DESIGN AND SIMULATION OF InGaAs-BASED PLANAR ELECTRONIC NANODEVICES AS TERAHERTZ RECTIFIERS BASED ON CURVATURE COEFFICIENT ANALYSIS

by

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LIST OF ABBREVIATIONS

2D	Two-Dimension
2-DEG	Two-Dimensional Electron Gas
AC	Alternating Current
DC	Direct Current
FET	Field Effect Transistor
GD	Geometric Diode
IC	Integrated Circuit
InAlAs	Indium Aluminum Arsenide
InGaAs	Indium Gallium Arsenide
IoT	Internet of Things
ISM	Industrial, Scientific, and Medical
MMIC	Monolithic Microwave Integrated Circuit
PBD	Planar Barrier Diode
PDBD	Planar-Doped Barrier Diode
RF	Radio Frequency
SSD	Self-Switching Diode
SWaP-C	Size, Weight, Power and Cost
BW	Bandwidth
CMOS	Complementary Metal–oxide–semiconductor
FET	Field Effect Transistor
UHF	Ultra-high Frequency
ZnO	Zinc Oxide
ITO	Indium Tin Oxide
SOI	Silicon-on-insulator
MFPL	Mean Free Path Length
MTJ	Magnetic Tunnel Junction
PPBD	Planar-doped Potential-well Barrier Diode
MC	Monte Carlo
NEP	Noise Equivalent Power
InP	Indium Phosphide
AlGaAs	Aluminum Gallium Arsenide

AlGaSb	Aluminum Gallium Stibium
AlGaN	Aluminum Gallium Nitride
P3HT	Poly(3-hexylthiophene)
MOS_2	Molybdenum Disulfide
SST	Self-Switching Transistor
TCAD	Technology Computer-Aided Design
THz	Terahertz

LIST OF SYMBOLS

A	Amplitude
A^*	Richardson constant
C	Capacitance
D	Diffusion coefficient
E	Electric field
$f^{(1)}$	First derivative of I-V
$f^{(2)}$	Second derivatives of I-V
f_c	Cut-off frequency
G_n	generation rates
I_{fwd}	Forward current
I_{leak}	Leakage current
J	Current density
k	Boltzmann constant
L	Channel Length
q	Couloumb’s constant
Q_p	Area density of ionized acceptors
R_n	Recombination rates
R_s	Series resistance
S_n	Flux of energy
T	Temperature
V_{th}	Threshold voltage
W	Channel width
W_t	Trench width
W_v	vertical width of the device
β	Current responsivity
γ	Curvature coefficient
θ	Angle, Angle of inclination
μ_n	Electron mobilities
ϕ	Energy barrier

Rekabentuk Dan Penyelakuan Peranti Nanoelektronik Satah Berasaskan InGaAs Sebagai Penerus Terahertz Berdasarkan Analisis Pekali Kelengkungan

ABSTRAK

Frekuensi "Sela Terahertz" antara 0.1 hingga 10 THz mempunyai karektiristik-karektiristik unik dengan banyak kebaikan aplikasi dalam pelbagai bidang seperti imbasan selamat, perubatan, dan pengesan bahan letupan. Tetapi, bilangan pengesan dan punca optimum (sambutan arus, $\beta > 3.5$ V^{-1}) yang terhad dalam kawasan ini memberi hanya sedikit alternatif untuk penyelidik mengeksplorasi kawasan ini. Dalam kajian ini, pencirian menggunakan penyelaku peranti ATLAS Silvaco bertujuan untuk meningkatkan prestasi β pada Diod Pensuisan-Sendiri (DPS) dan penyelakuan peranti-peranti satah baru; Diod Sawar Satah (DSS) dan Diod Pensuisan-Sendiri Sawar Satah (DPSSS) telah dilaporkan. β banyak disumbangkan oleh satu parameter yang dikenali sebagai pekalikelengkungan, γ yang diperoleh daripada kelakuan arus-voltan (A-V) peranti tersebut. Dengan itu, γ telah dianalisa dalam kajian ini, bukan sahaja dengan mengubah struktur geometri peranti, malah dengan melaksanakan kebertelusan dielektrik yang berlainan pada bahan penebat dengan julat 1.0 – 10 dibawah julat suhu 300 – 600 K. Keputusan telah menunjukkan peningkatan suhu telah merendahkan prestasi penerusan DPS dan DSS disebabkan oleh arusbalikan yang boleh merosotkan ciri ketaklelurusan A-V peranti tersebut. Untuk DPS, γ pada ~32 V^{-1} dan 30 V^{-1} telah dicapai, masing-masing pada 30 mV dan tanpa-pincang. Frekuensi potong, f_c bagi DPS dalam kajian ini diperoleh pada ~80 GHz, beroperasi pada kondisi tanpa pincang. Tambahan lagi, peningkatan sawar telah diperkenalkan pada peranti DSS baru, yang mana telah menyumbang kepada kelajuan pensuisan yang lebih tinggi dalam saluran. Prinsip operasi DSS yang baru ini dijelaskan menggunakan teori pancaran ion haba. Dengan mengaplikasi parameter struktur yang optimal, γ tanpa-pincang sebanyak ~4 V^{-1}, dengan puncak ~14V^{-1} pada 0.10 V telah dicapai. Dengan pincang AT 50 mV untuk mengeksploitasi puncak, frekuensi potong DSS telah dicapai pada 270 GHz. Tambahan lagi, struktur bersepadu DPSSS menunjukkan keputusan lebih baik dalam f_c dengan pengesanan pada 360 GHz pada tanpa-pincang. γ tanpa-pincang sebanyak ~6 V^{-1}, dengan puncak ~19 V^{-1} pada pincang 70 mV telah dilihat pada DPSSS. $\beta > 3.5$ V^{-1} dalam kesemua peranti yang diselaku menunjukkan keupayaan penukaran optimum sebagai suatu peranti penerus. Keputusan yang diperoleh dalam kajian ini membuktikan kefungsian DPS sebagai penerus gelombang-mm, dan peranti-peranti baru DSS dan DPSSS sebagai penerus THz dan kelak boleh membantu dalam penambahbaikan peranti-peranti tersebut.

Design and Simulation of InGaAs-Based Planar Electronic Device as Terahertz Rectifier Based on Curvature Coefficient Analysis

ABSTRACT

The “Terahertz gap” frequencies between 0.1 to 10 THz possess unique characteristics with a lot of promising application in various fields such as safe imaging, medical and explosive detections. However, limited numbers of optimal (current responsivity, $\beta > 3.5$ V^{-1}) detectors and sources in this region leave researchers only a few alternatives in exploring the region. In this work, characterizations using ATLAS device simulator aimed to increase β performance of Self-switching Diode (SSD) and simulations of new planar devices; the Planar Barrier Diode (PBD) and Self-switching Planar Barrier Diode (SSPBD) are reported. The β is mainly contributed by a parameter known as the curvature coefficient, γ which is derived from the current-voltage (I-V) behavior of the device. As such, the γ was analyzed in this work, not only by varying the device’s geometrical structure, but also by implementing different dielectric relative permittivity of the insulating material ranging from 1.0 – 10 under temperature range of 300 – 600 K. The results showed that increased temperature degraded the SSD’s and PBD’s rectifying performance due to increased reverse current which can deteriorate the nonlinearity of the device’s I-V characteristic. For SSD, the γ of ~32 V^{-1} and 30 V^{-1} has been achieved at 30 mV and zero-bias, respectively. The cut-off frequency, f_c of SSD attained in this work was ~80 GHz, operating at unbiased condition. In addition, an enhanced barrier is introduced in the new PBD device, which contributed to higher switching speed in the channel. The working principle of the new PBD is explained using thermionic emission theory. By employing the optimized structure parameters, the zero-bias γ of ~4 V^{-1}, with peak of ~14 V^{-1} at 0.10 V bias were achieved. With DC bias of 50 mV to exploit the rectification peak, the f_c of the PBD was attained at 270 GHz. In addition, hybrid structure of SSPBD shows improved performance in f_c with detection of 360 GHz at zero-bias. Zero-bias γ of ~6 V^{-1}, with peak of ~19 V^{-1} at 70 mV bias were observed in the SSPBD. The β of >3.5 V^{-1} in all simulated devices indicates optimal conversion ability as a rectifying device. The results obtained in this work proved the functionality of SSD as mm-wave rectifiers, and the new devices of PBD and SSPBD as THz rectifiers and may assist in future improvement of the devices.

CHAPTER 1 INTRODUCTION

1.1 Introduction

The “Terahertz gap” (THz gap) refers to the region of the electromagnetic spectrum from 0.1 to 10 THz (Shim, Mao, Sankaran & O, 2011) which has been almost inaccessible because of the sources and detectors limitations, until recent decades where the interests in developing efficient, low cost and small sizes detectors in this region grows (Minamide, 2015; Lewis, 2014). The advancement into this gap which is the frequency gap for practical electronic and photonic applications has also been given high attention because of its own unique characteristics; (1) the ability to penetrate through a wide variety of dielectric materials, (2) have minimal effects on the human body (non-ionizing effects), (3) has a very large absorption due to water, and (4) has a very high reflection on metals (Garbacz, 2016).

Due to these characteristics, THz technologies are highly explored in various fields such as imaging, radio astronomy, environment control, medicine, and explosive detection. THz imaging for example is suitable and highly explored for many biomedical applications, because the non-ionizing character of THz radiation makes it less harmful to living tissue compared to X-ray. Apart from that, THz radiations are highly applicable for medical field applications including cancer diagnosis (Yu, Fan, Sun, & Pickwell-MacPherson, 2012), and identification of dental caries (Leiss-Holzinger et al., 2015). The interaction of THz radiation with molecules of water can be utilized in applications such as inspection of water contents in materials (Gente & Koch, 2015; Gorenflo et al., 2006).

In addition, many of chemical and biological materials have unique spectral fingerprints in the THz range which can be used for identification and detection of contamination in materials, as well as for detection of concealed weapons and explosive in the field of defense and security (Liu, Zhong, Karpowicz, Chen, & Zhang, 2007).

The vast majority of research works in such applications are mostly dependent upon the availability of THz detectors and sources. That is why interest in the THz research activities up to now have been devoted to the generation and detection of THz radiation technique development. The interests in developing efficient, low cost and small sized detectors in this region just started in the last decades, simultaneously escalates the exploration and researches on the application in the THz region (Hiroaki, 2015; Lewis, 2014; Mittleman, 2013). Furthermore, the capability of the rectifying diodes to be used in this region needed to be carefully examined to ensure that the electron transport in the device can cope with the high transition rate between the positive and the negative cycles. It is this purpose that set the direction of the work presented in this thesis. The development of InGaAs based planar nano-devices may assist to offer alternative devices for contribution as a detector in this THz gap region.

1.2 Research Background

Because of the RC time constant limitation, the use of plate diodes as rectifier is not suitable for this high frequency application, and conventional used of pn junction semiconductor diodes in high frequency region are also irrelevant because of the phase lag caused by the slower transition of the minority carriers (Mishra & Singh, 2008). Hence, unipolar or majority carrier devices are more useful to be utilized as high frequency diode detectors. Research on improving solid-state diode detectors to function as high frequency detectors have been extensively conducted by researchers. The results in term of current responsivity, β and cut-off frequency, f_c can be used to determine the performance of the diodes.

Early solid-state diode detectors started with Schottky diode in 1968 which is the improved version of earlier cat whisker diode detector. This diode has been researched and improvised over years, and with optimization in the junction resistance, highest f_c of the Schottky diodes have been detected at 3.4 THz (Hajo, Al-Daffaie, Yilmazoglu, Haidar & Kuppers, 2017; Jingtao, Chengyue, Ji & Zhi, 2013) with maximum β at 19.4 V^{-1} because of its thermal voltage limitation. Esaki tunnel diode is introduced later (1974), and the comeback of tunnel diode as backward tunnel diode in 2015 which utilizes the more conductive negative bias current had a high current responsivity, β with highest value recorded of -24.7 V^{-1} at 94 GHz (Takahashi, Sato, Nakasha, & Hara, 2015). Miwa et al. (2014) has introduced spin diode with highest β of ~2.1 V^{-1} at 1.6 GHz while highest current responsivity of 10.6 V^{-1} at a bias of 0.72 V and f_c of 47.4 GHz were realized in planar-doped barrier diode (Akura, Dunn & Missous, 2017), and recent introduced Geometric diode (GD) using inverse arrow-head shaped graphene layer on Si/SiO2 substrate had obtained a detection at 29.8 THz with better current responsivity of 1.646 V^{-1}. Mestizo et al. (2016) shows L-shaped Self-switching Device (SSD) with current responsivity of 9.6 V^{-1}. The f_c of the device is not mentioned in the report, but highest f_c of 1.5 THz has been experimented in room temperature by Balocco et al. (2011), with highest at 2 THz by simulation (Mateos et al., 2005), both not reporting on the performance of β. The SSD and the GD has a unique structure where it requires only one-step lithography process on the substrate to create the channel in the device.

1.3 Problem Statement

The scarce numbers of detectors and sources that can optimally function in the THz gap region leave a few alternatives for the usage in the THz technology applications. Often in most devices, the performance of β and f_c is in mutual opposite, in which if one is going higher the other one goes lower. Nonetheless, for an optimal conversion, an effective rectification performance with β above 3.5 V^{-1} is desired (Periasamy et al., 2011). However, the performance of β in most high frequency detectors are low such as in GD and spin diode. Device with optimal β performance, however is not in the THz gap frequencies such as backward tunnel diode, leaving only Schottky diode as the suitable candidate that can function in the region. SSD in the other hand, shows a good β performance in one report, and high THz gap detection in other reports, and none has reported on both performances.

The performance of β can be indicated by the curvature coefficient, γ where $\beta = \gamma/2$. This γ defined as the ratio of $f^{(2)}$ to $f^{(1)}$ where $f^{(1)}$ and $f^{(2)}$ are the first and second order derivatives of the device's I-V function, respectively. By deliberate alteration on the parameters that affected the I-V, the γ can be calculated and optimized to achieve desired value of β in the simulated devices. Thus, in this work γ analysis is implemented, first to evaluate and optimize the performance of the SSD (which both parameters had not collectively concluded), and then to propose alternative devices optimally functional in the THz region.

1.4 Research Objectives

This research is aiming to develop functional devices to rectify AC signal in the mm-wave region with the following objectives:

- To increase the rectification performance, β of existing detector (SSD) of 9.6 V^{-1} by using γ analysis.
- To simulate a new asymmetrical planar rectifying device (PBD) as THz diode detector functioning in the range of 0.1 to 10 THz which can achieve functional β of minimum 3.5 V^{-1} at zero-bias by using γ analysis.
- To propose and simulate a hybrid device of SSD and PBD which can achieve functional zero-bias β of minimum 3.5 V^{-1} at zero-bias in a higher THz frequency than SSD/PBD.

1.5 Research Scopes

The evaluation of the behaviours and performances of these rectifying devices will be based on simulation using Silvaco Technology Computer-Aided Design (TCAD) simulator on $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ substrate devices, and the rectification performance is based on the curvature coefficient, γ analysis. The performance of β will also be evaluated both at the peak, and at zero-bias to optimally utilize the advantages of the zero-bias region. Since the aim is to serve as THz detector, the performance at zero-bias will not be compared to other zero-bias detectors functioning in lower frequencies, but is compared to the performance of the diodes (Schottky diode) that functioned in the same region.

Various parameters will be used and varied to alter the I-V characteristics. Variation of geometrical parameters in each device will be different based on the parameters that most affected the I-V characteristic of each device. Note that the parameters included in final optimized design will includes only the parameters variation of geometrical structure to simplify future fabrication complexity.

It is worth to note that this research is aiming for detection of signals for electronics purposes, thus the work is aiming for the detection in the region below the infrared of 10 THz frequency for electronic application. Rectification at higher THz frequencies (infrared region of >10 THz) for optical application has been widely researched using optical rectenna (Grover & Moddel, 2011; Xia, Datta & Forrest, 2005).