DESIGN, FABRICATION AND CHARACTERIZATION OF CAPACITIVELY COUPLED GALLIUM ARSENIDE-BASED INTERDIGITAL-GATED PLASMA DEVICES

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

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ABSTRACT

In the recent years, solid-state terahertz (THz) devices to fill the so-called "THz" gap have become a hot topic. Since the transit-time effect is so severe in this frequency range for conventional devices, one possibility is to utilize traveling wave interaction in semiconductor plasma. The theoretical results on the interactions of plasma wave with the EM space harmonic slow wave generated by interdigital slow-wave circuits indicated the occurrence of negative conductance in two-terminal interdigital admittance when the carrier drift velocity slightly exceeds the phase velocity of the fundamental component of the EM waves. Experimental studies in microwave region using DC-connected interdigital gate structure are carried out and plasma wave interactions are successfully confirmed. However, the negative conductance is not obtained due to the non-uniformity of electric field distribution under such interdigital gate structure. This work presents an analysis including the newly proposed AlGaAs/GaAs HEMT plasma device with capacitively coupled interdigital gate structure. This structure is introduced in order to produce uniform field distribution and thus produce uniform drift velocity along the channel. The interdigital fingers are designed and fabricated on AlGaAs/GaAs HEMT substrate. The carrier mobility and the carrier sheet density of AlGaAs/GaAs HEMT structure obtained by Hall measurements at room temperature is 6040 cm^2/V-s and 8.34 x $10^{11}/cm^2$, respectively. Theoretical analysis of potential distribution in the interdigital-gated HEMT plasma wave device is carried out. The DC *I–V* characteristics of capacitively coupled interdigital structure showed that uniformity of electric field under the interdigital gates is improved compared to the DC-connected interdigital gate structure. Admittance measurements of capacitively coupled interdigital gate structure in the microwave region of 10–40 GHz showed the conductance modulation by drain–source voltage. This absolutely can be explained in terms of interactions between the input RF signals and 2DEG surface plasma waves. Absolute conductance values are smaller than the theoretical prediction, due to the small capacitance between interdigital fingers attenuating the propagation of RF signal at these frequencies. These results indicate the existence of plasma wave interactions. Further optimization of device structure and measurement method may lead to the occurrence of negative conductance.

ABSTRAK

Penggunaan peranti keadaan-pepejal terahertz (THz) dalam kawasan "THz" telah menjadi isu yang sering diutarakan sejak kebelakangan ini. Oleh kerana kesan masa-alihan begitu teruk dalam julat frekuensi ini bagi peranti konvensional, satu kemungkinan adalah disebabkan oleh interaksi gelombang bergerak semikonduktor dalam plasma. Keputusan yang diperolehi secara teori, pada interaksi antara gelombang plasma dengan ruang gelombang EM harmonik yang dihasilkan oleh litar gelombang perlahan antara digit, konduksian negatif di dua terminal admitan antara digit ditunjukkan ketika kelajuan hanyut pembawa melebihi sedikit kelajuan fasa komponen gelombang asas EM. Kajian secara eksperimen di kawasan mikrogelombang menggunakan struktur get-antara digit tersambung-DC dan interaksi gelombang plasma telah berjaya dilakukan. Namun, konduksian negatif tidak diperolehi kerana edaran medan elektrik yang tidak seragam pada struktur get antara digit. Tesis ini membincangkan tentang analisis termasuk cadangan peranti baru AlGaAs/GaAs HEMT plasma terganding-kapasitif dengan struktur get antara digit. Struktur ini diperkenalkan untuk menghasilkan taburan medan seragam dan seterusnya menghasilkan halaju hanyut seragam sepanjang saluran. Struktur jari antara digit direka dan difabrikasi di atas substrat AlGaAs/GaAs HEMT. Kelincahan pembawa dan ketumpatan kepingan pembawa AlGaAs/GaAs struktur HEMT diperolehi melalui pengukuran Hall pada suhu bilik adalah 6040 cm^2/V-s dan 8.34 x $10^{11}/cm^2$. Analisis teori tentang taburan keupayaan pada peranti get-antara digit HEMT gelombang plasma dilakukan. Ciri-ciri DC *I-V* struktur terganding-kapasitif get antara digit menunjukkan bahawa keseragaman medan elektrik di bawah get antara digit lebih baik berbanding dengan get antara digit tersambung-DC. Pengukuran admitan untuk struktur terganding-kapasitif get antara digit di kawasan mikrogelombang pada 10-40 GHz menunjukkan perubahan konduktans oleh voltan salir-punca. Ini dapat dijelaskan dalam bentuk interaksi antara isyarat input RF dan gelombang permukaan plasma 2DEG. Nilai mutlak konduksian adalah lebih kecil daripada anggaran teori, kerana nilai kapasitif yang kecil di antara jari-jari antara digit mengecilkan perambatan isyarat RF pada frekuensi-frekuensi ini. Keputusan telah menunjukkan bahawa adanya interaksi gelombang plasma. Pengoptimuman lanjut pada struktur peranti dan kaedah pengukuran boleh membawa kepada kehadiran konduksian negatif.

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LIST OF ABBREVIATIONS

2DEG - Two Dimensional Electron Gas
A/D - Analog to Digital
Al - Aluminium
AlGaAs - Aluminium Gallium Nitride
Au - Aurum
BHF - Buffered Hydrofluoric Acid
Cr - Chrome
Cu - Copper
CVD - Chemical Vapour Deposition
D/A - Digital to Analog
DI - De Ionized
EBS - Electron Beam Sputtering
EM - Electromagnetic
FET - Field Effect Transistor
GaAs - Gallium Arsenide
GaN - Gallium Nitride
Ge - Germanium
G-S-G - Ground Signal Ground
H_2O_2 - Hydrogen Peroxide
H_2SO_4 - Sulfuric Acid
HCl - Hydrochloric Acid
He - Helium
HEMT - High Electron Mobility Transistor
HFET - Heterostructure Field Effect Transistor
IC - Integrated Circuit

LED - Light Emitting Diode

MEK - Methyl Ethyl Ketone

MIM - Metal Insulator Metal

MMIC - Monolithic Microwave Integrated Circuit

MOS - Metal Oxide Semiconductor

N_2 - Nitrogen

NH_3 - Ammonia

Ni - Nickel

PECVD - Plasma Enhanced Chemical Vapor Deposition

RF - Radio Frequency

RTA - Rapid Thermal Annealing

Si - Silicon

Si_3N_4 - Silicon Nitride

SiH_4 - Silane

SiO_2 - Silicon Dioxide

SSTWA - Solid State Traveling Wave Amplifier

THz - Terahertz

TWT - Traveling wave tube

VCC - Voltage Coefficient Capacitance

LIST OF SYMBOLS

$2D$ - 2 dimensional

A - Ampere

$\mathring{A}$ - Angstrong

a - Finger width and spacing

b - Thickness of AlGaAs barrier layer

eV - Electron Volt

h - Plank constant

h - Thickness of semi-insulated GaAs substrate

K - Kelvin

P - Pitch

V - Voltage

W - Channel width

Z - Impedance

Γ - Reflection coefficient

δ - Delta

ε - Dielectric constant

Ω - Ohm

CHAPTER 1

INTRODUCTION

1.1 Research Background

In the recent year, solid-state devices operating in the so-called “Terahertz (THz) gap” region of electromagnetic (EM) waves are highly demanded for possible applications in advanced information technology (IT), biochemistry, nanotechnology and so on. Terahertz frequencies, somewhat loosely defined as those in the range 100 GHz-10 THz, form a significant region in the electromagnetic spectrum that has not yet been opened up for commercial exploitation. The main reason for this is the virtual absence in this frequency range of reliable, low cost, miniaturized solid-state power source. Related to this is the fact that the technology for the fabrication of the necessary passive component is also not well developed.

Being motivated by the tremendous success of vacuum travelling wave tubes (TWT), the possibilities of obtaining an extremely large amplification of electromagnetic waves by utilizing a coupling between drifting carriers in semiconductor and electromagnetic waves propagating in slow-wave circuits were theoretically explored [1-3]. Some innovative experimental work was also carried out to realize a solid-state traveling wave amplifier (SSTWA) [4-5]. All of this work was done in the 1960s and 1970s when the semiconductor technology was still poor.

These activities faded out without remarkable success mainly due to the strongly collision-dominant nature of semiconductor plasma as compared with electrons flowing in vacuum. Due to significant progress in semiconductor material and device technologies, frequencies handled by semiconductor devices have been remarkably enhanced, approaching THz frequencies where transit time limitation of conventional devices now imposes very severe limitations on the frequency and power capabilities of devices.

With this background, the traveling wave concept has been reintroduced recently in the THz detector developed by Dyakonov and Shur [6]. They proposed the use of plasma waves supported by a non-drifting two-dimensional electron gas (2DEG) with an AlGaAs/GaAs heterostructure under a metal gate. Recently, they reported a theoretical transverse magnetic (TM) mode analysis of the behaviour of surface waves in bulk and 2DEG semiconductor plasma under drifting condition [7-9]. The theoretical results of their analysis on the interactions of plasma waves with EM slow waves produced by interdigital slow-wave circuits indicated the occurrence of negative conductance in two-terminal interdigital admittance, when the carrier velocity slightly exceeds the phase velocity of the fundamental component of the EM waves from microwave region up to THz region.

These negative conductance characteristics should lead to the realization of SSTWA. The theoretical results also show that the interactions are more favourable in the THz region by the increasing of negative conductance magnitude. The presence of interactions between carrier plasma waves in a 2DEG at AlGaAs/GaAs heterostructure and EM slow waves was successfully observed in the microwave region using the proposed interdigital-gated high electron mobility transistor (HEMT) plasma devices and agreed very well with the theoretical results. However, the predicted net negative conductance was not observed due to the nonuniformity of electric field under the interdigital slow wave circuit.

In this project, both theoretical and experimental studies will be continuously developed. An improved structure of a slow-wave circuit will be proposed and studied, which should improve the uniformity of electric field under the interdigital slow-wave circuit. All fingers are capacitively coupled by introducing Si_3N_4 layer while fingers of previous structure are directly connected.

III-V semiconductor is the best material to be used due to its high electron mobility and also high electron peak velocity can be achieved with low electric field which should lead to the realization of a device with large power conversion effectiveness and high operation frequency. Furthermore, by applying n-AlGaAs/ GaAs heterostructure, the drifting electrons are confined in the 2DEG layer where the diffusion loses due to electromagnetic wave component known as quasi-solenoidal wave can be reduced.

It is possible to utilize such surface plasma wave interaction mode in semiconductors which should lead to a realization of solid-state devices operating in THz gap in near future by the establishment of accurate theoretical approach and proper device design supported by remarkable progress semiconductor technology.

1.2 Objective of this work

In this study, a design, fabrication and characterization a capacitively coupled interdigital-gated structure in order to improve the interaction between electromagnetic waves and carrier plasma waves in semiconductor are carried out. This structure is expected may lead to the phenomena of negative conductance.

1.3 Scopes of Research

The scopes of this research can be summarized as follows:

i. Fabrication of improved interdigital-gated structure by introducing thin dielectric layer with high dielectric permittivity value, which will form the metal-insulator-metal (MIM) capacitor structure.

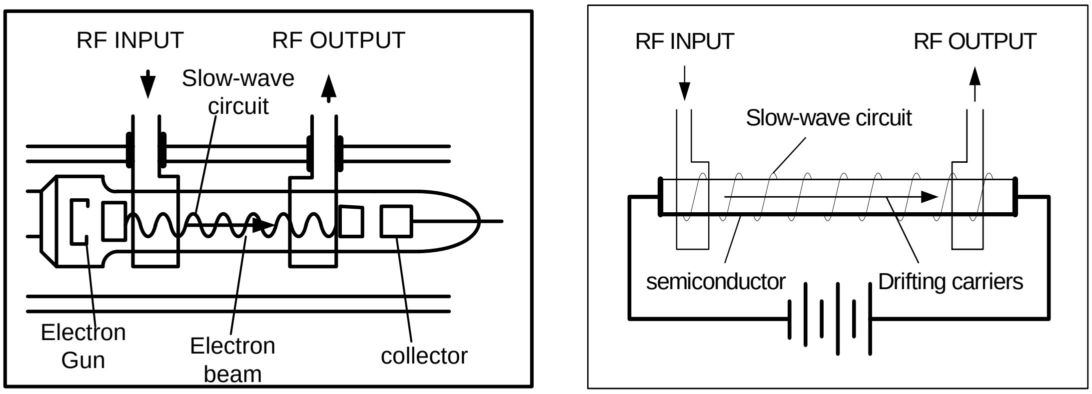
ii. The results obtained by this structure will be compared with the previous DC-connected structure in terms of:

   a. Electric field distribution in the channel by evaluating the DC *I*-*V* characteristics. The threshold voltage should shift to higher value or ideally, no pinch off for capactively-coupled structure.
   b. The conductance modulation should begin at low voltage, meaning that the drift velocity is improved.
   c. The observation of negative conductance.

1.4 Research Motivation

From the view point of the conventional electron approach, to fill the THz gap seems to be very difficult due to the limitations of high frequency signal detection/amplification usually come from carrier transit times where extremely small feature sizes are required for operation in sub-millimeter (sub-mm) frequency region [1,2]. This tendency will result in the decreasing of output power. One way to overcome these limitations is to employ the traveling waves type approach like classical TWTs where no transit time limitation is imposed. The TWTs as schematically shown in **Figure 1.1(a)** are known as an amplifier of microwave energy. It accomplishes this through the interaction of an electron beam and a radio frequency (RF) circuit known as a slow-wave circuit. The term “slow-wave” comes from the fact that the RF wave velocity is much less than the speed of light as it travels down the circuit in free-space. As the electron beam travels down this interaction region, an energy exchange takes place between the particles and the RF circuit wave. One of the most important features of the slow-wave structure is that it must control the velocity of the RF wave such that it matches that of the beam. This is a characteristic known as synchronism and is very important to the operation of the traveling wave device.

Figure 1.1(b) shows a schematic of solid-state analog of TWTs. The coupling/interaction of carriers plasma waves and EM waves via slow wave structure leads to transferring of energy from carriers to EM waves due to the electric forces on the carriers and the induced charges on the slow wave structure [1-3]. The interaction principle of carrier plasma waves and EM waves is thought to be in the same manner with TWTs which can lead to the amplification of EM waves.



(a) (b)

Figure 1.1: (a) Schematic structure of TWT and (b) schematic of solid-state analog of traveling wave

1.5 Thesis Organization

This thesis is organized into 5 chapters. After this introduction, in chapter 2, the traveling wave tube approach and the importance of this approach these days in device applications are presented. Also, the basic properties of compound semiconductor which is AlGaAs/GaAs material used for this project and the importance of devices for the future by exhibiting present state of semiconductor device technology have been discussed.

In chapter 3, a theoretical three-dimensional TM mode analysis to describe the presence of interactions between surface plasma waves of carriers in a 2DEG at AlGaAs/GaAs heterostructure and electromagnetic space harmonics slow waves using the so-called interdigital-gated HEMT plasma wave devices is presented. Previous study on DC-connected interdigital gates is reviewed.

In chapter 4, the fabrication process and measurement setup for a capacitively coupled interdigital gates structure is presented.

Finally, chapter 5 concludes the contributions of present work and the directions of future work.

There are some appendices which present details procedure and some information about our research.