FABRICATION AND CHARACTERIZATION OF PLANAR DIPOLE ANTENNA AND SCHOTTKY DIODE FOR ON-CHIP ELECTRONIC DEVICE INTEGRATION

FARAHIYAH BINTI MUSTAFA

UNIVERSITI TEKNOLOGI MALAYSIA

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FARAHIYAH BINTI MUSTAFA

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Especially dedicated to my beloved parents, brothers and sisters who have encouraged guide and inspired me throughout my journey in education

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ABSTRACT

Recent revolutionary progress of the internet and wireless technologies has created a concept of the *"ubiquitous network society"* for this 21st century. A so-called Intelligent Quantum (IQ) chip has been proposed as the promising electronic device for the ubiquitous network society environments. An IQ chip is an III-V semiconductor chip with sizes of millimeter square or less where nanometer scale quantum processors and memories are integrated on the same chip with other capabilities of wireless power supply and various sensing functions. It is an attempt to endow "more intelligence" than simple identification (ID) like in radio frequency identification detector (RFID) chips to semiconductor chips so that they can be utilized as versatile tiny "knowledge vehicles" to be embedded anywhere in the society, or even within the bodies of human beings and other living species. This study is carried out to focus on the development of wireless microwave power transmission/supply and detector technology. Integrated on-chip device (integration between antenna and Schottky diode) is one of the most potential devices to be integrated on the IQ chip to act as the wireless power supply as well as power detector. The feasibility of direct integration between planar dipole antennas with Schottky diode via coplanar waveguide (CPW) transmission line without any matching circuits inserted between them for nanosystem application is studied. First, the fabrication and radio frequency (RF) characterization of planar dipole antenna facilitated with CPW structure on semi-insulated gallium arsenide (GaAs) are performed. The return loss of dipole antennas are evaluated by varying their lengths, widths and also metal thicknesses for the purpose of use in the super high frequency (SHF) band. Experimentally, the return loss down to -54 dB with a metal thickness of 50 nm is obtained. The difference is only 2 % - 4 % between simulated and measured results for the frequency bandwidth at -10 dB. It is shown that the fundamental resonant frequency of dipole antennas can be controlled by the dipole length but unchanged with the width and metal thickness. Next, the fabrication, direct current (DC) and RF characterization of the AlGaAs/GaAs high-electron mobility-transistor (HEMT) Schottky diode is performed. The fabricated devices show good rectification with a Schottky barrier height of 0.5289 - 0.5468 eV for Nickel/Gold (Ni/Au) metallization. The differences of Schottky barrier height from theoretical value are due to the fabrication process and smaller contact area. The RF signals are well detected and rectified by the fabricated Schottky diodes and stable DC output voltage is obtained. The cut-off frequency up to 20 GHz is estimated in direct injection experiments. The output current is in the range of several tens of microamperes (µA) which is adequate for low current device application. Finally, an integrated device is fabricated and tested in direct RF irradiation. However, a reception of RF signal by dipole antenna is weak. Further considerations on the polarization of irradiation and radiation distance of the antenna need to be carried out. These results provide new breakthrough ideas for the direct on-chip integration technology towards realization of fast RF damaging signal detection and towards realization of ultra-low power on-chip rectenna technology for nanosystem application.

ABSTRAK

Kemajuan internet dan teknologi wayarles telah mencipta satu konsep *"ubiquitous network society"* untuk abad ke-21. Cip Kuantum Pintar (IQ) dicadangkan sebagai peranti elektronik yang berpotensi untuk persekitaran "*ubiquitous network society"*. Cip IQ adalah cip III-V semikonduktor yang berukuran milimeter persegi atau kurang dimana mempunyai pemproses skala kuantum nanometer dan ingatan yang dimuatkan dalam satu cip dan berkebolehan sebagai bekalan kuasa wayarles dan pelbagai fungsi penderiaan. Satu lembaran baru yang "lebih pintar" dihasilkan berbanding pengenalan mudah (ID) seperti cip pengesan pengenalan radio frekuensi (RFID) kepada cip semikonduktor yang serba boleh seperti "perantara ilmu" untuk digunakan dimana jua atau dalam badan manusia dan hidupan lain. Penyelidikan ini menumpu kepada penghasilan penghantaran/bekalan kuasa mikrogelombang wayarles dan teknologi pengesan. Peranti dalam cip (penyepaduan antara antena dan diod Schottky) adalah peranti yang berpontensi untuk dimuatkan dalam cip IQ untuk bertindak sebagai bekalan kuasa wayarles dan pengesan kuasa. Penyepaduan secara terus antara antena dwikutub dan diod Schottky melalui pandu gelombang sesatah (CPW) tanpa menggunakan sebarang litar penyesuaian untuk aplikasi nanosistem dibentangkan. Pertama, fabrikasi dan pencirian radio frekuensi (RF) struktur antena dwikutub sesatah dengan struktur CPW atas substrat separuh tebat galium arsenida (GaAs) dikaji. Kehilangan balikan struktur antenna dwikutub ini dikaji dengan mempelbagaikan panjang dan tebal antena dan beroperasi dalam julat frekuensi yang sangat tinggi (SHF). Secara eksperimen, kehilangan balikan sebanyak -54 dB dengan ketebalan logam 50 nm diperolehi. Perbezaan sebanyak 2 % - 4 % sahaja antara keputusan simulasi dan pengukuran untuk kelebaran jalur frekuensi pada -10 dB. Ini menunjukkan, frekuensi salun struktur antena dwikutub dapat dikawal dengan panjang antena tetapi tidak berubah dengan perubahan ketebalan antena dan logam. Kemudian, fabrikasi dan pencirian arus terus (DC) dan RF untuk AlGaAs/GaAs transistor-pergerakan-elektron-tinggi (HEMT) diod Schottky dibentangkan. Peranti yang difabrikasi menunjukkan sifat rektifikasi yang bagus dengan penghalang kualiti Schottky antara 0.5289 - 0.5468 eV dengan kelogaman Nikel/Emas (Ni/Au). Perbezaan nilai penghalang kualiti Schottky ini dengan nilai teori mungkin disebabkan oleh proses fabrikasi dan kawasan hubungan yang kecil. Isyarat RF dikesan dengan baik dan diolah oleh diod Schottky dan voltan keluaran DC yang stabil diperolehi. Frekuensi potong sehingga 20 GHz diperolehi daripada eksperimen suntikan secara terus. Arus keluaran adalah dalam julat mikroampere (μA) yang bersesuaian untuk aplikasi peranti arus rendah. Akhirnya, peranti dalam cip difabrikasi dan diuji dalam sinaran RF secara terus. Walaubagaimanapun, penerimaan isyarat RF oleh antena dwikutub adalah sangat lemah. Pertimbangan-pertimbangan lanjut pada sinaran polarisasi dan jarak sinaran antara antena perlu dilaksanakan untuk meningkatkan sambutan isyarat. Keputusan awal ini akan membuka lembaran baru untuk teknologi kombinasi cip secara terus ke arah merialisasikan pengesanan isyarat RF yang cepat dan juga dapat bertindak sebagai pemberi kuasa yang rendah dalam teknologi rektena untuk aplikasi nanosistem.

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LIST OF ABBREVIATIONS

2DEG – Two-dimensional electron gas
Al – Aluminum
AlGaAs – Aluminium Gallium Arsenide
As – Arsenide
Au – Gold
BDD – Binary diagram
BW – Bandwidth
CMOS – Complementary metal–oxide–semiconductor
CPW – Coplanar Waveguide
Cr – Chromium
dB – Logarithmatic Magnitude
DC – Direct Current
DI – Di-ionized
EM – Electromagnetic
FET – Field-effect-transistor
Ga – Gallium
GaAs – Gallium Arsenide
Ge – Germanium
G-S-G – Ground-Signal-Ground
H_2O – Water
H_2O_2 – Hydrogen Peroxide
H_2SO_4 – Sulfuric
HCl – Hydrochloric
HEMT – High-electron-mobility-transistor
HF – High Frequency

IC – Integrated Circuit
IQ – Intelligent Quantum
LF – Lower Frequency
MBE – Molecular beam epitaxy
MEK – Methyl-ethyl-ketone
MESFET – Metal-semiconductor field effect transistor
MF – Medium Frequency
MMIC – Monolithic Microwave Integrated Circuit
mV – Millivolt
Ni – Nickel
PR – Photoresist
Q-LSI – Quantum-large scale integration
RF – Radio Frequency
RFID – Radio Frequency Identification Detector
RTA – Rapid Thermal Annealing
SBH – Schottky barrier height
SHF – Super High Frequency
SI – Semi-Insulating
Si – Silicon
SOLT – Short-Open-Load-Through
TRL – Through-Reflect-Line
UHF – Ultra High Frequency
ULSI – Ultra-large-scale integration
UV – Ultraviolet
VHF – Very High Frequency
VNA – Vector Network Analyzer

LIST OF SYMBOLS

μ – Mobility of Electron

μA – Microampere

$\mathring{A}$ – Angstrong, 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

d_{diode} – Distances between Schottky-ohmic contacts

E_F – Fermi level

f – Frequency

f_r – Resonant frequency

h – Substrate thickness

I_s – Reverse saturation current

k – Boltzmann's Constant

$L_{antenna}$ – Antenna length

L_{CPW} – CPW length

N_d – Donor doping concentration

$Ø_B$ – Barrier height

$Ø_m$ – Metal work function

$Ø_s$ – Semiconductor work function

P_{in} – Input power

q – Filling fraction

r – Distance between integrated device and horn antenna

R_{add} – Additional resistor

R_j – Nonlinear junction resistance

R_{osc} – Oscilloscope internal input resistance

R_s – Series resistance

S_{11} – Return loss

T – Absolute temperature

$tan\ \delta$ – Loss tangent

V_a – Applied voltage

V_{bi} – Built-in potential

$V_{in\ (peak)}$ – Input voltage (peak)

V_t – Thermal voltage

V_{TH} – Threshold voltage

$W_{antenna}$ – Width of antenna

Z_o – Characteristic impedance

ε_{eff} – Effective dielectric constant

ε_r – Dielectric constant = 12.9

ε_s – Permittivity of the semiconductor

λ – Wavelength

χ – Electron affinity

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Explosive growth of internets and wireless technologies starting in the late 20th century has opened up prospects towards an advanced ubiquitous network society. Wireless power technologies have been proposed for many years and are expected to be one of the most promising energy transfer methods in the near future, especially in space power supply and emergency power recovery [1]. This wireless system would be the groundwork for ubiquitous network society. The vision of ubiquitous network society suggests a world in which any information can be accessed from anywhere at anytime and by anyone [2]. New and existing technologies making this vision a reality.

A so called Intelligent Quantum (IQ) chip with sizes of several millimeters square proposed by Hasegawa et al. [3] is capable to coincide to this ubiquitous concept. The integration of antenna and Schottky diode can be used as radio frequency (RF) detectors and hence are ideal for applications as rectenna device to supply direct current (DC) power to generate other on-chip devices. Schottky diode is widely considered as a major rectifier due to its fast rectifying operation and suitability for on-chip integration. As a semiconductor material for Schottky diode, three-five (III-V) based compound materials have been considered as the most promising materials because of their stability, capability of making a good Schottky contact and well-developed fabrication process technology. Higher electron mobility exists in two dimensional electron gas (2DEG) layer making it suitable for high-frequency devices [4, 5]. It has also emerged to be suitable for nanostructure formation for the development of the IQ chip [3]. A novel feature here is the total integration with excellent outcomes over and above those obtained from putting together the commercial components. The small dimensions and the ease of manufacturing with low cost are the desirable attributes.

In this study, the investigation on the direct integration of planar dipole antenna to Schottky diode via coplanar waveguide (CPW) transmission line without insertion of any matching circuit is carried out. First, the fabrication and RF characterization of planar dipole antenna facilitated with CPW structure on semi-insulated gallium arsenide (GaAs) are performed. Next, the design, fabrication and RF characterization of Schottky diodes on *n*-AlGaAs/GaAs high-electron-mobility-transistor (HEMT) structure are performed. Finally, an integrated device (Schottky diode + dipole antenna) is fabricated and tested in direct RF irradiation.

1.2 Research Motivation

Current advancements in communication technology and significant growth in the wireless communication market and consumer demands demonstrate the need for smaller, more reliable and power efficient integrated wireless systems [6]. Integrating entire transceivers on a single chip is the vision for future wireless systems. This has the benefit of cost reduction and improving system reliability. As mentioned, an IQ chip is a III-V semiconductor chip with sizes of millimeter square where nanometer scale quantum processors and memories are integrated on chip. **Figure 1.1** shows the concept of the IQ chips [3].

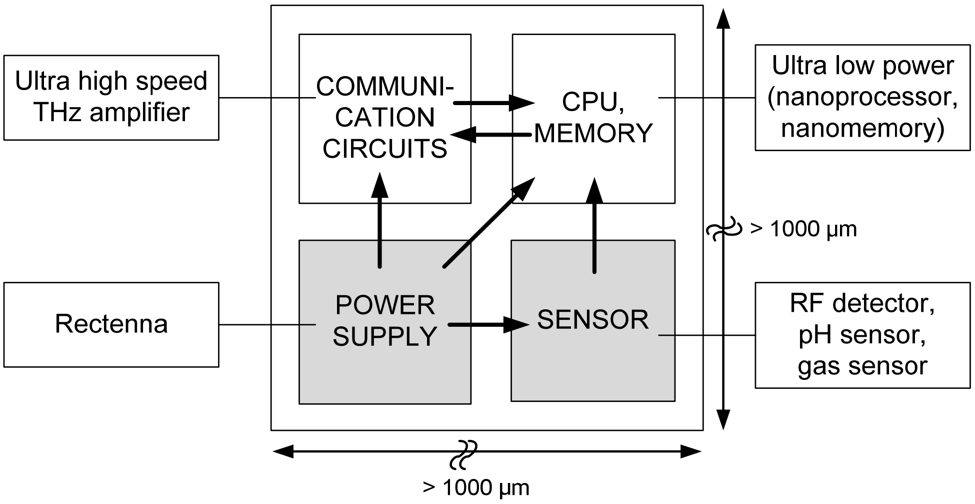

Figure 1.1: The concept of the IQ chips

Rectenna is one of the most potential devices to be integrated on the IQ chip to form the wireless power supply. Therefore, the rectenna should have small dimensions as well. This results in small antenna area and consequently, a low amount of received power. Because of these limitations, wireless power transfer using such devices is considered to be suitable for low power applications. To our knowledge, almost all past rectennas were designed for over 100 milliwatt (mW) rectifying and the RF-to-DC power conversion efficiency is less than 20 % at the 1 mW microwave input [7]. Various kinds of rectennas today have been developed using the matching circuit. Consequently, the dimensions of the rectenna enlarge making it a high cost rectenna. Thus, a small dimension of rectenna devices needs to be developed.

RF power detector also the most potential devices to be integrated on the IQ chips. RF detector is build to sense the potentially damaging electromagnetic (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 [8]. The Schottky diode rectifies the incident RF signal, and the capacitor and the resistor produce a DC output by filtering out the high frequency part of the rectified signal. RF detection up to 100 GHz have been reported [9] in special molecular beam epitaxy (MBE) grown nanostructures. However, detection of only up to 600 MHz has been reported [10, 11] in foundary-fabricated Si-based diodes. Schottky diodes fabricated using complimentary metal-oxide semiconductor (CMOS) technologies are found to detect RF signals up to 10 GHz in direct injection experiments. The detection in the range of 9.5 - 19.5 GHz in microwave irradiation experiments have also been reported [12]. However, the design and fabrication of planar dipole antenna and Schottky diode on III-V semiconductor based HEMT structure for RF power detector and rectenna are not extensively investigated.

1.3 Research Objectives

The objective of this research is to investigate the possibility of direct integration between dipole antenna and III–V based Schottky diode without any insertion of matching circuit by applying direct connection between dipole antenna and Schottky diode through CPW structure.

1.4 Scopes of the Research

The scopes set for this research are as follows:

i. Design and characterization of the planar dipole antenna structure using Commercial Electromagnetic Sonnet Suites Simulator.

ii. Fabrication of the dipole antenna to verify simulation results.

iii. Analysis of the dependence of antenna dimensions and metal thickness on the return loss characteristics and resonant frequency.

iv. Design, fabrication and characterization (DC & RF) of an *n*-AlGaAs/GaAs HEMT Schottky diode.

v. Preliminary experimental work on integrated dipole antenna and Schottky diode without insertion of any matching circuit.

1.5 Research Activities

The implementation of this research is summarized into flowchart as shown in **Figure 1.2**. This study is focused on the direct integration of dipole antenna and Schottky diode without insertion of any matching circuit. At the beginning stage, the design, fabrication and characterization of individual planar dipole antenna and Schottky diode are conducted in parallel. Here, the RF characteristics of planar dipole antenna and Schottky diode facilitated with CPW structure are investigated by applying direct injection of RF signals. Then, the fabrication and characterization of the integrated dipole antenna and Schottky diode fabricated on *n*-AlGaAs/GaAs HEMT structure are investigated by applying direct irradiation of RF signals. **Figure 1.3** and **Figure 1.4** show the research flow of planar dipole antenna and Schottky diode respectively.

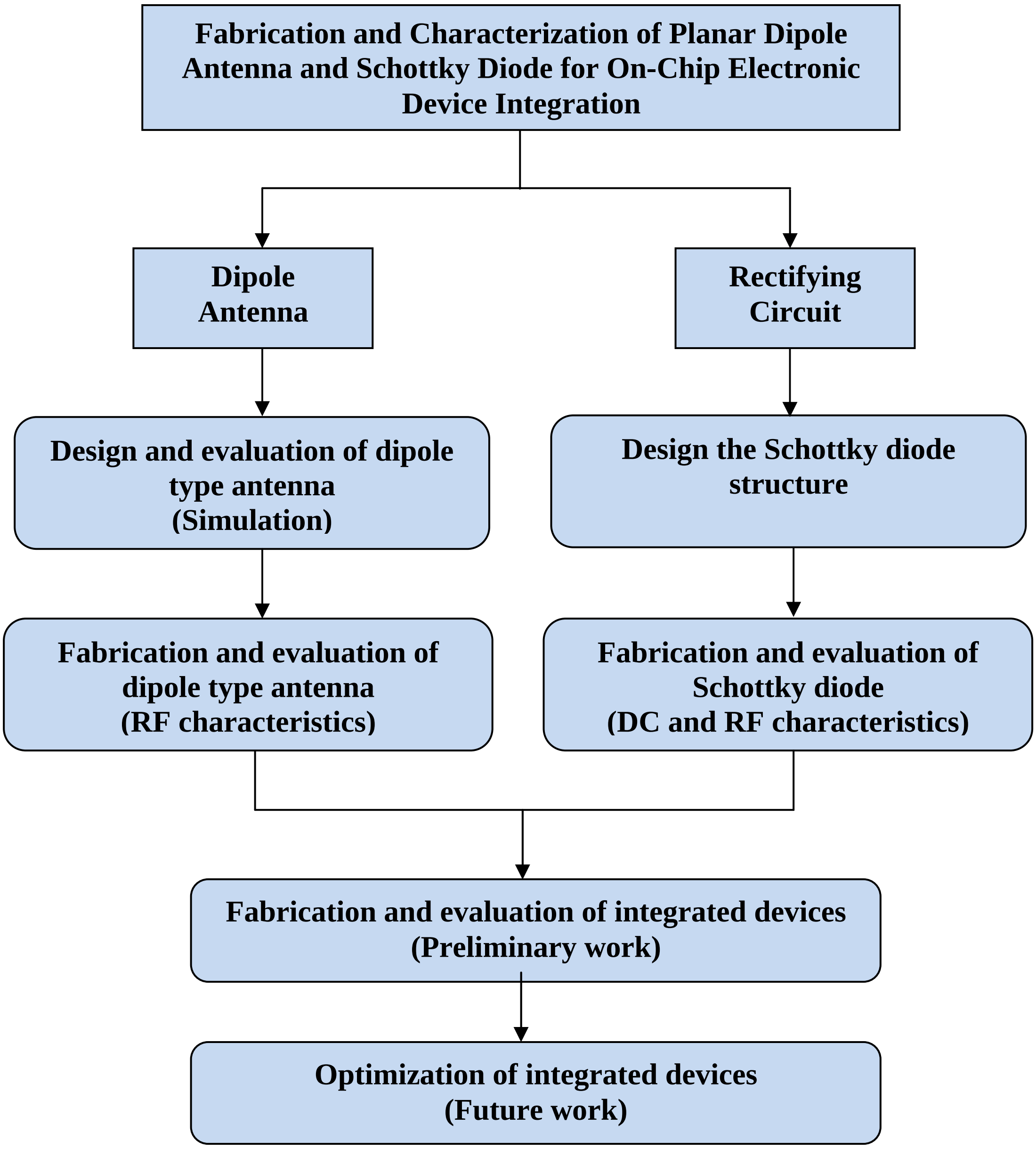

Figure 1.2: Research activities.

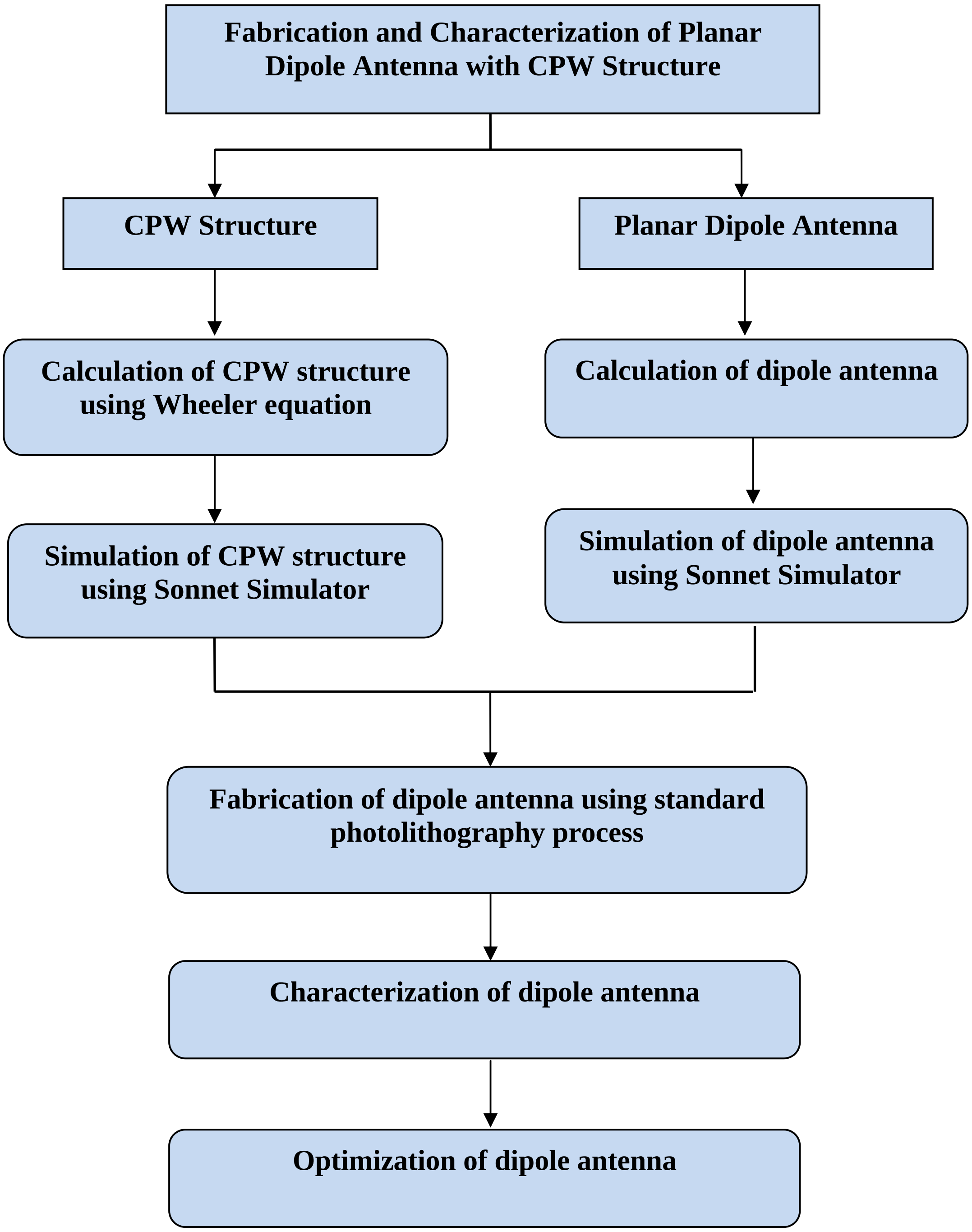

Figure 1.3: Research flow of planar dipole antenna.

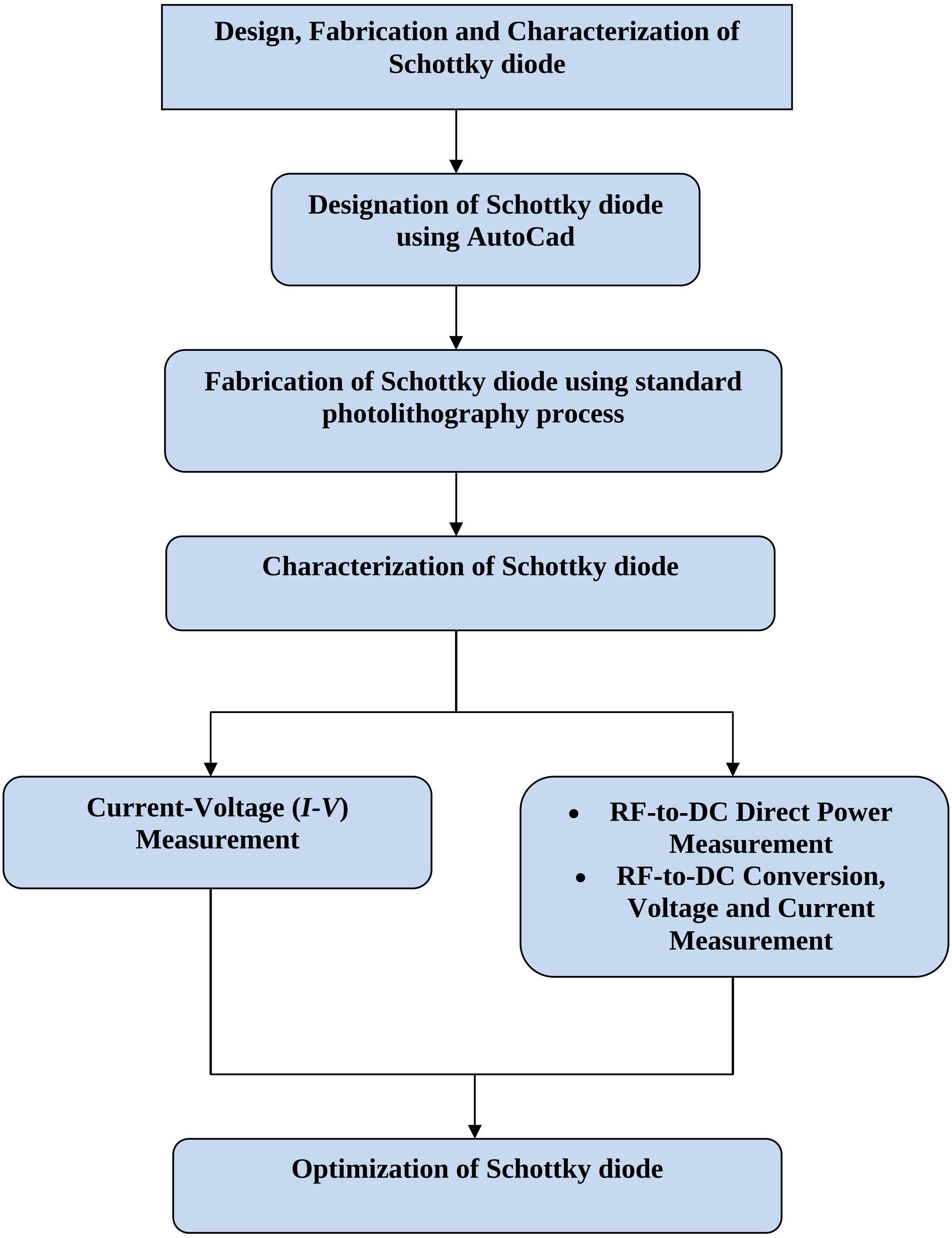

Figure 1.4: Research flow of Schottky diode.

1.6 Overview of Thesis Organization

This thesis is organized into 7 chapters. Chapter 1 gives an overview of the research background, objective, scopes and research activities.

In Chapter 2, a brief discussion of unique applications of microwaves technologies is presented. The discussion of basic material for microwave technologies is also presented. This chapter also describes the basic concept and theory of planar dipole antenna and Schottky diode as the devices of microwave technologies. Furthermore, the fundamental of CPW structure are also discussed briefly.

In Chapter 3, mainly a discussion about the device fabrication and measurement technique is presented. In particular, this chapter describes the fabrication process for the dipole antenna, Schottky diode and integrated devices structure, and a measurement system. In this research, the fabrication of dipole antenna, Schottky diode and integrated devices is carried in clean room facilities. The major fabrications involved are photolithography, wet chemical etching, metal deposition and a standard lift-off technique. In addition, the semiconductor material structure for the devices also discussed briefly.

In Chapter 4, the RF characteristics of planar dipole antenna facilitated with CPW structure in millimeter-wave region is described. The dependence of fundamental resonant frequency of the dipole antenna on the antenna's width, length and metal thickness is presented. Basically, the characteristics of reflection or return loss are measured.

In Chapter 5, the DC and RF characteristics of Schottky diode on *n*-AlGaAs/GaAs HEMT structure are presented. The feasibility for direct integration planar dipole antenna with Schottky diode via CPW transmission line without insertion of any matching circuit for fast conversion of RF signals in nanocircuits and nanosystems to avoid circuit failure and also to apply ultra-low DC current to generate those other on-chip nanodevices are presented.

In Chapter 6, the preliminary experimental results of integrated dipole antenna and Schottky diode fabricated on an *n*-AlGaAs/GaAs HEMT structure which should lead a new breakthrough for on-chip electronic device application in nanosystem is presented. From the obtained results of the dipole antenna and Schottky diode that presented in previous section, it is expected that direct integration via short CPW transmission line between dipole antenna and Schottky diode can be achieved without any matching circuit.

Finally, Chapter 7 concludes the contribution of present work and the directions of future work.

There are some appendices which present detail information regarding to this research.