilon\varepsilon_0 A_{active}/D_{deletion} \quad (5-16)$$

where A_{active} is the device active area which can be calculated with device diameter, $D_{deletion}$ is the thickness of deletion layer, which can be considered as the thickness of collection layer when it is fully depleted.

However, it is difficult to use direct extraction method to determine the capacitance of the dipole-doped structure C_{dd} . Therefore, a semi-analytical method with optimization procedure is needed [40, 73]. The value of C_{dd} can be determined using the procedure as follows [35].

- 1) Setting initial value of C_{dd} .
- 2) Calculating the error as a function of the reflection coefficient at port 2:

$$\varepsilon = \frac{1}{N-1} \sum_{i=0}^{N-1} |S_{22}^m - S_{22}^s|^2 \quad (5-17)$$

where ε is the error function criterion, superscript s denotes the simulated S-parameter, m denotes the measured S-parameter, and $i = (0 \dots N-1)$ is the number of sampling points [34-36, 40].

- 3) If $\varepsilon > \varepsilon_0$ (ε_0 is the error target, normally 0.1%), the value of C_{dd} needs to be updated to reduce ε .
- 4) If $\varepsilon < \varepsilon_0$ is achieved, the value of C_{dd} can be confirmed.

The whole parameter extraction procedure is shown in corresponding flowchart in Figure 5-8.

Figure 5-8 Flowchart of parameter extraction procedure used in this work.

This equivalent circuit modeling and parameter extraction method can be performed by using commercial circuit simulation softwares such as Advanced Design System. Because only one parameter needs to be optimized in proposed model, besides manual adjustment, a simple optimization algorithm such as Newton's method can also be applied to determine the optimum parameter values [35]. Figure 5-9 shows an example of applying the modeling procedure in ADS.

Figure 5-9 Modeling of dipole-doped UTC-PD in ADS.

To validate the effectiveness and accuracy of the equivalent circuit model and the semi-analytical parameter extraction method, the model parameters for UTC-PDs with different diameters under various biasing and optical power conditions are extracted and analysed.

Figure 5-10 shows the extracted pad capacitance C_p and inductance L_p as a function of frequency. The values of C_p and L_p are almost constant in the measured frequency range. The extracted contact resistance R_c and dipole-doped resistance R_{dd} for UTC-PDs with diameter 18 μm at different reverse biases, are shown in Figure 5-11. The results for the devices with diameters of 44 μm and 70 μm at -5 V are also included for comparison. The R_c is determined by the values of R_s in the high frequency range, while $R_{dd} + R_c$ can be determined at low frequencies. The R_{dd} can thus be estimated by subtraction of R_c from $R_{dd} + R_c$. At the same bias voltage -5 V, both R_c and R_{dd} decrease with the increasing of device size. For the 18 μm diameter device, R_s decreases slightly with increasing of reverse bias voltage from 1 V to 5 V. Figure 5-13 shows the value of junction capacitance C_j extracted from UTC-PD

devices with diameter $18\text{ }\mu\text{m}$ at -1 V , -3 V and -5 V . Again, the results for the UTC-PDs with $44\text{ }\mu\text{m}$ and $70\text{ }\mu\text{m}$ at -5 V are also included for reference. For a given bias voltage such as -5 V , C_j increases with the increasing of device size. The C_j decreases with the increase of reverse bias due to the widening of depletion region.

Figure 5-10 Extracted pad capacitance C_p and inductance L_p versus the frequency.

Figure 5-11 Extracted series resistance R_s (R_c and $R_c + R_{dd}$) as a function of frequency for UTC-PD with diameter of $18\text{ }\mu\text{m}$ under different bias voltages.

Figure 5-12 Extracted series resistance R_s (R_c and $R_c + R_{dd}$) as a function of frequency for UTC-PD with diameter of 18, 44 and 70 μm under -5V bias voltages.

Figure 5-13 Extracted junction capacitance C_j of UTC-PD with 18 μm diameter with different bias voltages.

Figure 5-14 Extracted junction capacitance C_j of UTC-PD with 18, 44 and 70 μm diameter under -5V bias voltages.

After confirmation of C_p , L_p , R_{dd} , R_c , and C_j , C_{dd} can be extracted from reflection coefficient measurements (S_{22}) following the procedure described in the previous section. It can be seen that the values of C_{dd} and R_{dd} are independent of the change of reverse bias voltage. This is due to the full depletion of the dipole-doped layers in the biasing range from -1 V to -5 V, which has been further verified by simulating the distributions of the electric field and free carrier concentrations in the dipole-doped structure of our PD using a 1-D simulator [7, 64]. The f_T (or τ_T) can be determined by matching the simulated S_{21} to the measured S_{21} . Table 2 summarizes the extracted model parameters for 18, 44 and 70 μm -diameter UTC-PDs under an optical input power of 75 mW. The f_T increases with increasing of reverse bias voltage. This can be attributed to the depletion of collection layer and thus shorten the electron transit time τ_T at high bias voltages. The collection layer is approaching

full depletion when the reverse bias voltage increases to -5 V. This was confirmed by simulation using the 1-D simulator [64].

Table 5-2 Extracted model parameters.

C_p (fF)	34				
L_p (pH)	135				
Parameters	D=18 μm			D=44 μm	D=70 μm
V_{RB} (V)	-1	-3	-5	-5	-5
R_{dd} (Ω)	4	4	4	2	2
R_c (Ω)	11	9	8.5	8	7
C_j (pF)	0.095	0.063	0.06	0.39	1.9
C_{dd} (pF)	0.8	0.8	0.8	1.2	1.5
g_m (S)	0.01	0.01	0.01	0.01	0.01
R_t (Ω)	30	20	15	25	18
C_t (pF)	0.055	0.02	0.018	0.09	0.2

5.4 Results and Discussion

As can be seen from the Smith Chart in Figure 5-15, modeled S_{22} data (symbols) based on the equivalent circuit model and semi-analytical parameter extraction method match well with measured S_{22} data (solid lines) (which we also showed in Chapter 4) for UTC-PDs with different diameters 18, 44 and 70 μm over the whole frequency range at -5 V bias.

Figure 5-15 Comparison of measured (symbols) and modeled (line) S_{22} of 18, 44 and 70- μm -diameter UTC-PD under -5 V reverse bias voltage.

For the equivalent circuit parameters extracted by using measured S_{22} data the effectiveness and accuracy of the model is further verified by comparison of the modeled S_{21} parameters (frequency response) with measured S_{21} parameters. Figure 5-16 and 5-17 show measured (solid line) and modeled (symbols) S_{21} for 18, 44 and 70- μm -diameter UTC-PDs under -5 V bias and 75mW optical input powers in magnitude and phase. Figure 5-18 and 5-19 show comparison of measured (solid line) and modeled (symbols) S_{21} magnitude for 18- μm -diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input in magnitude and phase. Figure 5-20 and 5-21 show measurement (symbols) and modeling (solid lines) S_{21} results of a 18- μm -diameter UTC-PD at -1, -3 and -5 V bias when the optical power is 75 mW in magnitude and phase. Good agreements between the modeling and measurement results for both magnitude and phase over the whole frequency range

is obtained from these figures. And 3-dB bandwidth of 60 GHz at -5 V and 55 GHz at -3 V can be obtained from simulation results of 18- μm -diameter UTC-PD with dipole-doped structure by using this method when injecting an 75 mW optical power.

Figure 5-16 Comparison of measured (solid line) and modeled (symbols) S_{21} magnitude for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.

Figure 5-17 Comparison of measured (solid line) and modeled (symbols) S_{21} phase for 18, 44 and 70- μm -diameter UTC-PDs under -5 V biasing and 75 mW optical input.

Figure 5-18 Comparison of measured (solid line) and modeled (symbols) S_{21} magnitude for 18-μm-diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.

Figure 5-19 Comparison of measured (solid line) and modeled (symbols) S_{21} phase for 18-μm-diameter UTC-PD under -5 V biasing and 25 mW, 50 mW and 75 mW optical input.

Figure 5-20 Measurement (symbols) and modeling (solid lines) S_{21} magnitude results of a 18- μm -diameter UTC-PD at -1, -3 and -5 V bias when the optical power is 75 mW.

Figure 5-21 Measurement (symbols) and modeling (solid lines) S_{21} phase results of a 18- μm -diameter UTC-PD at -1, -3 and -5 V bias when the optical power is 75 mW.

Figure 5-22 shows measurement (symbols) and modeling (solid lines) results of a 18- μm -diameter UTC-PD at various optical power conditions at -4 V. For the

measurements at high optical power, the 3-dB bandwidth is far beyond 40 GHz. By using the accurate semi-analytical modeling method based on the actual device structure of high-photocurrent and high-speed dipole-doped UTC-PD, a better prediction of device bandwidth has been achieved. The modeling results are plotted as the solid lines, which agree well with measurement results in symbols for different input powers in the lower frequency range. On the other hand, it can also be seen that at higher frequency range there is some deviation between the modeling results and measurement results. This should be due to (1) At higher frequency the accuracy of the calibration for the testing system is relatively lower; (2) Some microwave distributed parasitic effects (such as the transmission line) are not taken into account in the equivalent circuit model. Thus a refinement to the equivalent circuit model needs to be performed in the future to produce better fit with the high-frequency responses.

Figure 5-22 Measurement (symbols) and modeling (solid lines) results of a 18- μm -diameter UTC-PD at various optical power conditions at -4 V.

The influence of device bias on f_{3dB} measured for an 18- μm -diameter UTC-PD is shown in Figure 5-23. The optical input power is set at 100mW. A drastic increase

in f_{3dB} can be seen when the reverse bias voltage is increased from 1 V to 2 V. This could be attributed to the widening of the depletion region as carrier collection layer may not be fully depleted at the reverse bias voltages below 2 V. The device shows a maximum 3-dB bandwidth of 103 GHz measured at a reverse bias of 4 V. The result shows good agreement with theoretical predictions in the design consideration in Chapter 3.

Figure 5-23 Measurement (symbols) and modeling (solid lines) results of a 18-μm-diameter UTC-PD at various dc bias conditions and 100 mW optical input.

In summary, the semi-analytical method introduced above, which combines the advantages of using analytical method and numerical optimization method, for extracting the small-signal model parameters of UTC-PD is proposed in this thesis has the following advantages compared to previous literatures [25-27, 28-32] :

- 1) The equivalent circuit model is developed basing on actual device structure and physics. The dipole-doped structure at the InGaAs/InP heterostructure interface

has been taken into account in the equivalent circuit model to simulate its effectiveness on suppressing the current blocking effect [73].

2) Most of the circuit component parameters, including parasitic and intrinsic parameters, can be extracted directly from a set of closed-form expressions based on the measured reflection coefficients (S_{22}) and frequency responses (S_{21}) of devices.

3) Only one parameter (capacitance of the dipole-doped structure C_{dd}) cannot be extracted directly by using analytical method. It is obtained by using optimization method. The results obtained from analytical method are taken as an initial value for the subsequent fitting and optimization procedure, leading to the final results of all the parameters of the equivalent circuit model [35-40]. The semi-analytical method combines the advantages of the analytical and numerical optimization methods, to enable the extracted results more accurate.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

As the key component for optical fiber communication, the photodiode has to fulfil three requirements which are high speed, high responsivity, and high output power. However, photodiodes reported currently always have some tradeoffs or drawbacks, as we have elaborated in Chapter 1. Although different types of UTC-PD (conventional UTC-PD, modified UTC-PD, waveguide UTC-PD, refracting-facet UTC-PD, etc) have been developed to resolve these issues compared to widely used PIN-PD, as described in Chapter 2, research on improving the performance of UTC-PD and simplifying the material growth and fabrication remains an important topic for research and development. The main objective of our work is to realize a InP-based UTC-PD device aiming for high-speed, high responsivity and high photocurrent (power) performance at 1.55 μm wavelength.

The design, structure optimization, fabrication, performance measurement and modelling of UTC-PD have been introduced and analysed in following Chapters. The major novelty of UTC-PDs presented in the thesis is the use of a InGaAs/InP dipole-doped structure to replace conventional used compositional graded InGaAsP as the transitional part between the small bandgap InGaAs absorption layer and wide bandgap InP carrier collection layer, to reduce the energy barrier, facilitate carriers traveling and relieve the carrier accumulation. The results suggest that the new structure eases the material growth and fabrication of UTC-PD device without compromising its performances. The devices show a low dark current of nA range

with highest photocurrent of 160 mA and high responsivity of 0.6A/W. 3-dB bandwidth of over 40 GHz, which is due to the limitation of equipment, has been obtained. Clear eye opening at 30 Gbit/s (limitation of equipment) with output RF power of 13.2 dBm have also been realized. A semi-analytical approach has been developed to model the dipole-doped UTC-PD. A 3-dB bandwidth of 103 GHz is predicted for the top-illumination UTC-PD with diameter of 18 μm .

6.2 Future Work

6.2.1 Linearity Characterization

The spur-free dynamic range (SFDR) is a uniquely important figure of merit for analog optical links because, unlike other performance parameters such as loss or noise figure, SFDR can not be improved by adding pre- or post-amplification [45, 74]. The SFDR is usually characterized using a two-tone method. Assume that the input of the link consists of two equal-power fundamental frequencies. The two-tone SFDR is defined as the signal-to-noise ratio at the link output when the power of the intermodulation distortion products equal the noise. Among all the intermodulation products and harmonics, the third order intermodulation products (IMD3) at $2f_1 - f_2$ and $2f_2 - f_1$ are important, because they are close to the fundamental frequencies f_1 and f_2 and thus difficult to be filtered, as shown in Figure 6-1. The third-order output intercept point (OIP3) is a key figure of merit to evaluate the linearity of an analog optical link; it is defined as the extrapolated intercept point of the power of fundamental frequency and IMD3, assuming that the fundamental power has a perfect slope of 1 and the power of IMD3 has a perfect slope of 3, as shown in Figure 6-2. Based on its definition, OIP3 can be calculated from the measured fundamental power and the power of IMD3 with this simple equation [45, 75]:

$$OIP3 = P_f + \frac{1}{2}(P_f - P_{IMD3}) \quad (6-1)$$

where P_f is the power of the fundamental frequency and P_{IMD3} is the power of the IMD3. As discussed in Chapter 1, the photodiode is frequently the limiting factor for the linearity performance of an analog optical link. Thus, the characterization behavior of OIP3 of UTC-PD is crucial for UTC-PD's application.

Figure 6-1 RF output representation of optical signal components for a two-tone input to photodiode, showing fundamentals, harmonic distortions and intermodulation distortion [76].

Figure 6-2 Fundamental and IMD3 as a function of input RF power.

The two-tone Mach-Zehnder Modulator (MZM) setup (Figure 6-3) can be adopted to measure the nonlinearity of UTC-PD. The two-tone MZM setup is a

simpler and more widely used measurement system [77-79]. The setup consists of two lasers input into their respective MZM. Two synthesizers provide the RF input to each MZM. The output is combined in a 50/50 coupler and detected at the DUT. The modulation depth is controlled by increasing or decreasing the RF input to the MZMs. The setup typically biases the MZM at the quadrature point to minimize HD2 which contributes to the IMD3 when mixed inside the detector. Additionally, polarizers before the MZMs and erbium doped fiber amplifiers (EDFA) can be added to boost the optical power input to the device.

Figure 6-3 Two laser two-tone MZM nonlinearity setup [79].

6.2.2 *Balanced Photodiode*

Balanced photodiode (BPD) is attractive because it can provide high output and suppress laser relative intensity noise (RIN). The desired features for a coherent receiver are high linearity, high power, and comparatively large common mode rejection ratio (CMRR). Figure 6-4 shows a typical basic BPD which comprises two waveguide PDs on a single chip. Such configuration insures an excellent uniformity of these two photodiodes. Furthermore, the waveguide approach make it's possible to realize a linear frequency response at very high optical powers not only in power

but also in phase even at very high optical powers. Therefore, edge-illuminated UTC-PDs can also be explored in future work for better performances.

Figure 6-4 Basic design example of the BPD [80].

Appendix

The optimized main UTC-PD process steps are described as follows:

a) Step 01: P-type metal module (P-metal)

1. P-metal Mask (1.4 μ m AZ5214, Scope Inspection and CD Measurement)
2. O₂ Descum (RF=60W, O₂=50sccm, Time = 4mins)
3. Oxide Removal (HCl:H₂O = 1:10, Time = 30s)
4. P-metal Metallization (Ti/Au/Ni=50/250/50nm)
5. P- Metal Liftoff & Scope Inspection
6. Ohmic Contact Resistance (Spec < 0.5 ohms/mm)
7. Wafer Clean

b) Step 02: P-mesa Module (P-mesa)

1. P-mesa Mask (1.8 μ m AZ1518, Scope Inspection and CD Measurement)
2. O₂ Descum (RF=60W, O₂=50sccm, Time = 4mins)
3. Oxide Removal (HCl:H₂O = 1:10, Time = 30s)
4. Measure resist thickness before Wet Mesa Etch
5. Mesa Etch

- InGaAs layers: Etched by H₃PO₄:H₂O₂:H₂O=15:5:200, Ending-point determined by measuring the mesa height using surface profiler

- InP layers: Etched by $\text{HCl}:\text{H}_3\text{PO}_4=1:5$, Ending-point determined by measuring the mesa height using surface profiler

6. Measures etch depth with resist
7. Resist Strip and Wafer Clean
8. Scope Inspection

c) Step 03: N-type metal Module (N-metal)

- 1 N-metal Mask ($1.4\mu\text{m}$ AZ5214, Scope Inspection and CD Measurement)
- 2 O_2 Descum (RF=60W, $\text{O}_2=50\text{sccm}$, Time = 4mins)
- 3 Oxide Removal ($\text{HCl}:\text{H}_2\text{O} = 1:10$, Time = 30s)
- 4 N-metal Metallization (Ti/Au=50/300/50nm)
- 5 N- Metal Liftoff & Scope Inspection
- 6 Ohmic Contact Resistance (Spec < 0.5 ohms/mm)
- 7 Wafer Clean

d) Step 04: N-mesa & Isolation Module (N-mesa)

1. N-mesa Mask ($1.8\mu\text{m}$ AZ1518, Scope Inspection and CD Measurement)
2. O_2 Descum (RF=60W, $\text{O}_2=50\text{sccm}$, Time = 4mins)
3. Oxide Removal ($\text{HCl}:\text{H}_2\text{O} = 1:10$, Time = 30s)
4. Measure resist thickness before Wet Mesa Etch
5. Mesa Etch

- InGaAs layers: Etched by $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}=15:5:200$, Ending-point determined by measuring the mesa height using surface profiler

- InP layers: Etched by $\text{HCl}:\text{H}_3\text{PO}_4=1:5$, Ending-point determined by measuring the mesa height using surface profiler

6. Measures etch depth with resist and DC electrical isolation check
(Spec < 100 nA @ +/-10V)

7. Resist Strip and Wafer Clean

8. Scope Inspection

e) Step 05: VIA 1 (BCB dry etch)

1. Blanket BCB Coat + SB + Hard cure (280 °C hard cure for 2.5 hours.

BCB thickness after hard cure is about 2.5 μm)

2. VIA1 mask: Dark Field, Positive Tone resist, 4.2um thickness. FHI-560EP

3. BCB Dry Etching by CF_4/O_2

4. Resist Strip and Wafer Clean

5. Scope Inspection

f) Step 06: VIA (BCB dry etch)

1. VIA mask: Dark Field, Positive Tone resist, 4.2um thickness. FHI-560EP

2. BCB Dry Etching by CF_4/O_2

3. Resist Strip and Wafer Clean

4. Scope Inspection

g) Step 07: Interconnect Module (Metal 1)

1. Au Seeding Metal by sputtering (Ti/Au 50/50 nm);
2. M1 Mask: Dark Field, Positive Tone resist, 4.2um thickness. FHI-560EP
3. 1.5 µm Gold plating
4. Gold Seed Metal Etch (Au Etching / HF:H₂O 1:20 for Ti) & Scope

Inspection

5. Wafer Clean

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