

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

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ANTENNA FOR APPLICATION IN PROXIMITY COMMUNICATION SYSTEM

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*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.*

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## 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 berpotensi 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.

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**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 <sub>2</sub> O	–	Water
H <sub>2</sub> O <sub>2</sub>	–	Hydrogen Peroxide
H <sub>2</sub> SO <sub>4</sub>	–	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 <sub>2</sub>	–	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

$^{\circ}C$	–	Degree Celsius
$K$	–	Kelvin
$\mu_e$	–	Mobility of Electron
$\mu A$	–	Microampere
$\mu m$	–	Micrometre
$\text{\AA}$	–	Angstrom, $1 \text{\AA} = 1 \times 10^{-10} \text{ m}$
$a$	–	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
$\eta$	–	Conversion efficiency
nA	–	Nanoampere
$N_d$	–	Donor doping concentration
nm	–	Nanometre
$\phi_B$	–	Barrier height
$\phi_m$	–	Metal work function
$\phi_s$	–	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
$\epsilon_{eff}$	–	Effective dielectric constant
$\epsilon_r$	–	Dielectric constant
$\epsilon_s$	–	Permittivity of the semiconductor
$\lambda$	–	Wavelength
$\chi$	–	Electron affinity
$\Omega$	–	Ohm

**LIST OF APPENDICES**

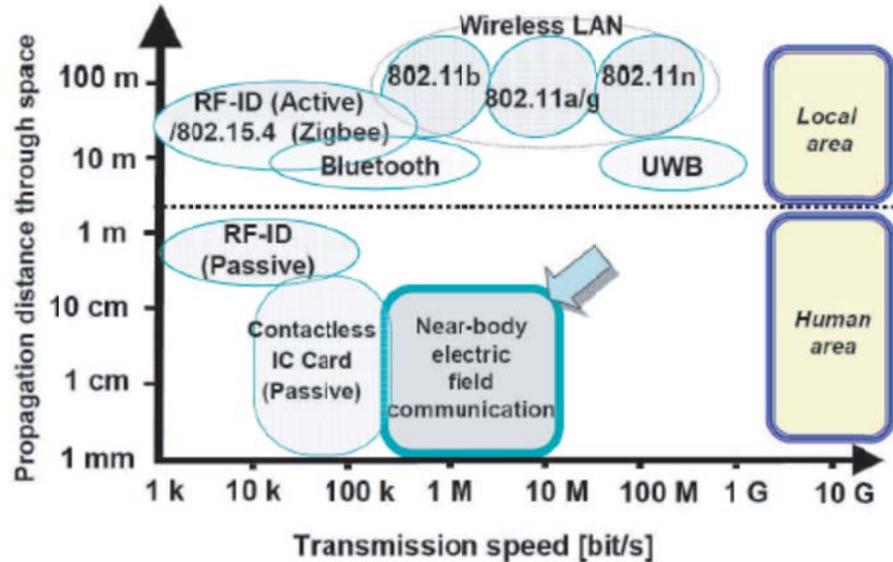
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## CHAPTER 1

### 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 al.* [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  $\Omega$ . 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 k $\Omega$ . 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

<b>Integration of discrete device</b>	<b>Planar on-chip integration</b>
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

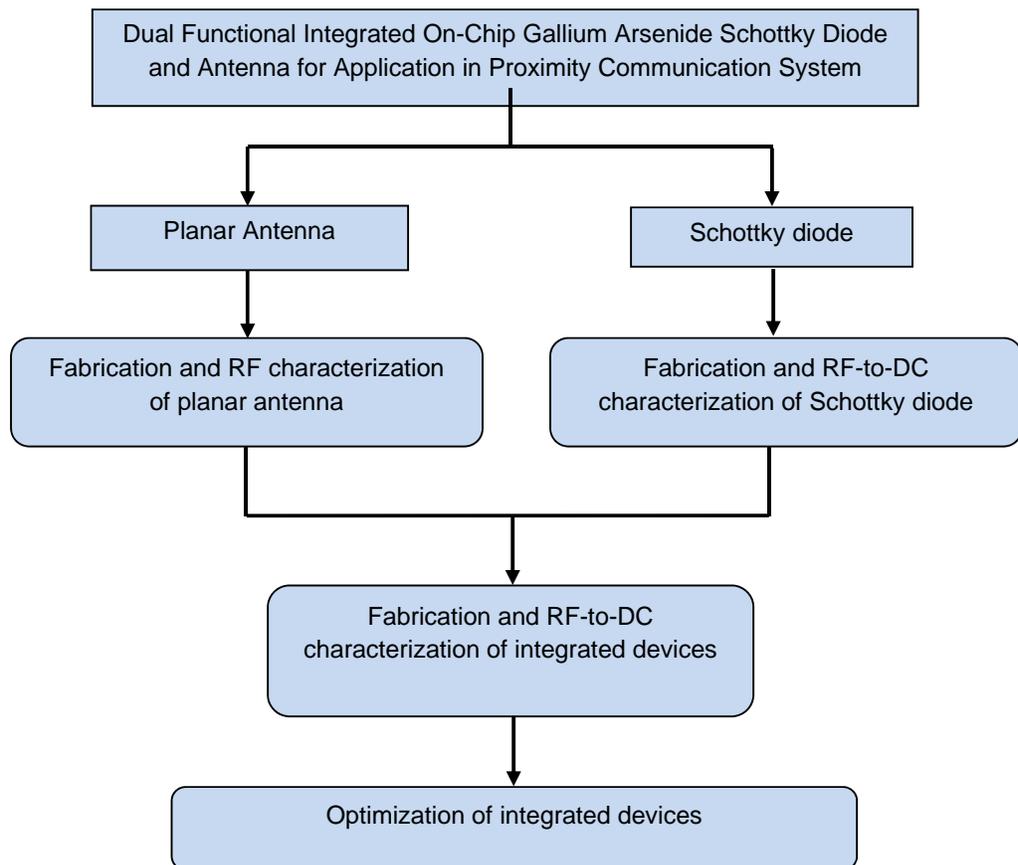
Hypothesis of the research are as follows;

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.

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