INTEGRATED ON-CHIP GALLIUM ARSENIDE SCHOTTKY DIODE AND ANTENNA FOR APPLICATION IN PROXIMITY COMMUNICATION SYSTEM

FARAHIYAH BINTI MUSTAFA

UNIVERSITI TEKNOLOGI MALAYSIA

INTEGRATED ON-CHIP GALLIUM ARSENIDE SCHOTTKY DIODE AND ANTENNA FOR APPLICATION IN PROXIMITY COMMUNICATION SYSTEM

FARAHIYAH BINTI MUSTAFA

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2014

To my wonderful husband, my lovely son and my beloved family. I am so thankful for the understanding, continuous support, strength and prayer. I would not be the person I am today without prayer and love from you all. Thanks for loving me.

ACKNOWLEDGEMENT

Alhamdulillah, thanks to Allah S.W.T the most merciful and the most compassionate for the knowledge and guidance in all the effort to finish this piece of work. Piece is upon him, Muhammad the messenger of God.

Throughout the time I spent at Material Innovations and Nanoelectronics (MINE) Research Group and Advanced Devices and Materials Engineering (ADME) iKohza, there have been many people who helped me in this challenging work. It is a pleasure to thank a few of them here.

Special appreciation goes to my supervisor, Assoc. Prof. Ir. Dr. Abdul Manaf Bin Hashim for his continuous guidance and support. He gave me an opportunity to take challenge on this hard task. I have been fortunate work under him as I have learned so much from him, not only on how to perform research in the right and most effective way but also on how to be more responsible person. His energy and enthusiasm for research never seem to end. This work would not be possibly done without his invaluable advices and guidance.

I would like to express my deepest gratitude to Prof. Dr. Mohamad Rusop Bin Mahmood from Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM) and Assoc. Prof. Dr. Nafarizal Bin Nayan from Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn (UTHM) for their willingness to co-supervise my research. Without their support and input, this thesis would have not completed.

Simulating and helpful discussion with all MINE's staff, Mr. Abdul Rahim Bin Abdul Rahman, Prof. Vijay Kumar Arora, Dr. Nihad K. Ali and Dr. Ridzuan Bin Ahmad throughout this work are also highly appreciated.

I would like to thank Prof. Dr. Zulkafli Bin Othaman, Universiti Teknologi Malaysia (UTM) and Assoc. Prof. Dr. Azlan Bin Abdul Aziz, Universiti Sains Malaysia (USM) for serving on my oral examination committee and for reading my thesis.

I would like to thank Mr. Mohd Nizam Bin Osman of Telekom Malaysia Research and Development (TMR&D), Mr. Mohd Hasnirol Bin Baharom and Mr. Shukri Bin Korakkottil Kunhi Mohd of Collaborative MicroElectronic Design Excellence Centre (CEDEC), USM for their most valuable advices and discussions especially during measurement process and their kind assistance in both formal and informal business.

I also indebted to all staffs and technicians of Ibnu Sina Institute, Faculty of Science and Faculty of Electrical Engineering, UTM, Nano-Optoelectronics

Research and Technology Laboratory, School of Physics, USM and Faculty of Electrical Engineering, UiTM for their assistance in supplying the relevant trainings, guidance and equipments. There are no other words that I can express my gratitude to all of them.

Numerous people contributed to the success of this work. It would not be possible without guidance and advices from my colleagues, Dr. Mastura Shafinaz Binti Zainal Abidin, Dr. Shaharin Fadzli Bin Abd. Rahman, Dr. Budi Astuti, Mrs. Nurul Izni Binti Rusli, Ms. Siti Sarah Binti Mohd Azlan, Mrs. Noorradiyah Binti Ismail, Ms. Nur Suhaili Binti Abdul Aziz, Ms. Nurul Azzyaty Binti Jayah, Ms. Nurul Fariha Binti Ahmad, Ms. Norizzawati Binti Mohd Ghazali, Ms. Nur Hamiza Binti Zainal Abidin, Ms. Nur Ashikyn Binti Hambali, Mr. Amgad Ahmed Ali, Mr. Tahsin Morshed, Mr. Desrino Bin Jalani and Mr. Mohammad Sarwan Bin Mohd Sanif. Thank you for their thoughtful advices, guidance and valuable friendship. To the other ADME's member, thank you for everything.

My deepest and sincerest thanks to my dear husband, Ahmad Husni Bin Abu Hasan and my son, Firas Hamzi Bin Ahmad Husni, your company, understanding and endless love has been a constant source of support, emotionally and morally. I am deeply grateful to have both of you all these years, throughout my PhD journey. Thank you very much for supporting me in so many ways from the beginning until the end.

I would also like to give my special heartfelt thanks to my parents, Mr. Mustafa Bin Abdullah and Mrs. Jamaliah Binti Abu Bakar, my sisters, Nazahiyah, Nur Hanani, Nur Hanim, Nur Farhana, Nurul Nabilah and Azura and my brothers, Muhammad Fariz, Muhammad Fahmi, Muhammad Fauzan, Ahmad Fahmi and Mohd Muzhar. Special thanks to my parents-in-law, Mr. Abu Hasan Bin Hamid and Mrs. Khasnah, my brothers-in-law, Aznazar and Azahar and my sisters-in-law, Azlila, Azahania, Siti Nazirah and Siti Nabilah. Their endless love is the priceless treasure to give me light to overcome the darkest time.

I would like to thank Universiti Teknologi Malaysia for sponsoring my PhD course. This work was supported by various institutions, namely the Ministry of Science, Technology and Innovation (MOSTI), MOHE, the Hitachi Foundation (HSF), the Nippon Sheet Glass Corp (NSG), the UTM and the Malaysia-Japan Institute of Technology (MJIIT) through several research grants.

There are many other people who helped and contributed in this work. I wish I could acknowledge them in person but that would double the size of this thesis. To them, thank you very much.

ABSTRACT

The objective of this research is to investigate the possibility of direct integration between III–V based materials of Schottky diode and planar antenna without any insertion of the matching circuit by applying direct connection through Coplanar Waveguide (CPW) structure. Gallium Arsenide (GaAs) and integrated on-chip Schottky diode and antenna are considered as the promising material and device structure, to achieve such purposes. This kind of device structure should be able to function as wireless power supply as well as power detector. To achieve this objective, several basic components were studied. Firstly, the design, fabrication and characterization of individual Schottky diode and planar antenna were conducted in order to understand both Direct Current (DC) and Radio Frequency (RF) characteristics. RF signals were well detected and rectified by the fabricated Schottky diodes with the cut-off frequency of up to several tens GHz, and a stable DC output voltage was generated. The RF characteristics of planar dipole and meander antenna as a function of antenna dimension were investigated. Good return loss was obtained at the resonant frequency of the antenna. From the direct injection experiment, the conversion efficiency up to 80 % of 1 GHz signal to the diode was achieved. Then, the integrated device was evaluated by transmitting RF signal from a different planar antenna and also using a horn antenna placed at a certain distance. The irradiated signal was successfully received by the planar antenna and rectified by the integrated diode. The rectification achieved was due to enough power received by the antenna to turn on the diode (Schottky barrier height = 0.381 eV- Cr/Au metallization, turn on voltage = 0.8 V). The output voltage of several volts (V) was generated at the load which was connected in parallel to the diode. A maximum output voltage of around 0.6 V and 130 mV were generated at the load resistance for frequency of 2 GHz and 7 GHz, respectively. A closed-form equation for the conversion efficiency of the Schottky diode has been derived to analyse the diode for the high frequency rectenna. The measured results were in good agreement with calculated results with small discrepancy between them due to resistance blow up effect, effect of non-linear junction capacitance, effect of the finite forward voltage drop and the breakdown voltage of the diode. From these presented results, the proposed on-chip AlGaAs/GaAs HEMT Schottky diode and antenna seems to be a promising candidate to be used for application in proximity communication system as a wireless low power source as well as a highly sensitive RF detector device.

ABSTRAK

Objektif kajian ini adalah untuk menyiasat kemungkinan integrasi langsung antara diod Schottky berasaskan bahan III-V dan satah antena tanpa memasukkan sebarang litar pengantara dengan menggunakan sambungan terus melalui struktur pandu gelombang sesatah (CPW). Galium Arsenida (GaAs), diod Schottky dan antenna bersepadu atas cip dianggap sebagai bahan dan struktur peranti yang berpontensi menyumbang dalam mencapai tujuan tersebut. Struktur peranti jenis ini akan dapat berfungsi sebagai bekalan kuasa tanpa wayar dan juga pengesan kuasa. Untuk mencapai matlamat ini, beberapa komponen asas telah dikaji. Pertama, reka bentuk, fabrikasi dan pencirian diod Schottky dan satah antena secara individu telah dijalankan untuk memahami kedua-dua ciri-ciri arus terus (DC) dan frekuensi radio (RF). Isyarat RF telah dikesan dan ditukarkan oleh diod Schottky dengan frekuensi potong sehingga beberapa puluh GHz dan keluaran voltan DC yang stabil telah dijana. Ciri-ciri RF untuk satah antena dwikutub dan antena lingkaran sebagai fungsi dimensi antara antena telah dikaji. Kehilangan pulangan yang baik telah diperolehi pada frekuensi salunan antena. Dari eksperimen suntikan secara langsung, penukaran kecekapan sehingga 80 % daripada isyarat pada 1 GHz untuk diod telah dicapai. Kemudian, peranti bersepadu dinilai dengan menghantar isyarat RF dari satah antena yang berbeza dan juga menggunakan antena tanduk yang diletakkan pada jarak tertentu. Isyarat radiasi telah berjaya diterima oleh satah antena dan ditukarkan oleh diod bersepadu. Penukaran ini dapat dicapai kerana kuasa yang mencukupi telah berjaya diterima oleh antena untuk menghidupkan diod (Ketinggian sawar Schottky = 0.381 eV- pelogaman Cr/Au, voltan hidup = 0.8 V). Voltan keluaran dalam beberapa volt (V) telah dijana pada beban yang disambung secara selari dengan diod. Maksimum voltan keluaran sebanyak 0.6 V dan 130 mV telah dijana pada rintangan beban pada frekuensi 2 GHz dan 7 GHz. Satu persamaan tertutup untuk mengira kecekapan penukaran diod Schottky telah dikaji untuk diod tersebut beroperasi pada frekuensi peranti yang tinggi. Keputusan yang diperolehi secara eksperimen bersamaan dengan keputusan yang dikira dengan perbezaan kecil di antara satu sama lain kerana kesan daripada rintangan pecahan, kesan tidak linear persimpangan kapasitor, kesan kejatuhan voltan hadapan terhingga dan voltan pecahan diod. Daripada keputusan yang dibentangkan, AlGaAs/GaAs transistor-pergerakan-elektron-tinggi (HEMT) diode Schottky dan antena atas cip menjadi calon yang amat berguna bagi aplikasi sistem perhubungan jarak dan sebagai sumber tenaga yang rendah tanpa wayar serta peranti pengesan RF yang sangat sensitif.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2DEG	–	Two-dimensional electron gas
AC	–	Alternating current
Al	–	Aluminium
AlGaAs	–	Aluminium Gallium Arsenide
APDs	–	Anti-phase domains
As	–	Arsenide
Au	–	Gold
BDD	–	Binary diagram
BW	–	Bandwidth
CMOS	–	Complementary metal–oxide–semiconductor
CPW	–	Coplanar Waveguide
Cr	–	Chromium
DC	–	Direct Current
DI	–	De-ionized
EM	–	Electromagnetic
EPD	–	Each Pit Density
fcc	–	face centered cubic
FET	–	Field-effect-transistor
Ga	–	Gallium
GaAs	–	Gallium Arsenide
Ge	–	Germanium
GeOI	–	Germanium on insulator
G-S-G	–	Ground-Signal-Ground
GSM	–	Global system for mobile communications
H_2O	–	Water
H_2O_2	–	Hydrogen Peroxide
H_2SO_4	–	Sulphuric Acid

HCl	–	Hydrochloric Acid
HEMT	–	High-electron-mobility-transistor
HFET	–	Heterojunction field-effect-transistor
IC	–	Integrated Circuit
MBE	–	Molecular beam epitaxy
MESFET	–	Metal-semiconductor field effect transistor
MMIC	–	Monolithic Microwave Integrated Circuit
mm-wave	–	millimetre wave
MOS	–	Metal-oxide-semiconductor
M-S	–	Metal-semiconductor
mV	–	Millivolt
N_2	–	Nitrogen
NEM	–	Nano-electro-mechanical switches
Ni	–	Nickel
RF	–	Radio Frequency
RFIC	–	Radio Frequency Integrated Circuit
RFID	–	Radio Frequency Identification Detector
RTA	–	Rapid Thermal Annealing
SBH	–	Schottky barrier height
SHF	–	Super High Frequency
SI	–	Semi-Insulating
Si	–	Silicon
SOC	–	System-on-chip
SOLT	–	Short-Open-Load-Through
SWR	–	Standing wave ratio
TRL	–	Through-Reflect-Line
ULSI	–	Ultra-large-scale integration
UV	–	Ultraviolet
UWB	–	Ultra wide band
VNA	–	Vector Network Analyzer
WLAN	–	Wireless local area network

LIST OF SYMBOLS

°C	–	Degree Celsius
K	–	Kelvin
μ_e	–	Mobility of Electron
μA	–	Microampere
μm	–	Micrometre
$\mathring{A}$	–	Angstrom, 1 Å = 1 x 10^{-10} m
a	–	Gap of CPW structure
A	–	Schottky contact area
$A*$	–	Richardson constant
b	–	Width of CPW structure
c	–	Velocity of light
C_{add}	–	Capacitor added
C_j	–	Junction capacitance
C_{osc}	–	Internal capacitance
dB	–	Decibel
d_{diode}	–	Distances between Schottky-ohmic contacts
E_c	–	Conduction band edge
E_F	–	Fermi level
eV	–	Electron volt
E_v	–	Valence band edge
f	–	Frequency
f_c	–	Cut-off frequency
F_C	–	Center frequency
F_H	–	Highest frequency
F_L	–	Lowest frequency
f_r	–	Resonant frequency
GHz	–	Gigahertz

h	–	Substrate thickness
I_s	–	Reverse saturation current
k	–	Boltzmann's Constant
$L_{antenna}$	–	Antenna length
L_{CPW}	–	CPW length
mA	–	Miliampere
MHz	–	Megahertz
mm	–	Milimetre
mV	–	Milivolt
mW	–	Miliwatt
η	–	Conversion efficiency
nA	–	Nanoampere
N_d	–	Donor doping concentration
nm	–	Nanometre
$\O_B$	–	Barrier height
$\O_m$	–	Metal work function
$\O_s$	–	Semiconductor work function
P_{in}	–	Input power
P_{out}	–	Output power
q	–	Filling fraction
r	–	Distance between integrated device and horn antenna
R_{add}	–	Additional resistor
R_j	–	Nonlinear junction resistance
R_{load}	–	Load resistance
R_{osc}	–	Oscilloscope internal input resistance
rpm	–	rate per minute
R_s	–	Series resistance
s	–	Second
S_{11}	–	Return loss
T	–	Absolute temperature
$tan\ \delta$	–	Loss tangent
V	–	Voltage
V_a	–	Applied voltage
V_{bi}	–	Built-in potential

V_{br}	–	Breakdown voltage
$V_{in\ (peak)}$	–	Input voltage (peak)
V_{in}	–	Input voltage
V_t	–	Thermal voltage
V_{TH}	–	Threshold voltage
$W_{antenna}$	–	Width of antenna
Z_{CPW}	–	Characteristic impedance of CPW
Z_{diode}	–	Characteristic impedance of diode
Z_o	–	Characteristic impedance
ε_{eff}	–	Effective dielectric constant
ε_r	–	Dielectric constant
ε_s	–	Permittivity of the semiconductor
λ	–	Wavelength
χ	–	Electron affinity
Ω	–	Ohm

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Overview

Generally, the development of wireless communications technology can be traced to the convenience it offers by sending signals to distance locations. Recently, attention has come to focus on local area wireless technologies for use within the office or home and human area wireless communication technologies for use within the reach of human limbs. In particular, close proximity wireless technology, whose spread distance through space is limited to less than 10 cm, reduces the risk of unauthorized signal reading compared to close range wireless technologies like Bluetooth and ZigBee whose propagation distance is greater than 10 m [1]. It can be used to initiate communications by simple and intuitive operations, which suggests a wide variety of applications such as contactless integrated circuit (IC) card and radio frequency identification (RFID) cards. **Figure 1.1** shows some examples of short range wireless technologies [2]. The use of close proximity wireless communications also enables simple actions like touching or holding something to act as a trigger for initiating communications. This feature can be used to enable anyone to operate an information device or home usage in an easy-to-understand and intuitive way [1].

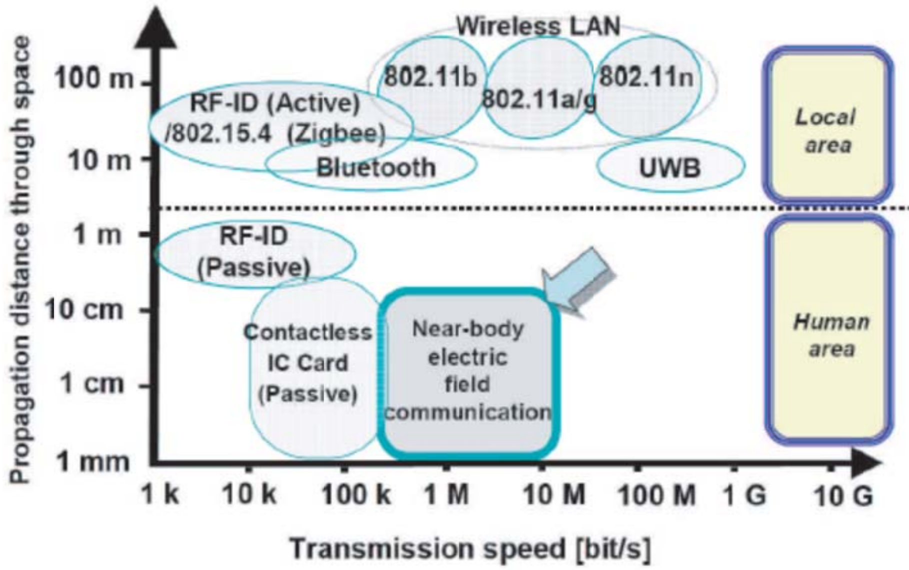

Figure 1.1 Short range wireless technologies application [2]

III-V materials are the most promising materials for high frequency devices to be used in proximity communication because of the high electron mobility and other unique features such as the formation of two-dimensional electron gas (2DEG) layer [3-5]. One of the potential gallium arsenide (GaAs)-based device structures to be used in proximity communication is rectenna device which can provide dual functions as wireless low power supply and RF power detector [6-9]. On-chip rectenna device is termed as a combination of on-chip Schottky diode and planar antenna. Basically, the rectenna should have small dimensions as well. Because of this requirement, wireless power transfer using such a device is considered to be suitable for low power applications [10, 11]. Various kinds of rectennas today have been developed by integrating discrete diodes and antennas through matching circuits. Consequently, the dimensions of the rectennas increase; this results in a high cost device. Thus, a small dimension rectenna devices need to be developed.

In this research, the feasibility of direct integration between Schottky diode and planar antenna on III-V materials via coplanar waveguide (CPW) transmission line without any matching circuits inserted between them is studied. The proposed on-chip integrated device seems to be a promising candidate to be used for application in proximity communication system as a wireless low power source as well as a highly sensitive radio frequency (RF) detector device.

1.2 Research Motivation

A rectenna is an important device to convert RF power into dc power to be used in low power applications as wireless power supply. It contains an antenna which collects microwave incident power and a rectifying circuit to convert it into useful DC power. Since the 1970s, one of the major reasons for intensive researches on rectenna is due to the development of solar power satellites in space for energy harvesting from sunlight [12]. In recent years, interest has turned up into the exploitation of on-chip rectenna as wireless low power source for application in wireless microelectronic systems. The most common application of rectenna is in RFID tags [13], proximity cards and contactless smart cards [14], which contain an IC which is powered by a small rectenna element. When the device is brought near to an electronic reader unit, radio waves from the reader are received by the rectenna, powering up the IC, which transmits its data back to the reader.

Various kinds of rectennas have been developed since Brown demonstrated the dipole rectenna using aluminium bars to construct the dipole and the transmission line [15]. He also presented the thin-film printed-circuit dipole rectenna [16] with 85 % of conversion efficiency at 2.45 GHz. Linearly polarized printed dipole rectennas were developed at 35 GHz in [17] and [18] with the conversion efficiency of 39 % and 70 %, respectively. 5.8-GHz printed dipole rectenna was developed in 1998 [19] with a high conversion efficiency of 82 %. In 2002, Suh *et a*l. [20] presented a rectenna designed for over 100 milliwatt (mW) rectifying and the RF-to-DC power conversion efficiency was less than 20 % at the 1 mW microwave input. Tu *et al*. [21] published an experimental on a 5.8 GHz rectenna using dipole antenna with conversion efficiency of 76 % at load resistance of 250 Ω. In 2011, Harouni *et al.* [22] presented an analysis of 2.45 GHz rectenna with maximum conversion efficiency of 63 % at load resistance of 1.6 kΩ. Recently, a new design for a compact and wideband circularly-polarized rectenna including matching circuit were developed at 9.5 GHz with the conversion efficiency of 71.9 % [23].

However, these reports have thoroughly discussed the results of the integrated large-scale discrete diodes and antennas through the matching circuits [15-33]. Consequently, due to the large dimensions, make the rectenna not suitable for several tens millimeter-scale on-chip system. Thus, a small dimension on-chip rectenna devices with the omission of impedance matching circuit needs to be developed for the application in on-chip proximity communication system. **Table 1.1** shows the difference between available rectenna and the proposed rectenna to be used in the proximity communication technology.

Table 1.1: Difference between conventional and proposed rectenna structure

Integration of discrete device	**Planar on-chip integration**
Contains matching circuit between antenna and Schottky diode	No matching circuit between antenna and Schottky diode
Disadvantages: Increase area and cost (fabrication process)	Advantages: Low power (same wafer), fast switching, reduce area and cost (fabrication process)
Cannot be applied for nanosystems	Can be applied for nanosystems

Nanoelectronic systems are increasingly vulnerable to malfunction due to incident electromagnetic (EM) radiation, particularly since many integrated circuits (IC) operate at lower voltages. Lower voltages generally result in lower power operation for the devices and are easier to supply using batteries in small devices [34]. The damaging RF radiation can be produced intentionally such as by high power microwave generator [35], or accidentally such as by ambient sources like lightning. Then, it becomes a great interest to know how, and at what level, microwaves penetrate equipment shielding and reach the vulnerable chips. This motivates our group to work on the on-chip RF detectors both for measuring power at the chip level and for developing strategies to mitigate its effects. Knowing the RF power levels in various chips and locations within chips is likely to be more useful than the "digital" information that a given external RF power level made the circuits fail. RF power detector is also the most potential device to be used in proximity communication. RF detector is built to sense the potentially damaging EM signals to avoid circuit failures.

It is well known that sufficiently intense EM signals in the frequency range of 200 MHz to 5 GHz can cause upset or damage in electronic systems [36]. The Schottky diode rectifies the incident RF signal, and the capacitor and the resistor produce a direct current (DC) output by filtering out the high frequency part of the rectified signal. In special molecular beam epitaxy (MBE) grown geometries, RF detection up to 100 GHz has been reported [37-39]. However, in foundry fabricated Si-based diodes detection of only up to 600 MHz has been reported [37, 40]. Recently, the CMOS fabricated Schottky diode detected RF signals up to 10 GHz in direct injection experiments and in the range of 9.5-19.5 GHz in microwave irradiation experiments have also been reported [41]. However, the design and fabrication of Schottky diodes and planar antennas on III-V semiconductor based HEMT structures for low power rectennas and RF detector have not been extensively investigated.

1.3 Research Objectives and Scopes

The objectives of this research are;

1. To fabricate and characterize the Schottky diode structure on an AlGaAs/GaAs HEMT for high RF-to-DC conversion efficiency and high detection capability.
2. To fabricate and characterize the planar antenna on semi-insulated GaAs for efficient signal reception and transmission.

3. To fabricate and characterize an integrated Schottky diode and planar antenna on an AlGaAs/GaAs HEMT structure without any matching circuit inserted.
4. To develop a reliable model for the device and circuit characteristics based on the experimental results.

The scopes of this research are as follows;

1. The Schottky diode is fabricated on an AlGaAs/GaAs HEMT structure using standard photolithography and lift off process. The DC and RF characteristic of diode is investigated in order to check the capability of the Schottky diode for direct integration of planar antenna. In the preliminary study, the fabricated Schottky diode provides low conversion efficiency, high ohmic resistance and high Schottky barrier height. The optimization of the Schottky diode is carried out for high RF-to-DC conversion efficiency and high detection capability.
2. The dipole and meander type of planar antenna are chosen and fabricated on the semi-insulated GaAs substrate. The RF characteristics of the planar antenna are investigated. The obtained results are compared with the simulation results. The planar antenna structures are simulated using Commercial Electromagnetic Sonnet Suites Simulator. Finally, the antennas with high return loss at the resonant frequency are chosen to integrate with the diode.
3. The on-chip integrated device is fabricated on an AlGaAs/GaAs HEMT structure. The RF-to-DC characteristics of the integrated devices are conducted under the direct injection and irradiation condition. Direct injection experiment is carried out in order to confirm the capability of the Schottky diode and planar antenna. Whereas, the direct RF irradiation experiment is carried out in order to investigate the capability of the integrated devices for real practical applications.
4. In this work, the measurement of RF-to-DC conversion efficiency with series and parallel connection of diode and load are performed. The modeling for series and parallel circuits are carried out since correct and reliable modeling is important so that correct device and circuit design can be performed at design stage.

1.4 Research Hypothesis

Hypothesis of the research are as follows;

1. In this research, knowing the RF power levels in a chip is more useful than the digital information that given external RF power level made the circuits fail.
2. Schottky diode: The threshold voltage of the Schottky diode should be small, so only low power are needed to supply in order to turn on the diode making it suitable for low power application. The Schottky diode should be designed with lower Schottky barrier height (SBH) in order to reduce the turn on voltage and also produce good RF response.
3. Antenna: The planar antenna should be designed with high return loss at the fundamental resonant frequency to make it well match and reduce loss at the reflected signal.
4. On-chip integration:
    a. The advantages of on-chip integration such as low power (due to same material/layer), fast switching, reduce area and cost to fabricate the devices make it suitable for electronic application.
    b. The matching circuit should be omitted and impedance characteristic of the diode and antenna should be same. The CPW structure is used as transmission line to directly integrate both devices.
    c. III-V based material such as GaAs should be used as the material for the rectenna device to make it easily integrate with other microelectronics devices and also suitable for high frequency devices.

1.5 Research Activities

The implementation of this research is summarized in a flowchart as shown in **Figure 1.2**. This study is focused on the direct integration of Schottky diode and planar antenna without insertion of any matching circuit. At the beginning stage, the fabrication and characterization of individual Schottky diode and planar antenna are conducted in parallel. Here, the RF characteristics of Schottky diode and planar antenna facilitated with CPW structure are investigated by applying direct injection of RF signals. Then, the fabrication and characterization of the integrated Schottky diode and planar antenna fabricated on *n*-AlGaAs/GaAs HEMT structure are investigated by applying direct irradiation of RF signals. The optimization of the integrated devices is carried out for high conversion efficiency.

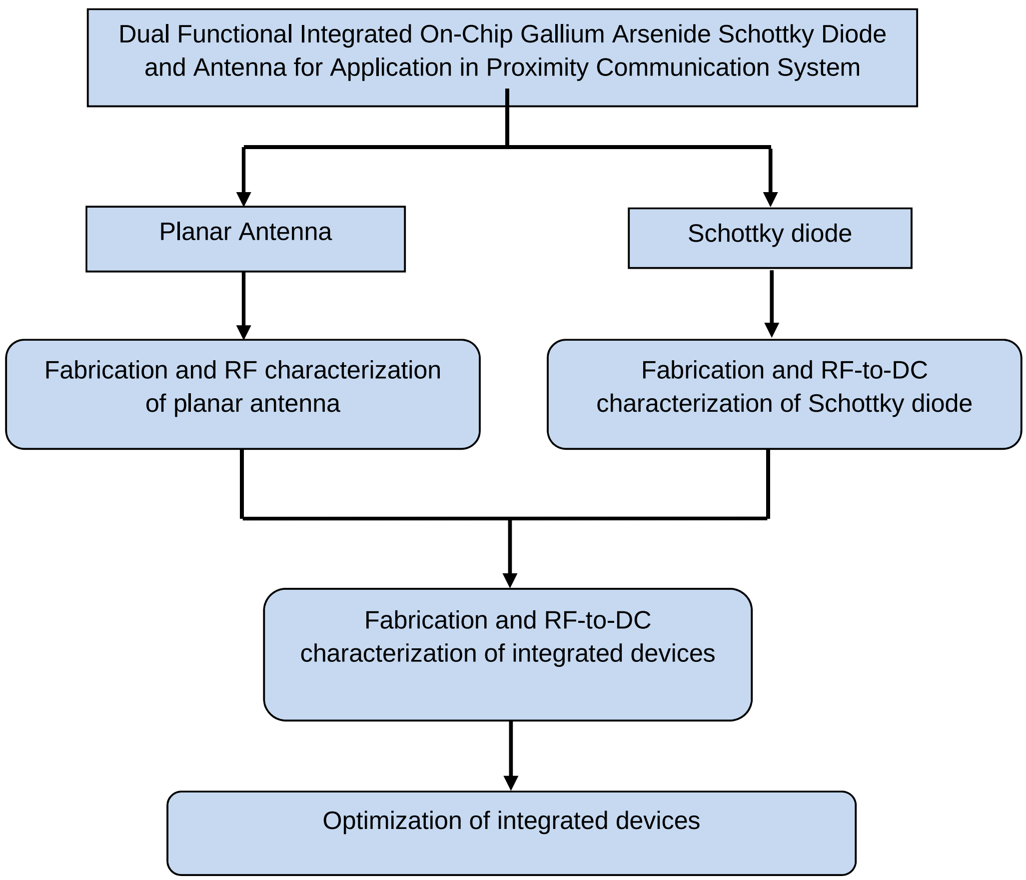

Figure 1.2 Research activities

1.6 Overview of Thesis Structure

This thesis consists of 8 chapters. This chapter gives an overview of the research background, motivation, objectives, scopes and research activities.

Chapter 2 provides an overview of on-chip technology and its application. Recent technology on the proximity communication application especially on the rectenna and RF detector are studied. This chapter also describes the basic concept and theory of Schottky diode and planar antenna as the devices of on-chip technology. Furthermore, the fundamental of CPW structure are also discussed briefly.

Chapter 3 presents the details on the basic material structure for application in on-chip technology. In addition, the material structure for the devices also discussed briefly. The unique features formed by AlGaAs/GaAs HEMT structure make it suitable as a core material for the development of the on-chip integrated device which has been considered as the most promising chip structure for realizing advanced heterogeneous integration on Si platform.

The research contents can be divided to four subtopics that are described in chapter 4, 5, 6 and 7. **Chapter 4** presents the development of the Schottky diode on an AlGaAs/GaAs HEMT structure. First, the design and fabrication process are described. Then, the obtained results which confirm the feasibility of Schottky diode to be integrated with planar antenna are discussed. The optimizations of the Schottky diode are discussed in this chapter.

Chapter 5 presents the work on GaAs-based planar antenna device. The fabrication procedures of the device are described. Then, the RF characteristics of planar dipole antenna facilitated with CPW structure are presented and discussed. The dependence of fundamental resonant frequency of the dipole antenna on the antenna's width and length are studied. Basically, the characteristics of reflection or return loss are measured.

Chapter 6 presents the work on GaAs-based on-chip integrated devices. After the experimental procedures are described, the obtained results are presented and discussed. The devices are tested under direct injection and RF irradiation using horn antenna and antenna-antenna method.

Chapter 7 presents the development of reliable model for series and parallel connection between diode and load. This model can be used in order to design a correct device with good performance at the design stage.

Chapter 8 concludes the main findings of present work and the directions of future work.

REFERENCES

1. Y. Kado, M. Shinagawa, H.-J. Song and T. Nagatsuma. Close proximity wireless communication technologies using shortwaves, microwaves, and sub-terahertz waves. *PIER Symposium Proceedings, Xi'an, China*, 22-26 March 2010: 777-781.
2. Y. Kado. A human-area networking technology as a universal interface. *2009 Symposium on VLSI Circuits, Kyoto, Japan*, 15-18 June 2009: 120-105.
3. T. Mimura, S. Hiyamizu, T. Fujii and K. Nanbu. A new field-effect transistor with selectively doped GaAs/n-$Al_xGa_{1-x}As$ heterojunctions. *Japan. J. Appl. Phys*. 1980. 19: L255-L227.
4. M.S. Shur, W.C. Peatman, H. Park, W. Grimm and M. Hurt. Novel hetero-dimensional diodes and transistors. *Solid-State Electron.* 1990. 38(9): 1727-1730.
5. T. Mimura. The early history of the high electron mobility transistor (HEMT). *IEEE Trans. Microwave Theory Tech.* 2002. 50(3): 780-782.
6. A.M. Hashim, F. Mustafa, S.F.A Rahman and A.R.A Rahman. Dual-functional on-chip AlGaAs/GaAs Schottky diode for RF power detection and low-power rectenna applications. *Sensors.* 2011. 11: 8127–8142.
7. F. Mustafa, N. Parimon, A.M. Hashim, S.F.A. Rahman, A.R.A. Rahman and M.N Osman. RF–DC power conversion of Schottky diode fabricated on AlGaAs/GaAs heterostructure for on-chip rectenna device application in nanosystems. *Microsyst Technol.* 2010. 16: 1713–1717.
8. F. Mustafa and A.M. Hashim. RF-to-DC characteristics of direct irradiated on-chip gallium arsenide Schottky diode and antenna for application in proximity communication system. *Sensors.* 2014. 14: 3493-3505.
9. F. Mustafa, N. Parimon, A.M. Hashim, S.F.A. Rahman, A.R.A.l Rahman and M.N. Osman. Design, fabrication and characterization of a Schottky diode on

an AlGaAs/GaAs HEMT structure for on-chip RF power detection. *Superlattice Microst*. 2010. 47: 274-287.

10. S. Kasai, M. Yumoto and H. Hasegawa. Fabrication of GaAs-based integrated half and full adders by novel hexagonal BDD quantum circuit approach. *Solid-State Electron*. 2003. 47(2): 199-204.
11. H.Q. Zhao, S. Kasai, T. Hashizume, and N.J. Wu. Fabrication and characterization of active and sequential circuits utilizing Schottky-wrap-gate-controlled GaAs hexagonal nanowire network structures. *IEICE Trans. Electron*. 2008. E91-C(7): 1063–1069.
12. Torrey and Lee. A trap to harness the sun. *New Scientist (London: Read Business Information*). 1980. 87: 124–127.
13. R.H. Chen, Y.C. Lee and J.S. Sun. Design and experiment of a loop rectenna for RFID wireless power transmission and data communication applications. In *PIERS Proceedings, Beijing, China*. 23-27 March 2009: 528-531.
14. K. Finkenzeller. *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*. New York. 2nd Ed. Wiley. 2003.
15. W.C. Brown. The history of power transmission by radio waves. *IEEE Trans. Microwave Theory Tech.* 1984. MTT-32: 1230–1242.
16. W.C. Brown and J.F Triner. Experimental thin-film, etched-circuit rectenna. *IEEE MTT-S Int. Microwave Symp.* 1982. Dig.1: 185–187.
17. T.W. Yoo and K. Chang. Theoretical and experimental development of 10 and 35 GHz rectennas. *IEEE Trans. Microwave Theory Tech*. 1992. 40: 1259–1266.
18. P. Koert and J.T. Cha. Millimeter wave technology for space power beaming. *IEEE Trans. Microwave Theory Tech*. 1992. 40: 1251–1258.
19. J.O. McSpadden, L. Fan and K. Chang. Design and experiments of a high-conversion efficiency 5.8 GHz rectenna. *IEEE Trans. Microwave Theory Tech*. 1998. 45: 2053–2060.
20. Y.H. Suh and K. Chang. A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission. *IEEE Trans. Microwave Theory Tech.* 2002. 50: 1784-1789.
21. W.H. Tu, S.H. Hsu and K. Chang. Compact 5.8 GHz rectenna using stepped impedance dipole antenna. *IEEE Antenn. Wireless Propag. Lett*. 2007. 6: 282-284.

22. Z. Harouni, L. Cirio, L. Osman, A. Gharsallah and O. Picon. A dual circularly polarizad 2.45 GHz rectenna for wireless power transmission. *IEEE Antenn. Wireless Propag. Lett.* 2011. 10: 306-309.
23. J. Shin, M. Seo, J. Choi, J. So and C.L. Cheon. A compact and wideband circularly polarized rectenna with high efficiency at X-Band. *Prog. Electromagn. Res*. 2014. 145: 163-173.
24. Y. Ren and K. Chang. 5.8 GHz circularly polarized dual diode rectenna and rectenna array for microwave power transmission. *IEEE Trans. Microwave Theory Tech*. 2006. 54: 1495-1502.
25. F.J. Huang, T.C. Yo, C.M. Lee and C.H. Luo. Design of circular polarization antenna with harmonic suppression for rectenna application. *IEEE Antenn. Wireless Propag. Lett.* 2012. 11: 592-595.
26. B. Strassner and K. Chang. 5.8-GHz circularly polarized rectifying antenna for wireless microwave power transmission. *IEEE Trans. Microwave Theory Tech*. 2002. 50(8): 1870-1876.
27. H.K. Chiou and I.-S. Chen. High efficiency dual-band on-chip rectenna for 35- and 94-GHz wireless power transmission in 0.13µm CMOS technology. *IEEE Trans. Microwave Theory Tech.* 2010. 58(12): 3598-3606.
28. J. Kim, S.-Y. Yang, K.D. Song, S. Jones, J.R. Elliott, I.-S. Chen and S.H. Choi. Microwave power transmission using a flexible rectenna for microwave-powered aerial vehicles. *Smart Mater. Struct.* 2006. 15: 1243-1248.
29. L.W. Epp, A.R. Khan, H.K. Smith and R.P. Smith. A compact dual-polarized 8.51-GHz rectenna for high-voltage (50V) actuator applications. *IEEE Trans. Microwave Theory Tech.* 2000. 48(1): 111-120.
30. G. Monti, L. Tarricone and M. Spartano. X-band planar rectenna. *IEEE Antenn. Wireless Propagat. Lett.* 2011. 10: 1116-1119.
31. X.-X. Yang, C. Jiang, A. Z. Elsherbeni, F. Yang and Y.-Q. Wang. A novel compact printed rectenna for data communication systems. *IEEE Antenn. Wireless Propagat. Lett.* 2013. 61(5): 2532-2539.
32. Y.-Y. Gao, X.-X. Yang, C. Jiang and J.-Y. Zhou. A circularly polarized rectenna with low profile for wireless power transmission. *Prog. Electromagn. Res. Lett*. 2010. 13: 41-49.

33. P. Kim, G. Chaudhary and Y. Jeong. A dual-band RF energy harvesting using frequency limited dual-band impedance matching. *Prog. Electromagn. Res*. 2013. 141:443-461.

34. R. Harisson. The design of integrated circuits to observe brain activity. *Proc. IEEE*. 2008. 96(7): 1203-1216.

35. M. Abrams. Dawn of the E-bomb. *IEEE Spectrum.* 2003. 40: 24-30.

36. D.V. Giri and S.M. Tesche. Classification of intentional electromagnetic environments (IEME). *IEEE EMC Trans. Special Issue.* 2003. B-1: 1-7.

37. V. Milanovic, M. Gaitan, J.C. Marshall and M.E. Zaghloul. CMOS foundry implementation of Schottky diodes for RF detection. *IEEE Trans. Electron Devices*. 1996. 43(12): 2210-2214.

38. J.F. Luy, K.M. Strohm, J. Buechier and P. Russer. Silicon monolithic millimeter-wave integrated circuits. *IEEE Proceedings*. 1992. 139(3): 209-216.

39. K.M. Strohm, J. Buechler and E. Kasper. SIMMWIC rectennas on high-resistivity silicon and CMOS compatibility. *IEEE Trans. Micro. Theory Tech*. 1998. 46(5): 669-676.

40. B. Rivera, R.J. Baker and J. Melngailis. Design and layout of Schottky diodes in a standard CMOS process. *International Semiconductor Device Research Symp., Washington D.* 2001: 79-82.

41. W. Jeon, T.M. Firestone, J.C. Rodgers and J. Melngailis. Design and fabrication of Schottky diode on-chip RF power detector. *Solid-State Electron.* 2004. 48: 2089-2093.

42. J. Zhao. Development of integrated “chip-scale” active antennas for wireless applications. Master Thesis. Faculty of the Virginia Polytechnic Institute and State University. 2002.

43. US. Department of Homeland Security. Additional guidence and security controls are needed over systems using RFID and DHS. Department of Homeland Security (Office of Inspector General). 2006: OIG-06-53.

44. W. Yao, C.-H. Chu, Z. Li. The adoption and implementation of RFID technologies in healthcare: a literature review. *Journal of Medical Systems*. 2012. 36(6): 3507-3525.

45. F. Ali. Direct conversion receiver design for mobile phone systems challenges, status and trends. *IEEE Radio Frequency Integrated Circuits (RFIC) Symp*. 2002: 21-22.

46. D. Zelenchuk, V. Fusco, G. Goussetis and A. Mendez. Millimeter-wave printed circuit board characterization using substrate integrated waveguide resonators. *IEEE Trans. Micro. Theory Tech*. 2012. 60(10): 3300-3308.

47. G.P. Gauthier, J.P. Raskin, L.P.B. Katehi and G.M. Rebeiz. A 94-GHz aperture coupled micromachined microstrip antenna. *IEEE Trans. Antennas Propagat.* 1999. 47(12): 1761-1766.

48. D.S. -Hernández, Q.S. Wang, A.A. Rezazadeh and I.D. Robertson. Millimeter wave dual-band microstrip patch antennas using multilayer GaAs technology. *IEEE Trans. Microwave Theory Tech*. 1996. 44(9): 1590-1593.

49. K. Fujimoto, A. Henderson, K. Hirasawa and J.R. James. *Small Antennas*. Research Studies Press Ltd. 1987.

50. L. Talbi and G. Delisle. Experimental characterization of EHF multipath indoor radio channels. *IEEE J. Select. Areas Commun.* 1996. 14: 431-440.

51. R.L. Smith and J.T. Williams. Coplanar waveguide feed for microstrip patch antennas. *Electronics Lett.* 1992. 28: 2272–2274.

52. W. Menzel and W. Grabher. A microstrip patch antenna with coplanar feed line. *IEEE Microwave Guided Wave Lett*. 1991. 1: 340–342.

53. K. Kim, H. Toon and O.K. K. On-chip wireless interconnection with integrated antenna. *IEDM Tech. Dig.* 2010: 485–488.

54. F. Braun. On the electrical conductivity of sulphides. Posxendorffs Annalen B. 1874: 556-563.

55. L.O. Grondahl and P.H. Geiger. A new electronic rectifier. *Proc. AIEE Winter Convention*. 1927: 357.

56. Welker and Heinrich. *Physics Today.* 1976. 9(6): 63–64.

57. J. Behnam, C. Peter, R. Damith and Z. Zheng. Design and optimization of Schottky diodes in CMOS technology with application to passive RFID systems. *School of Electrical and Electronics Engineering*. The University of Adelaide, Australia.

58. T.M. Chiam, L.C. Ong, M.F. Karim and Y.X. Guo. 5.8 GHz circularly polarized rectennas using Schottky diode and LTC5535 rectifier for RF

energy harvesting. *2009 Asia-Pacific Microwave Conference (APMC 2009)*. 32-35.

59. B.E. Luquette and B. Michols. *Technical Report: Fabrication and Characterization of Schottky Diodes Using Single Wall Carbon Nanotubes*. Army Research laboratory. ARL-TR-4534, U.S. 2008
60. B.L. Sharma. *Metal-Semiconductor Schottky Barrier Junctions and Their Applications.* New York and London: Plenum Press. 1984.
61. D.A. Neamen. *Semiconductor Physics and Devices: Basic Principle*. University of Mexico. 3rd Edition. Mc. Graw Hill, International Edition. 2003.
62. J.I. Gersten and F.W. Smith. The Physics and Chemistry of Materials. Wiley. 2001.
63. C. Kittel. Introduction to Solid State Physics. 8th Ed. Wiley. 2005.
64. A.Y.C. Yu. Electron tunnelling and contact resistance of metal-silicon contact barriers. Solid-State Electron. 1970. 13: 239-247.
65. C.Y. Chang, Y.K. Fang and S.M. Sze. Specific contact resistance of metal-semiconductor barriers. Solid-State Electron. 1971. 14: 541-550.
66. B.L. Sharma. Semiconductors and Semimetals. Academic Press, New York. 1981. 15: 1.
67. G.Y. Robinson. *Physics and Chemistry of III-V Compound Semiconductor Interfaces*. New York and London: Plenum Press. 1985: 73.
68. S.M. Sze. Physics of Semiconductor Devices. Wiley, New York. 1981.
69. F.A. Padovani and R. Stratton. Field and thermionic-field emission in Schottky barriers. Solid State Electron. 1966. 9: 695-707.
70. L.F. Wagner, R.W. Young and A. Sugerman. A Note on the correlation between the Schottky diode barrier height and the ideality factor as determined from I-V measurements. *IEEE Electron. Device Lett.* 1983. 4(4): 320-322.
71. F.A. Padovani. Semiconductors and Semimetals. Academic Press, New York. 1971.
72. F. Chekir, G.N. Lu and C. Barret. Anomalies in Schottky diode I−V characteristics. Solid State Electron. 1986. 29: 519-522.

73. M. Murakami. Development of refractory ohmic contact materials for gallium arsenide compound semiconductors. *Science and Technology of Advanced Materials*. 2002. 3: 1-27.

74. C.R. Crowell and V.L. Rideout. Normalized thermionic-field (TF) emission in metal-semiconductor (Schottky) barriers. Solid-State Electron. 1969. 12: 89-105.

75. E.H. Rhoderick and R.H. Williams. Metal-Semiconductor Contacts. Clarendon, Oxford. 1988.

76. M.K. Hudait and S.B. Krupanidhi. Doping dependence of the barrier height and ideality factor of Au/n-GaAs Schottky diodes at low temperatures. *Physica B*. 2001. 307: 307: 125–137.

77. C.R. Crowell. The Richardson constant for thermionic emission in Schottky barrier diodes. *Solid State Electron.* 1965. 8: 395-399.

78. R.F. Broom, H.P. Meier and W. Walter. Doping dependence of the Schottky-barrier height of Ti-Pt contacts to n-gallium arsenide. *J. Appl. Phys*. 1986. 60: 1832.

79. L. Breslau. Advanced in network simulations. *IEEE Comp*. 2000. 33(5): 59-67.

80. M. Heiblum, M.I. Nathan and C.A. Chang. Characteristics of AuGeNi ohmic contacts to GaAs. *Solid-State Electron.* 198. 25: 185–195.

81. O. Aina, W. Katz, B.J. Baliga and K. Rose. Low-temperature sintered AuGe/GaAs ohmic contact. *J. Appl. Phys.* 1982. 53: 777–780.

82. S. Wu, D. Wang and K. Heime. An improved model to explain ohmic contact resistance of n-GaAs and other semiconductors. *Solid-State Electron.* 1986. 29: 489–494.

83. H.-C. Lin, S. Senanayake, K.-Y. Cheng, M. Hong, J. R. Kwo, B. Yang and J. P. Mannaerts. Optimization of AuGe–Ni–Au ohmic contacts for GaAs MOSFETs. *IEEE Trans. Electron Devices.* 2003. 50.

84. J. R. Waldrop. Schottky-barrier height of ideal metal contacts to GaAs. *Appl. Phys. Lett*. 1984. 44(10): 1002-1004.

85. E.H. Rhoderick and R.H. Williams. *Metal-Semiconductor Contacts*. Oxford: Clarendon. 1984.

86. R.V. Ghita, C. Logofatu, C. Negrila, A.S. Manea, M. Cernea, M.F. Lazarescu. Studies of ohmic contact and Schottky barriers on Au-Ge/GaAs and Au-Ti/GaAs. *J. Optoelectron. Adv. Mater*. 2005. 7(6): 3033 – 3037.
87. R.T. Tung. Recent advances in Schottky barrier concepts. *Mater. Sci. Eng. R*. 2001. 35(1-3): 1-138.
88. J.R. James, and P.S. Hall. *Handbook of Microstrip Antennas*. Peter Peregrinus, United Kingdom. 1989.
89. C.A. Balanies. *Antenna Theory: Analysis & Design*. New York, USA. John Wiley and Sons, Ltd. 1997.
90. L.K.E. Alkan. Microwave Planar Antenna Design Syracuse. University Department of Electrical Engineering and Computer Science, ELE 791 Project Report Spring. 2002.
91. R. Waterhouse. Small microstrip patch antenna. *Electron. Lett*. 1995. 31: 604-605.
92. D.M. Pozar and D. Schaubert. *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*. New York, USA. John Wiley and Sons, Ltd. 1992.
93. G. Kumar and K.P. Ray. *Broadband Microstrip Antennas*. Artech House, Inc. 2003.
94. R.B. Waterhouse, S.D. Targonski and D.M. Kokotoff. Design and performance of small printed antennas. *IEEE Trans. Antennas and Propagation*. 1998. 46: 1629-1633.
95. M.H. Jamaluddin, M.K.A. Rahim, M.Z.A. Abd. Aziz and A. Asrokin. A microstrip dipole antenna analysis with different width and length at 2.4 GHz. *2005 Asia Pasific Conference on Applied Electromagnetics Proceedings*. December 20-21. Johor Bahru, Malaysia. 2005.
96. M.H. Jamaluddin, M.K.A. Rahim and M.Z.A. Abd. Aziz. Direct conversion receiver for active integrated antenna. *2005 Asia Pasific Conference on Applied Electromagnetics Proceedings*. December 20-21. Johor Bahru, Malaysia. 2005.
97. R. Garg, P. Bhartia, I. Bahl and A. Ittiboon. *Microstrip Antenna Design Handbook.* Artech House Norwood, MA. 2001.

98. C.P. Wen. Coplanar waveguide: A surface strip transmission line suitable for nonreciprocal gyromagnetic device applications. *IEEE Trans. Microwave Theory Tech.* 1969. MTT-17(12): 1087-1088.

99. Nayak, J.S.N. Sahu, S.Nozaki. GaAs nanocrystals: Structure and vibrational properties. *Applied Surface Science.* 2006. 252: 2867–2874.

100. S.M. Sze. *Semiconductor Devices Physics and Technology.* 2nd Edition. New York, USA. John Wiley and Sons, Ltd. 2002.

101. R.F. Pierret, *Semiconductor Fundamentals*. Addison-Wesley Publishing, New York. 1989.

102. S.Y. Chiang. Properties of vacancy defects in GaAs single crystals. *J. Appl. Phys.* 1975. 45: 2986.

103. D. Look. *Semi-insulating III-V Materials*. Shiva Publishing Ltd., England. 1984.

104. R. Williams. *Modern GaAs Processing Methods*. Artech House, Dedham, MA. 1990.

105. J. Singh. *Physics of Semiconductors and Their Heterostructures.* McGraw Hill Book Company. New York, USA. 1993.

106. F. Ali and A. Gupta. *HEMTs and HBTs: Devices, Fabrication and Circuits* Artech House, Boston. 1991.

107. E.J. Koop, M.J. Iqbal, F. Limbach, M. Boute, B.J. Wees, D. Reuter, A.D. Wieck, B.J. Kooi and C.H. Wal. On the annealing mechanism of AuGe/Ni/Au ohmic contacts to a two-dimensional electron gas in GaAs/$Al_xGa_{1-x}As$ heterostructures. *Semicond. Sci. Technol.* 2013. 28: 025006.

108. D.H. Zhang. Metal contacts to n-type AlGaAs grown by molecular beam epitaxy. *Mater. Sci. Eng.* 1999. B60: 189-193.

109. W. Jeon. Design and fabrication of on-chip microwave pulse power detectors. Ph.D. Thesis, University of Maryland, College Park, MD, USA, 2005.

110. T. Nakamura, Y. Abe, S. Kasai, H. Hasegawa and Hashizume. Properties of GaAs single electron path switching node device using a single quantum dot for hexagonal BDD quantum circuits. *Journal of Physics: Conference Series.* 2006. 38: 104-107.

111. D.R. Greenberg and J.A. Alamo. Velocity saturation in the extrinsic device: a fundamental limit to HFET's. *IEEE Trans. on Electron Dev*. 1994. 41(8): 1334-1339.

112. V.K. Arora and M.B. Das. Effect of electric-field-induced mobility degradation on the velocity distribution in a sub-mu M length channel of InGaAs/AlGaAs Heterojunction MODFET. *Semicond. Sci. Technol*. 1990. 5(9): 967-973.

113. V.K. Arora and M.B. Das. Role of velocity saturation in lifting pinchoff condition in long channel MOSFET. *Electronics Lett*. 1989. 25(13): 820-821.

114. T.W. Yoo and K. Chang. Theoretical and experimental development of 10 and 35 GHz rectennas. *IEEE Trans. Microwave Theory Tech.* 1992. 40: 1259-1266.

115. M.L.P. Tan, T. Saxena, V.K. Arora. Resistance blow-up effect in micro-circuit engineering. *Solid-State Electron.* 2010. 54: 1617-1624.

116. M.L.P. Tan, I. Saad, R. Ismail and V.K. Arora. Enhancement of nano-RC switching delay due to the resistance blow-up in InGaAs. *NANO.* 2007. 2: 233-237.

117. J. Rashed and C.T. Tai. A new class of resonant antennas. *IEEE Trans. Antennas Propag.* 1991. 39(9): 1428–1430.

118. O.O. Olusola, W.D. Palmer and W.T. Joines. Characterization of meander dipole antennas with a geometry-based, frequency-independent lumped element model. *IEEE Antenn. Wireless Propag. Lett*. 2012. 11: 346-349.

119. H. Makimura, Y. Watanabe, K. Watanabe and H. Igarashi. Evolutional design of small antennas for passive UHF-band RFID. *IEEE Trans. Magn.* 2011. 47(5): 1510–1513.

120. M.C. Huynh. Wideband compact antennas for wireless communication applications. Virginia Polytechnic Institute and State University: PhD Thesis. 2004

121. T. Endo, Y. Sunahara, S. Satoh and T. Katagi. Resonant frequency and radiation efficiency of meander line antennas. *Electronics and Communications in Japan.* 2000. 2(83):52-58

122. A. Khaleghi, A. Azooulay and J.C. Bolomey, A dual band back couple meandering antenna for wireless LAN Applications. Gof Suryvette, France. (2005).

123. Hewlett Packard Co., Application Notes AN 64-1C. 1996.

124. T.S. Bird. Definition and misuse of return loss. *IEEE Antennas Propagat. Mag.* 2009. 51(2): 166-167.

125. M. Barakat, C. Delaveaud, F. Ndagijimana. 60GHz interdigitated SOI integrated dipole antenna with a CPW balun. Mediterranean Microwave Symposium 2006, Genova , Italy. 2006.

126. P.F. Goldsmith. Absorptive Loss and Antenna Performance and Measurements. Antenna Notes. 2002.

127. J.J. Nahas. Modeling and computer simulation of a microwave-to-dc energy conversion element. *IEEE Trans. Microwave Theory Tech.* 1975. 23: 1030-1035.

128. W.C. Brown and E.E. Eves. A microwave beam power transfer and guidance system for use in an orbital astronomy support facility. Final Report (Phase 11) to NASA. NAS-8-25374. 1972.