Photoconductive Terahertz Emitter

MTech Thesis

By

SUDHIR GILL

DEPARTMENT OF ELECTRICAL ENGINEERING

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Photoconductive Terahertz Emitter

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

of

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by

SUDHIR GILL

DEPARTMENT OF ELECTRICAL ENGINEERING

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Photoconductive Terahertz Emitter** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period from June 2023 to June 2024 under the supervision of Prof. Mukesh Kumar, Professor, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Gill
30/05/2024

Signature of the student with date
(Sudhir Gill)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

(Dr. Abhishek Singh) **(Prof. Mukesh Kumar)**

SUDHIR GILL has successfully given his/her MTech. Oral Examination held on **May 07,2024**.

Signature(s) of Supervisor(s) of MTech. thesis
Date: 28-05-2024

Convener, DPGC
Date:

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SUDHIR GILL

Dedicated to

My Father Shri Rajender Singh

Abstract

This thesis presents a comprehensive study on the optimization of terahertz emitters through various design modifications aimed at enhancing performance, reducing power consumption, and mitigating heating effects. The investigation focused on three distinct designs: one without an oxide layer, one incorporating an oxide layer, and the most advanced design integrating germanium on silicon.

The germanium on silicon design emerged as the superior configuration, demonstrating a remarkable reduction in dark current by up to 99%, resulting in a dark current of just 226 µA. This significant decrease in dark current led to improved power efficiency, minimized heating effects, and the capability to apply higher operational voltages, which collectively enhance the terahertz generation efficiency.

The simulation results confirmed that the germanium on silicon design is optimal for advanced terahertz emitters, effectively balancing low dark current, reduced heating, and enhanced terahertz output. This study provides a significant advancement in terahertz technology, presenting a practical and efficient solution for high-performance terahertz systems.

LIST OF PUBLICATIONS

Sudhir Gil, Prem Babu, Nikita Mohanta, Aasutosh Kumar, Abhishek Singh, and Mukesh Kumar, "**Optimized Design of Terahertz Emitter: Germanium Integration on Silicon Substrate**," **Optics Communications. June 10, 2024** (**Under Review**)

TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

ϵ	Dielectric Constant
λ	Wavelength
ω	Angular Frequency
μ	Permeability Constant
$\hbar$	Reduced Planck’s Constant
β	Propagation Constant
Φ	Phase Shift
E_F	Fermi Energy Level
K_o	Free Space Wave Number
ω_p	Plasma Frequency
e	Charge of the Electron
n_e	Electron Density
m_e	Effective mass of Electron
n_{eff}	Effective Refractive Index
L	Propagation Length
α	Transmission Coefficient
Q	Quality Factor
E	Electric Field Intensity
D	Density of States

Chapter 1

INTRODUCTION

1.1 The Terahertz Spectrum

The portion of the electromagnetic spectrum spanning from 100 GHz (3 mm) to 10 THz (30 µm) is known as THz radiation, the gap between millimeter and infrared frequencies. This spectrum range is referred to by various terms such as sub-millimeter, far infrared, and near millimeter wave. At a frequency of 1 THz, the corresponding signal has a wavelength of 300 µm in free space, a period of 1 ps, a photon energy of 4.14 meV, and a temperature equivalent of 48 K (where h is Planck's constant, f is frequency, and kb is Boltzmann's constant). The position of the THz band within the electromagnetic spectrum is illustrated in Fig. 1.1.

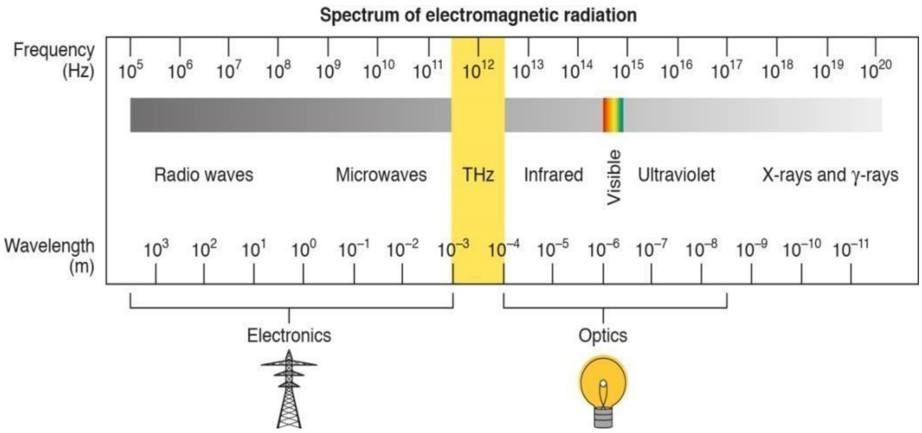

Figure 1. 1 Spectrum of electromagnetic radiation[1]

The THz region of the electromagnetic spectrum is relatively unexplored due to the lack of efficient, coherent, and compact sources and detectors. While devices operating in the microwave range, such as transistors or RF antennas, and those in the visible and infrared ranges, like semiconductor laser diodes, possess the necessary characteristics for their respective frequencies, these technologies are not suitable for the THz region because of significant power and efficiency reductions. Solid-state electronic devices, such as diodes, experience a power roll-off of $1/f^2$ at the lower end of the THz frequency range due to reactive-resistive effects and delayed transit times. Additionally, the absence of materials with sufficiently small band gap energies hampers the performance of optical devices like diode lasers in the THz range. This inadequacy has led to the term "THz gap," highlighting the underdeveloped nature of this band compared to neighboring spectral regions. Current research is focusing on new semiconductor-based emitters and detectors to bridge this gap. This chapter provides an overview of THz radiation, discussing its properties and applications, followed by a review and evaluation of various THz sources and detectors. This foundation sets the stage for outlining the research motivations and objectives of this thesis.

1.2 The Terahertz wave Properties and Application

Interest in the THz region dates back to the 1920s, but significant research efforts have only surged in the past three decades. The remarkable properties and vast potential applications of THz frequencies have spurred this renewed focus. Positioned between the microwave-millimeter and infrared regions, the THz band exhibits characteristics from both adjacent bands. Key properties of THz radiation include:

1. Penetration: THz wavelengths are longer than infrared wavelengths, resulting in reduced scattering and greater penetration depths (approximately centimeters) compared to infrared (approximately micrometers). As a result, THz waves can pass through dry, non-metallic materials that are opaque in the visible spectrum.

2. Safety: Unlike X-rays, THz radiation is non-ionizing due to its much lower photon energies.

3. Spectral Fingerprint: Many molecules exhibit inter- and intra-vibrational modes within the THz range, making it valuable for spectral analysis.

4. Resolution: THz waves have shorter wavelengths than microwave waves, providing better spatial imaging resolution.

These unique properties underscore the growing interest in the THz spectrum and its potential for diverse applications.

1.2.1 Atmospheric Characteristics of THz Waves

Compared to microwave and infrared waves, THz radiation unique atmospheric characteristics. Notably, THz waves experience substantial absorption in atmospheric conditions, especially in moist environments. Figure 1.2 illustrates the atmospheric attenuation across the electromagnetic spectrum, highlighting that signal degradation in the THz range, is significantly higher than in the microwave and infrared bands. This is primarily because THz signals are highly absorbed by water. Consequently, transmitting THz signals over long distances (greater than hundred meters) requires impractically high power.

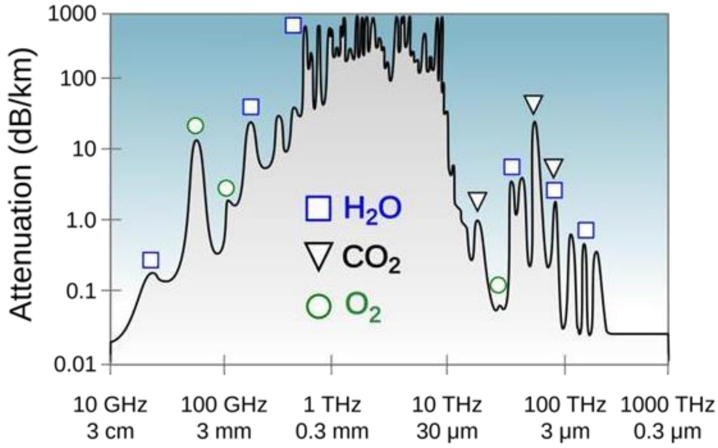

Figure 1. 2 Atmospheric attenuation of electromagnetic waves as a function of frequency and wavelength[2]

However, THz waves are beneficial in two specific scenarios:

1. In space, the near-vacuum conditions eliminate the issues of signal absorption and attenuation caused by water droplets. Additionally, the black body temperature range for THz signals (4.8-480 K) aligns with the majority of ambient radiation being THz waves. This makes THz technology valuable in radio astronomy and space science, particularly for observing the spectral signatures of interstellar dust in the THz region.

2. For short-range applications (typically less than 100 meters), atmospheric attenuation of THz signals is not a significant concern. Therefore, THz technology holds great promise fundamental research in various fields, such as chemistry and physics. Despite the negative impact of water vapour lines on THz signals, these lines are narrow and well-documented, allowing their effects to be mitigated or identified in THz applications like spectroscopy.

1.2.1 Applications of THz Radiation

1. **Medical Imaging and Diagnostics**: THz waves offer non-ionizing, high-resolution imaging capabilities, which are particularly advantageous in medical diagnostics. Unlike X-rays, THz radiation does not carry the risk of ionizing radiation, making it safer for frequent use. It is highly sensitive to water content and can differentiate between normal and cancerous tissues, aiding in early detection of skin and breast cancers. Additionally, THz imaging can visualize the hydration levels of tissues, providing insights into wound healing processes.

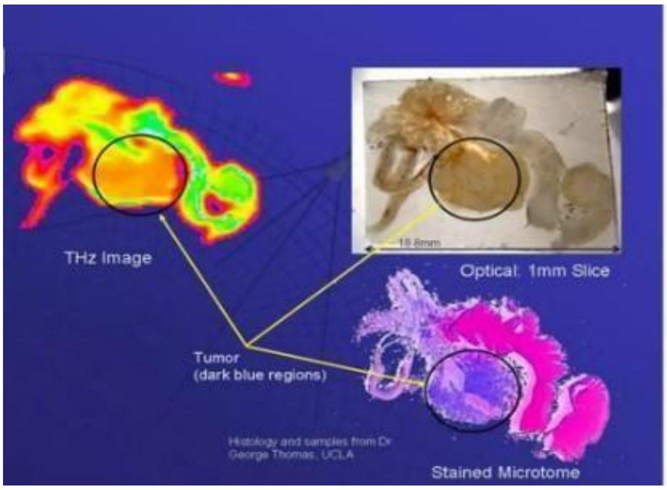

Figure1. 3 THz scanning image used to detect tumour[2]

1. **Security and Screening**: The ability of THz waves to penetrate fabrics and non-metallic materials makes them ideal for security screening applications. THz scanners can detect concealed weapons, explosives, and other illicit substances without the need for physical contact or the privacy concerns associated with traditional imaging techniques. This technology is increasingly deployed in airports and high-security areas for non-invasive, efficient security checks.

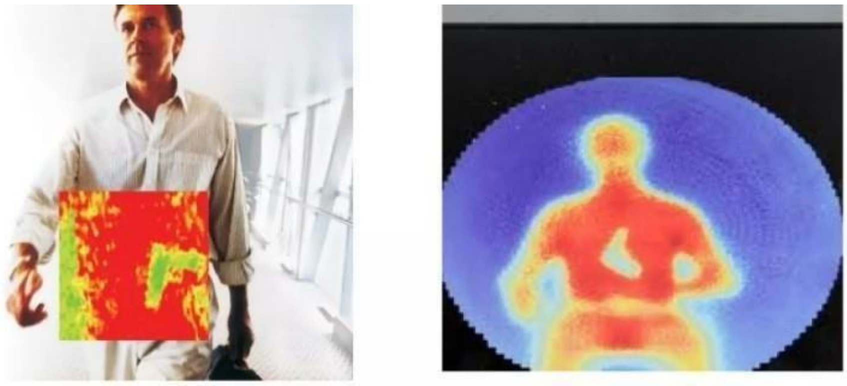

Figure 1.4 Contraband detection images[2]

3. Spectroscopy and Chemical Analysis: THz spectroscopy is a powerful tool for identifying and analyzing chemical compounds. The unique rotational and vibrational modes of many molecules fall within the THz range, providing distinct spectral fingerprints. This capability is utilized in various fields, including pharmaceuticals for quality control, and environmental science for monitoring pollutants. Furthermore, THz spectroscopy can study the intermolecular interactions and complex formation in materials.

4. Wireless Communication: The demand for higher data transfer rates and bandwidth efficiency in wireless communications has spurred interest in THz frequencies. THz technology promises ultra-high-speed wireless communication systems, capable of supporting data rates up to several terabits per second. This is particularly beneficial for short-range communication applications, such as within data centres, where high bandwidth and low latency are critical.

5. Material Characterization and Non-Destructive Testing: THz radiation is highly sensitive to the dielectric properties of materials, making it an excellent tool for non-destructive testing and material characterization. It can detect defects, cracks, and inclusions in materials such as ceramics, plastics, and composites without causing any damage. Industries such as aerospace, automotive, and manufacturing employ THz technology for quality assurance and structural health monitoring.

6. Astronomy and Space Science: In the field of astronomy, THz technology plays a crucial role in observing cosmic phenomena. The spectral signatures of various astrophysical entities, including interstellar dust and gases, fall within the THz range. Space missions, such as the Herschel Space Observatory launched by the European Space Agency, leverage THz detectors to study the formation and evolution of stars and galaxies

1.2.2 THz CW applications

Narrowband high-resolution systems are essential for certain applications, including gas-phase spectroscopy, high-frequency dielectric measurements of electronic materials, meta materials, and nanomaterials, as well as for signature analysis in microliter quantities of DNA. These applications can benefit significantly from the capabilities of THz continuous wave (CW) imaging and spectroscopy systems. In contrast, for applications such as imaging of aircraft glass-fiber composites or measuring the thickness of various samples, both pulsed and CW imaging techniques are applicable.

1.3 THz Source

The THz source is the most challenging component in THz technology. Extensive research has focused on adapting RF/MW and optical technologies for the THz band and integrating these approaches for better performance. THz sources are categorized into three main groups: those from RF/MW technologies, optical technologies, and a combination of both.

1. THz Sources from RF/MW Side:

a. Diodes and Frequency Multipliers: Diodes like Gunn, IMPATT, and resonant tunneling diodes are effective at lower THz frequencies but lose power as frequency increase Frequency multipliers extend lower GHz signals into the THz range, though efficiency and power drop at higher frequencies.

b. THz Vacuum Tube Sources: Tubes such as traveling wave tubes, backward wave oscillators, klystrons, and gyrations generate significant power at lower THz frequencies. However, they are bulky and require large magnetic biases and high voltage supplies, limiting their practicality.

2. THz Sources from Optical Side

a. Molecular Lasers: These generate THz signals by injecting grating-tuned CO_2 lasers into low-pressure gas cavities, producing tens of mill watts of power.

b. THz Semiconductor Lasers: THz Quantum-Cascade Lasers (QCLs) use engineered semiconductor materials to achieve population inversion and emit THz photons. They offer high power at higher frequencies but require cryogenic cooling.

c. Optical Down Converters: Nonlinear crystals convert optical power to THz waves via parametric oscillation and difference frequency generation (DFG) but need precise phase matching and high-power optical sources.

THz source is the most challenging component in THz technology. Extensive research has focused on adapting RF/MW and optical technologies for the THz band and integrating these approaches for better performance. THz sources are categorized into three main groups: those from RF/MW technologies, optical technologies, and a combination of both.

3. Combined RF/MW and Optical Techniques

Photoconductive THz Antennas: These use optical lasers to excite a photoconductive substrate, generating THz waves. They can operate in pulsed systems, producing ultrafast electrical pulses, or in continuous-wave (CW) systems, generating narrowband THz waves. This thesis will focus on the design and functionality of these antennas.

1.4 Working Principle of THz Emitter

1.4.1 Introduction

In a emitter there are basically two inputs one is voltage for strong electric fields and laser source for electron hole pair generation.

Figure1. 5 Block Diagram of THz emitter

This chapter delves into the THz photoconductive antenna, a critical component in THz technology that functions both as an emitter and detector. As an emitter, it converts optical waves into THz waves, while as a detector; it transforms THz energy into electrical signals that can be measured using a lock-in amplifier. The unique excitation method of THz antennas necessitates distinct approaches for analysis, simulation, fabrication, and measurement, unlike traditional RF/MW antennas. This chapter begins by underscoring the necessity of THz antennas, followed by a comparative analysis with RF/MW antennas, highlighting significant research avenues and laying the groundwork for the contributions of this thesis.

1.4.2 Working Principle of THz Emitter

Materials such as LT-GaAs and InP are known to generate THz waves when illuminated by femtosecond optical pulses. This process involves the creation and separation of electron-hole pairs on the semiconductor substrate's surface, leading to THz wave radiation due to carrier acceleration in the semiconductor's surface depletion layer. The amplitude and phase of the radiated THz field are influenced by carrier mobility and the internal electric field intensity. Applying an external magnetic field can enhance THz emission by reorienting the dipoles towards the surface. However, the power emitted through this method is generally low and can be improved by incorporating antenna electrodes on the semiconductor and applying an external bias field, which is more potent than the surface depletion field. Several companies, including Thor labs, Toptica, Tetechs, and Menlosystem, have commercialized THz antennas, underscoring their crucial role in THz generation and detection.

1.4.3 The THz Photoconductive Antenna

THz photoconductive antennas typically consist of two metal electrodes, usually gold, on a photoconductive substrate. When used as emitters, these electrodes provide a biasing mechanism and function as antennas. The gap between the electrodes, known as the photoconductive gap, is where laser pulses illuminate, and electron-hole pairs are generated.

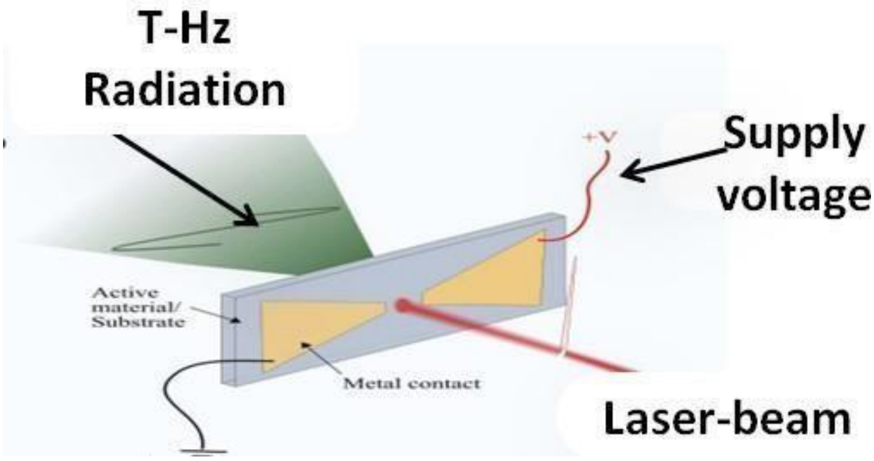

Figure1. 6 Device structure of a basic terahertz emitter[4]

Based on the size of the photoconductive gap, THz photoconductive antennas can be categorized into three types: small gap antennas (5 to 50 µm), large-aperture antennas (gap size significantly larger than the wavelength of emitted THz radiation), and semi-large gap antennas (gap size between the two previous types). Small gap antennas achieve a broader spectral range, whereas large-aperture and semi-large gap antennas offer better heat handling due to larger electrode areas on the substrate and are easier to fabricate. The impact of electrode design on the THz power and bandwidth is more significant in small gap antennas than in large-aperture antennas.

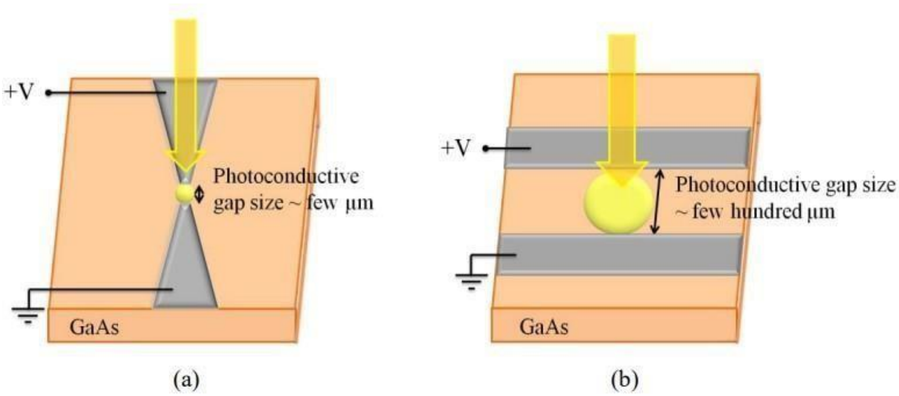

Figure1.7 **Sketch of THz photoconductive antennas (a) small gap bowtie antenna (b) large-aperture coplanar strip line[5]**

As Fig. 1.7, antenna electrodes can have various shapes and geometries. Bowtie antennas are commonly used in THz pulsed systems due to their frequency-independent characteristics and the enhanced THz radiation from their sharp ends. Large gap coplanar strip lines are also preferred due to their simpler fabrication and less sensitivity to laser focus alignment compared to small gap antennas.

1.4.4 Theoretical Principles of THz Photoconductive Antennas as Emitters

When a THz photoconductive antenna is excited by ultra-short laser pulses, electron-hole pairs are generated. The photon energy of these pulses exceeds the band gap energy of the semiconductor material, resulting in transient photocurrents due to carrier acceleration and deceleration under the bias voltage across the antenna electrodes. This process radiates THz waves into free space. The theoretical basis for THz photocurrent generation varies with the antenna gap size.

Large-Aperture Antennas: For large-aperture antennas, the emission of THz radiation follows the dipole antenna theory. The generated photocurrent is considered a surface current confined to a thin layer in the photoconductive gap under laser illumination. The on axis radiated THz field in the temporal domain is given by:

$E_{THz(r,t)} = -4\pi z\ \mu_0 \partial t \partial J_s(t)$

where $J_s(t)$ is the surface current density, μ_0 is the permeability, S is the photo-excited area in the antenna gap, and z is the on-axis distance from the antenna gap. The surface current density in a large-aperture antenna can be expressed as:

$J_s(t) = \sigma_s E_{bias}(t)$

where σ_s is the surface conductivity of the photoconductive substrate. Thus, the radiated THz field depends on the surface current density and the applied bias to the antenna electrodes.

Small Gap Antennas:

In contrast, the emission from small gap antennas follows the Hertzian dipole theory. The radiated electric field is proportional to the time derivative of the photocurrent, Ipc:

$$E_{THz}(t) \propto \partial I_{pc}(t)/\partial t$$

Here, the photocurrent density Jpc(t), is determined by the electron density n(t) and the velocity of carriers v(t), given by:

$$J_{pc}(t) = -en(t)v(t)$$

A simplified Drude-Lorentz model describes the carrier dynamics and the resulting photocurrent density, which involves interlinked differential equations relating the free carrier density, carrier velocity, and polarization due to the separated carriers under the bias field. These dynamics lead to the radiated THz field, which can be calculated through numerical methods.

Comparing the equations for large-aperture antennas and small gap antennas reveals that different gap sizes necessitate distinct analytical approaches. This thesis focuses on small gap antennas.

1.5 Organization of Thesis

The thesis is organized in following chapters starting with an introduction and literature survey, one chapter consisting of the original research work followed by the conclusion and the future scope.

Chapter 2 Literature Survey: This literature review covers basis of Photoconductive emitters for pulsed terahertz generation and the performance parameter. And the review of photo-conductive terahertz antenna. How to optimize photoconductive emitter using different designs.

Chapter 3 Optimized proposed Terahertz Emitter: In this section, three proposed designs of the terahertz emitter are presented: Design with Oxide Layer: This design has an oxide layer to enhance the emitter's performance. The role and impact of the oxide layer on the device’s operation are analysed and discussed. Ge on Si Design: This design focuses on the integration of germanium (Ge) on a silicon (Si) substrate, aims to balance performance enhancement and power dissipation reduction

Chapter 4 Conclusion and Future Scope: This chapter outlines the thesis and briefly discusses the future scope of the project.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Terahertz (THz) frequencies occupy a unique position in the electromagnetic spectrum, bridging the gap between conventional electronics and photonics. However, harnessing the potential of THz waves presents significant challenges due to limitations in conventional approaches. Microwave devices encounter barriers in frequency scaling due to material properties, while semiconductor transitions face energy constraints. Yet, the applications of THz waves span across various domains, from spectroscopy to medical imaging, promising breakthroughs in diverse fields.

In this context, the development of efficient Terahertz Photoconductive Antennas (THz-PCAs) emerges as a crucial endeavour. By enhancing the optical-to-THz conversion efficiency, these antennas offer a pathway to unlock the full potential of THz technology. This literature survey explores a computational approach to optimize THz-PCAs, leveraging the capabilities of the COMSOL Multiphysics finite element method solver.

The study proposes and optimizes two configurations of THz-PCAs using COMSOL's RF module and validates them through wave optics simulations. The optimized designs aim to overcome the challenge of low output power associated with traditional THz-PCAs. The investigation delves into the optical and electrical responses of the antennas, focusing on femtosecond optical pulse excitation and transient current analysis.

Through computational modelling and simulation, the research elucidates the intricate dynamics of THz generation and collection in the proposed antennas. By observing the transient current at the electrode terminals, the study confirms the efficient generation of THz waves, thus addressing a critical limitation in THz-PCA technology.

The literature survey underscores the significance of computational optimization in advancing THz technology. By providing insights into the design principles and performance characteristics of THz-PCAs, the study lays the groundwork for future developments in THz applications. The subsequent sections of the paper delve into the theoretical framework, computational methodology, and simulation results, culminating in a comprehensive analysis of the optimized THz-PCA designs.

2.2 Review: Photoconductive emitters for pulsed terahertz generation

over the past three decades, Photoconductive Antennas (PCAs) have emerged as essential tools for both generating and detecting terahertz (THz) band radiation, facilitating advancements in THz imaging and spectroscopy across various industries and research fields. This review provides an overview of the development of THz PCA technology, identifying key modalities for enhancing device performance and summarizing progress in these areas.

The terahertz region of the electromagnetic spectrum, spanning from 100 GHz to 10 THz, has historically posed challenges due to the difficulty in efficiently generating and detecting THz waves. This transitional region lies between classical electronics and photonics, where the quantum nature of light becomes predominant. Microwave devices face limitations in increasing operating frequencies due to semiconductor carrier mobility, while reducing photon energy in semiconductors is constrained by THz photon energies being lower than room temperature thermal energy. Consequently, the development of efficient THz generation and detection methods has been complex, necessitating approaches that blend aspects of both photonics and electronics.

Despite these challenges, THz technology has seen significant progress, with numerous practical applications emerging. These applications include non-destructive screening of pharmaceuticals, spectral fingerprinting for security purposes, quality control in electronics fabrication, composite material inspection, and biomedical imaging for cancer detection; burn wound assessment, and dental tissue imaging.

This review focuses primarily on THz PCA technology, while briefly discussing alternative approaches such as photo mixers, unbiased surface emission, and optical rectification. It delves into fundamental theories of THz generation in PCAs and categorically reviews key works from the literature. These works cover developments in photoconductive material, large area emitters, plasmonic nanostructures, broadband performance enhancement, and commercially available systems.

In summary, this review offers a comprehensive understanding of the evolution of THz PCA technology, highlighting its pivotal role in advancing THz imaging and spectroscopy applications. By synthesizing relevant literature, it aims to provide researchers with insights into the current state and future directions of THz PCA technology.

2.3 Review: Photoconductive terahertz antenna

The evolution of terahertz (THz) technology has been greatly influenced by the development and widespread adoption of photoconductive (PC) emitters, which have undergone significant performance enhancements over the past three decades. In this review, we present an overview of the literature, highlighting key milestones in the advancement of PC emitters and exploring their future prospects and existing challenges.

Since the first demonstration of PC emission and detection of THz radiation in 1990, PC emitters have played a crucial role in various applications, including non-destructive imaging and spectroscopy of pharmaceuticals, spectral analysis for security scans, and biomedical imaging for cancer detection. Their unique capability to excite intermolecular vibrations has opened avenues for studying large biomolecules and advancing biomedical research. Additionally, the integration of optical excitation for optical-pump-THz-probe spectroscopy has enabled the study of conductivity and time-resolved photo carrier dynamics in semiconductors, as well as defect detection in the semiconductor industry.

Recent advancements in ultrafast amplified laser systems have enabled the generation of higher THz fields, leading to investigations into the non-linear characteristics of materials in condensed matter physics. Despite the success of PC emission in the low-field regime, its utilization in high-field applications remains limited due to saturation effects. However, PC emitters offer desirable properties such as controllable output fields and switchable polarization, indicating their potential in the high-field regime with further research and development.

This review delves into the fundamental concepts of PC emission in semiconductors and THz time-domain spectroscopy. It provides an up-to-date review of active and substrate materials used in PC emission, categorized by excitation wavelengths. Furthermore, it explores various electrode designs and innovations that have led to higher output powers and conversion efficiencies. Additionally, the review discusses excitations of PC emitters with amplified laser systems, which have contributed to achieving significantly higher radiated electric fields.

In conclusion, this review comprehensively examines the progression of PC emitter technology, from its foundational principles to recent advancements. By identifying key developments and addressing existing challenges, it offers insights into the future direction of PC technology in the THz field.

2.4 Research Objectives

After doing the deep literature survey on the past works on THz photoconductive emitters, it is found that newly invented Ge based photoconductive THz emitters have huge potential as a broadband THz source. However, due to a lower bandgap in Ge, the emitter fabricated on Ge semiconductor suffers from large dark current and related heat generation in the device. These are the main objective:

1) In this project we will try to improve the efficiency of Ge based THz emitters by controlling the dark current flowing through the device. To optimize the device performance the dark current and the photocurrent flowing through the different device designs will be simulated

2) In this project we will study the transient photocurrent response of the device after pulsed laser excitation. We will also study the effect of the pump laser pulse width variation on the photocurrent dynamics and emitted THz spectrum.

Chapter 3

1.1 PROPOSED DESIGNS THz EMITTER

Introduction

We took a photoconductive material germanium of thickness 500um and from the top view its length and width are 200um. On the germanium we deposited 50nm of gold electrode of bowtie such that maximum electric field between the electrodes.

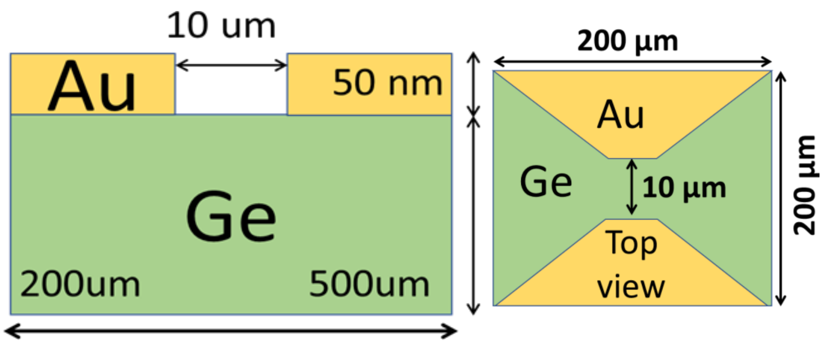

Figure3.1 Proposed device design of THz Emitter (a) cross-sectional view (b) Top view

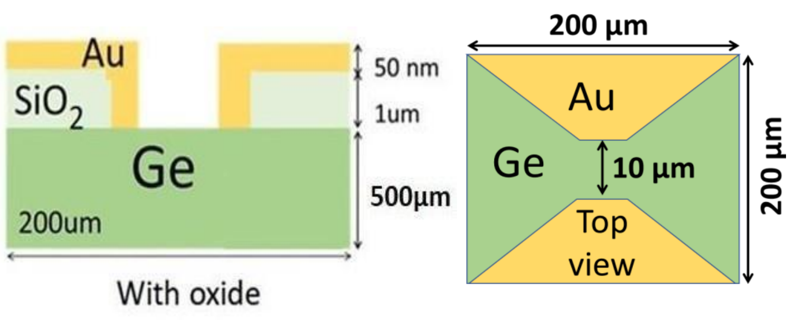

Figure3. 2 **Proposed device design of THz emitter (a) cross-sectional view (b) Top view**

In Design 1st germanium is used as a substrate of thickness 500um on which 50 nm of gold electrode in such way the gap is 10um. In the second design we uses 1um of oxide layer, where we take 500um of germanium, after that we put gold electrode of on the oxide layer in 1.05um such a way it contact with the germanium in a small area.

Using oxide layer gold electrode have less path with the germanium, so less path of current flow, so mainly through surface the current is flowing. Overall path current is decreased because of a smaller number of paths due to introduction of oxide layer.

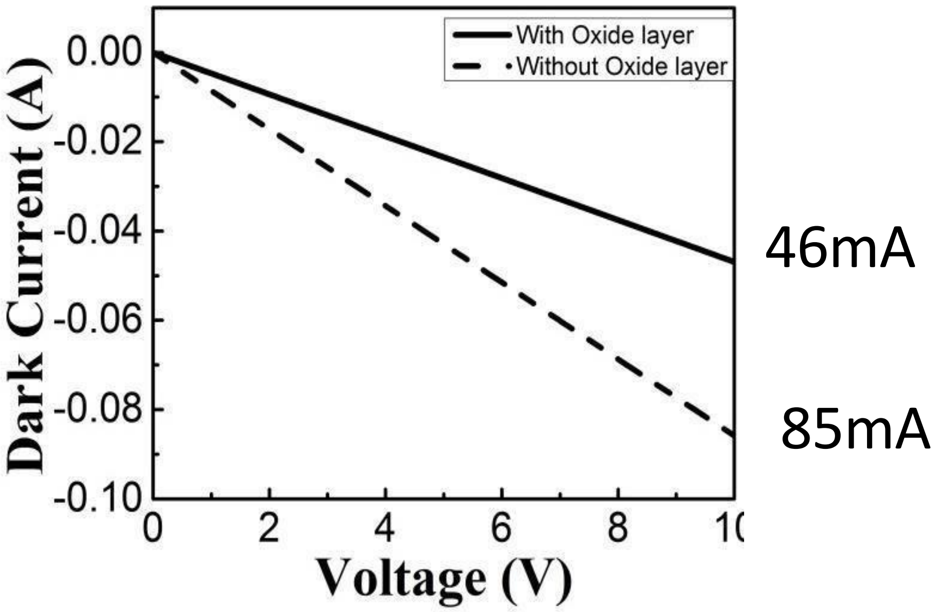

Figure 3.3 Dark current simulation with and without oxide layer of THz emitter.

without oxide layer. Without the oxide layer the simulated current is 46mA. So it’s almost half in the introduction of oxide layer. We vary the voltage from 0 to 10 volt. Ultimately the dark current is reduced along with the power consumption is also reduced and performance of the device is improved significantly.

1.2 Integration of Ge on Si design (optimized terahertz emitter)

High resistance materials are essential for efficient photocurrent generation in THz emitters. When a semiconductor with high resistance is illuminated by a femtosecond laser pulse, electron-hole pairs are generated. The high resistance helps to maintain a high internal electric field, which accelerates these charge carriers more effectively, leading to a stronger photocurrent. As we know that Si has resistivity of 640 ohmmeter while the Germanium has the 0.46 ohm-meter resistivity as a result of it Si gives high resistance. So when we used Gold as metal electrode, it now has the availability of two paths for the current to flow through the device.

As now as the basic rule of current states that "current always travels through the least resistive path in a circuit" therefore in the proposed device also the current chooses the path of flow via Germanium material.

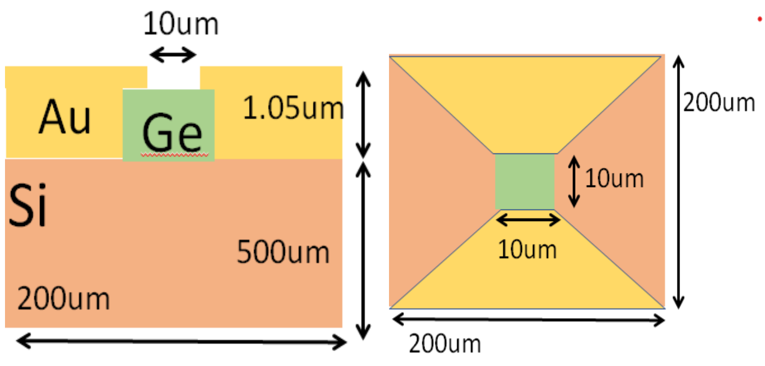

Figure3. 4 Proposed device Ge integration on Si substrate design of THz emitter (a) cross-sectional view (b) Top view

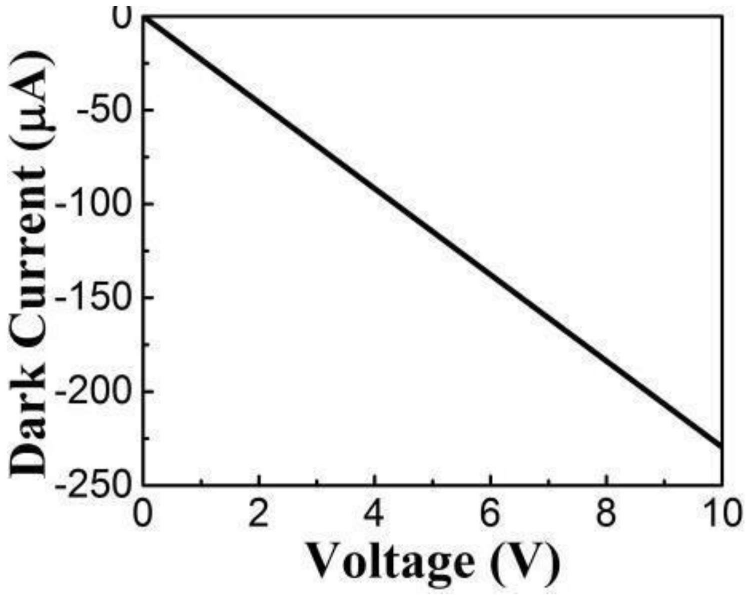

Figure 3.5 Dark current simulation

We took the following dimension of different materials in our device. The Si has length of 200 um, width of 200um and thickness of 500um. The Germanium mounted on the top of it works with following dimension of length 12um, width of 12um and height or thickness of

1um. Alongside the material of gold has following dimensions: length =90um, width=1.05um and is trapezoidal in nature.

Due to the introduction of the silicon the overall internal resistance of the device is increased. As a result, or efficiency of the device is significantly improved. Initially we had the current of 85mA in our first simulated design.

While as we introduced the oxide layer in between the gold and germanium the current is almost reduced to half of its magnitude that is 46mA.

In the previous design the integration of germanium on silicon leads to current reduction from 85mA to 225uA, which is almost ninety-nine percentage of reduction in current. So, this tells us that by varying design dimension and materials introduction can help us make a better device with improved performance parameter.

1.3 Optical Mode Distribution

In the context of FDTD (Finite-Difference Time-Domain) simulations using Lumerical software, light confinement refers to how well light is contained or localized within a particular region or structure.

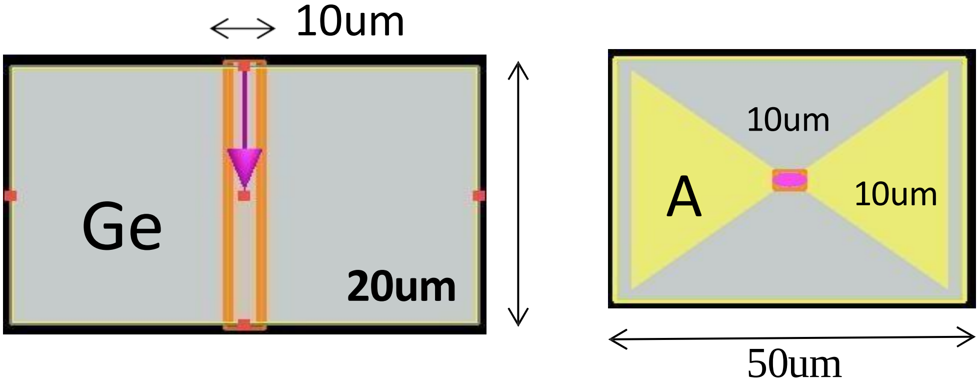

Figure3.6 Optical Confinement view

In FDTD we designed the device by taking thickness of 10um, length 50um and the width of 50um as well. Later we provided the 1550nm wavelength of light between the electrodes and observed its mode profile.

The deep dark red colour defines the maximum intensity of the light. Following the sequence of the “VIBGYOR” the light intensity is varying from red as maximum intensity to violet as the minimum intensity of light.

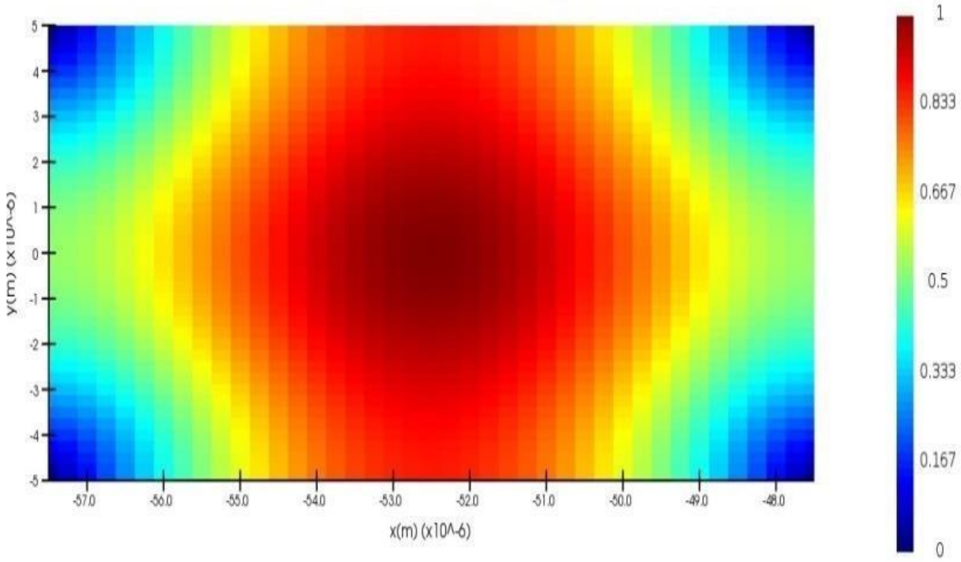

Figure3.5 Mode profile view

We have provided the laser light of 1550num wavelength between the gap of 10um and observed this mode profile. This tells us that the light is getting properly confined in the device. Proper light confinement tells us that there is charge generation in our device.

1.4 Charge Generation

Here we observed the charge generation of the device, we put light of wavelength 1550nm. So maximum absorption across the centre of the substrate or between the electrodes. According to the mode profile the maximum charge generation occurred at the centre as it shown in the results. With respect to x dimension -5um to 5um, the charge generation is maximum at the centre of the x axis. As you can see in figure 3.7

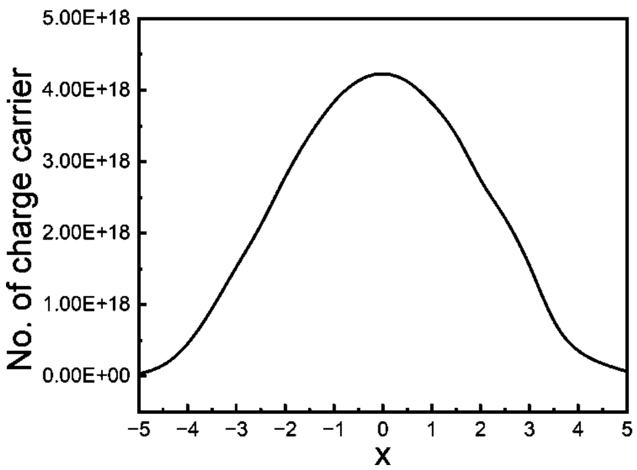

Figure 3. 7 Charge carrier generation with respect to x dimension

With respect to z dimension the maximum absorption of the light is at the surface i.e. at z = 10um. Later the absorption of light is decreasing with respect decreasing z dimension. And after moving towards some micro-meter thickness in z direction in the device absorption of light is completely done.

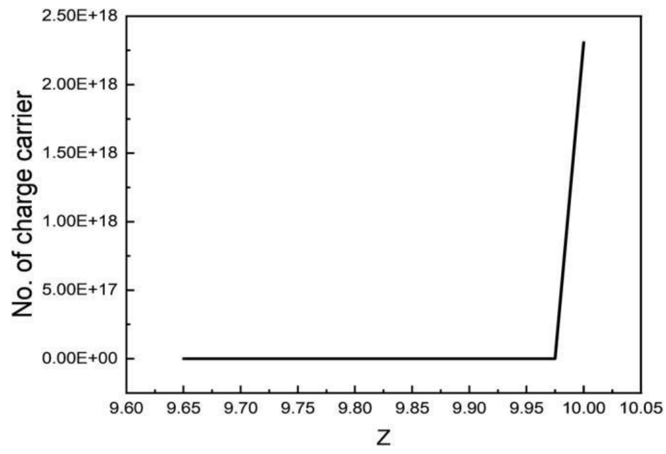

Figure 3. 8 Charge carrier generation with respect to z dimension

1.5 Simulation of Photo-current

The photocurrent simulation defines the performance of the terahertz emitter to generate a measurable current under the influence of a femtosecond laser pump and a moderate bias voltage.

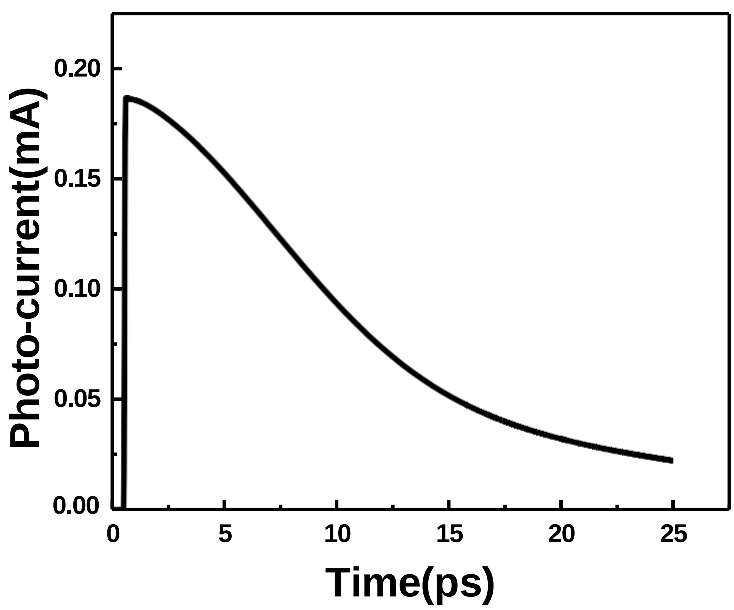

Figure 3.9 Simulation of Photocurrent with respect to time

In this section, we present the results of our photocurrent simulation for a terahertz emitter excited by a laser pump pulse with a width of 50 femtoseconds (fs). The simulation was conducted using a bias voltage of 1 volt applied across the device. The simulation yielded a photocurrent of 0.018 mA when a 1 volt bias was applied.

The generation of a measurable photocurrent under these conditions indicates efficient separation and acceleration of electron-hole pairs within the semiconductor material. The ultrafast 50 fs laser pulse provides sufficient energy to excite carriers across the bandgap, leading to the observed photocurrent.

The choice of a 50 fs pulse width is critical in achieving high temporal resolution and efficient carrier excitation. The relationship between the bias voltage and photocurrent can be further explored to optimize device performance.

1.6 Emitted terahertz electric field

Electric field of emitted tera hertz is directly proportional to the rate of change of photocurrent. Wavelength of light source is of wavelength of 1550nm. Input bias voltage provided in the device is 1 volt. Which is resulting in the Photocurrent emission of 0.18mA.

$$\text{ETHz} \propto \frac{dIph}{dt} \propto (\text{Vbias}, n, \mu, \Phi)$$

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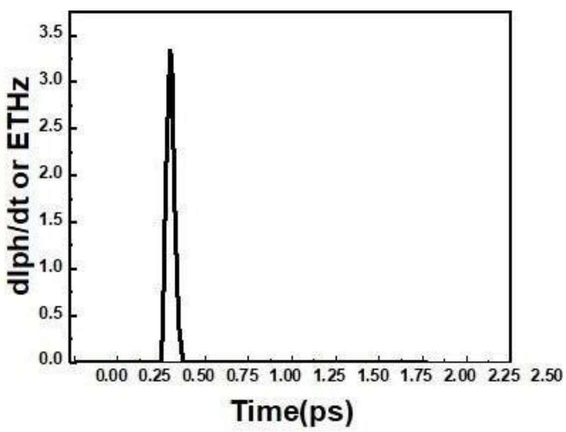

Figure 3. 10 Rate of change of photocurrent or emitted THz E-field

1.7 Amplitude of Emitted THz Field

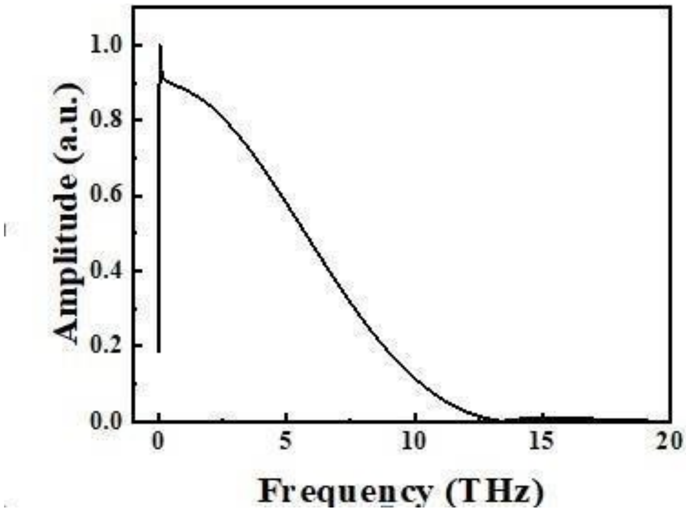

Figure 3. 11 Amplitude of Emitted THz field 50fs width of laser pump

For 50 fs the bandwidth is upto 10 terahertz. And we simulate the terahertz graph of the final geometry that will give the best performance.

For 100fs laser pump width:

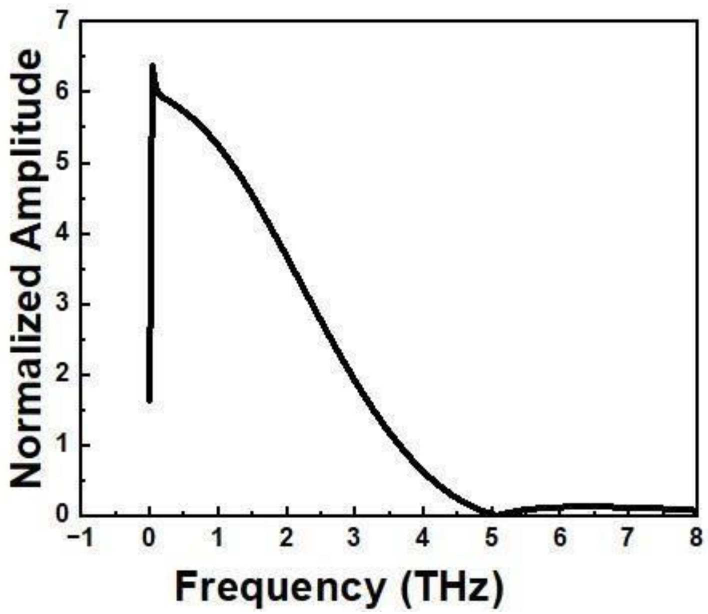

Figure 3.12 Amplitude of Emitted THz field 100fs width of laser pump

For 100 fs the bandwidth is upto 4.5 terahertz. Ultimately as we increase the pulse width the bandwidth starts to decrease

1.8 Bandwidth Calculation

Here we vary the laser pulse width and observed its respective bandwidth.

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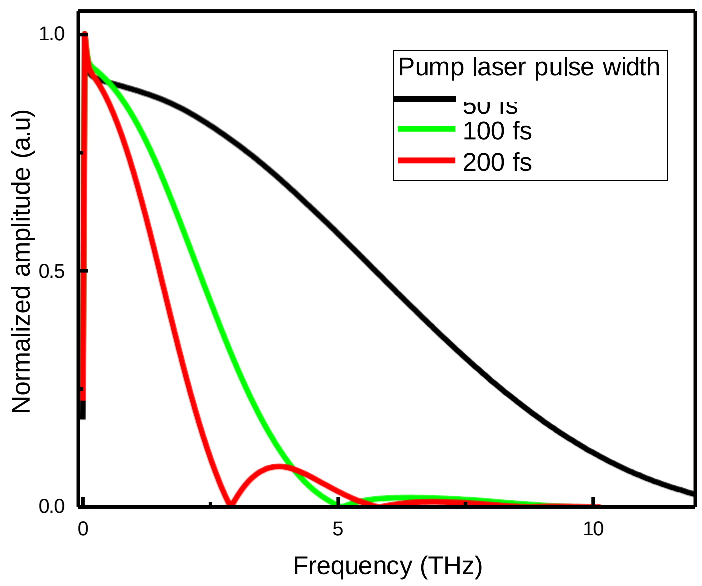

Figure3.13 Bandwidth calculation with respect to pump laser pulse width

In this section, we explore the effect of varying the laser pump pulse width on the bandwidth of the generated terahertz (THz) waves. The laser pump pulse widths tested were 50 fs, 100 fs, and 200 fs. Our findings demonstrate relationship between the pulse width and the resulting THz bandwidth:

Laser Pulse Widths Tested: 50 fs, 100 fs, and 200 fs, Bias Voltage: 1 V Measured Bandwidths:

50 fs: up to 10 THz

100 fs: up to 5.5 THz

200 fs: up to 2.5 THz

Analysis: The shortest pulse width of 50 fs produces the highest bandwidth. This is due to the ultra-short duration of the pulse, which generates a broader spectrum of frequencies. The rapid excitation and subsequent relaxation of carriers lead to a wide range of THz frequencies being emitted. Doubling the pulse width to 100 fs results in a significant reduction in bandwidth to 5.5 THz. The longer pulse duration means that the excitation of carriers is less abrupt, leading to a narrower spectrum. The temporal spread of the pulse reduces the range of frequencies generated during the excitation process. Further increasing the pulse width to 200 fs causes the bandwidth to decrease to 2.5 THz. The extended duration of the pulse results in even less abrupt carrier dynamics, which limits the range of frequencies in the emitted THz spectrum. The slower excitation rate corresponds to fewer high-frequency components being generated.

1.9 Summary

In this thesis, we explored and optimized three different designs of terahertz emitters to enhance performance and reduce power consumption and heating effects. The designs investigated were:

1 Without Oxide Layer: This design exhibited a dark current of 85 mA. While it provided a baseline for comparison, the high dark current indicated significant power consumption and associated heating effects.

2. With Oxide Layer: Introducing an oxide layer reduced the dark current to 46 mA. This reduction demonstrated the effectiveness of the oxide layer in lowering leakage currents and mitigating heating effects, though the dark current remained relatively high.

3. Germanium on Silicon: The final and most optimized design involved the integration of germanium on silicon, which drastically

reduced the dark current to 226 µA. This substantial reduction in dark current resulted in minimal power consumption and significantly lowers heating effects.

After simulating all three designs, it was evident that the germanium on silicon design was the superior configuration. This design not only minimized power dissipation and heating but also allowed for higher bias voltages, leading to more efficient and powerful terahertz generation.

The comprehensive simulation results confirmed that the germanium on silicon design is the optimal choice for advanced terahertz emitters. After that we simulated the terahertz for this optimized design.

Chapter 4

Conclusion and future scope

In this study, we focused on optimizing the terahertz emitter by integrating germanium on silicon. This integration significantly enhanced the power efficiency of the device. One of the key improvements observed was a substantial reduction in the dark current, up to 99%. This reduction in dark current has critical implications for the device's performance:

1. Improved Power Efficiency: The integration of germanium on silicon has resulted in a more efficient conversion of optical pump energy into terahertz radiation. By reducing the dark current, we minimized the unwanted leakage current that does not contribute to the terahertz generation, thereby improving the overall power efficiency.

2. Reduced Heating Effects: With the dark current reduced by 99%, the heating effects within the emitter are considerably lowered. Excessive heating can degrade device performance and longevity, but with reduced dark current, thermal management becomes less challenging. This allows the emitter to operate more efficiently over longer periods.

3. Higher Operational Voltage: The reduction in dark current and associated heating effects allows for the application of higher bias voltages to the emitter. Higher voltages can drive stronger photocurrents, which in turn can generate more intense terahertz radiation. This capability expands the operational range of the terahertz emitter, making it suitable for applications requiring higher power outputs.

Overall, the integration of germanium on silicon has proven to be a significant advancement in optimizing terahertz emitters. This innovation not only enhances the power efficiency and reduces heating but also enables higher operational voltages, leading to more robust and effective terahertz generation.

In future work, we can propose the introduction of grating structures between the electrodes of the terahertz emitter. This modification aims to maximize the absorption leading to increased terahertz emission. By tailoring the grating parameters (such as period, depth, and shape), it is possible to enhance the local electric field intensity within the photoconductive gap, leading to improved absorption of the pump laser.

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