The Design, Fabrication and Characterization of Integrated Photoconductive Antennas for On-Chip Terahertz Wave Radiation and Detection

Ruben Dario Velasquez Rios
Graduate Center, City University of New York

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The Design, Fabrication and Characterization of Integrated Photoconductive Antennas for On-Chip Terahertz Wave Radiation and Detection

by

Rubén Darío Velásquez Ríos

A dissertation submitted to the Graduate Faculty in Electrical Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

2016
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Rubén Darío Velásquez Ríos

This manuscript has been read and accepted for the Graduate Faculty in Engineering in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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THE CITY UNIVERSITY OF NEW YORK
Abstract

The Design, Fabrication and Characterization of Integrated Photoconductive Antennas for On-Chip Terahertz Wave Radiation and Detection

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Rubén Darío Velásquez Ríos

Adviser: Professor Sang-Woo Seo

Terahertz (THz) wave (between 0.1 and 10 THz) is attracting a lot of attention due to its unique properties that are favorable to various applications. These include non-ionizing radiation, better resolution than a microwave, unique spectral absorption, and an ability to propagate through many types of materials. It has been intensively researched in sensing and imaging technology for a wide range of applications in areas such as biology, pharmaceutical, food and drug control, medical science, and security screening. Driven by mostly scientific research interests, the majority of THz systems are more focused on system performance rather than system size, integration, and cost. Many THz applications aforementioned would be benefit from the compact integration of THz devices and other types of functional devices.

This dissertation research focuses on developing a THz source based on heterogeneous thin film device integration. The demonstration shows a cost-effective integration approach and a feasibility to develop a THz integrated system that utilizes separately optimized LTG-GaAs based THz devices with other types of Si-based devices. The key aspect of the integration lies in the thin-film format of LTG-GaAs based THz devices, which allows their
seamless integration on a final integration substrate and subsequent fabrication processes on the top of the THz devices. Using this approach, THz devices can be integrated on any host substrate (including organic and inorganic substrates), which gives a design freedom to enhance THz integrated system performances. Based on post-integration approach, the demonstrated method does not require significant modification of a host substrate technology. This allows THz functional devices to be integrated on various integration platforms including microfluidics, optics, and digital electronics. Intimate integration of THz devices with other functional devices will benefit a broad range of applications, which has limitations due to the current bulky THz systems.
Dedication:

To my mother
Acknowledgements

I give my heartfelt thanks to my mother, Mrs. Consuelo Rodriguez, for making me who I am and inspiring me to never give up and to always see the positive side of life. I could not have finished my Ph.D. work without her love and support.

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I am very grateful to Siméon Bikorimana for his hard work, inspiration, and contributions to the most intensive and comprehensive learning experience of my life. I want also to extend my thanks to all my peers in the semiconductor laboratory for their hard work inside the clean room facility and for keeping the laboratory running smoothly.

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Publications


2. **Rubén Darío Velásquez Ríos**, Siméon Bikorimana, Roger Dorsinville, and Sang-Woo Seo, "THz-wave characterization under DC electric field variations on two bow-tie PCAs patterned on dissimilar semiconductor substrates and fabrication techniques," *Submitted to IOP Journal on March 2016*. 
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List of Abbreviations and Symbols

AlAs  Aluminum Arsenide
API  Active Pharmaceutical Ingredients
As  Arsenide
Au  Gold
AZ4620  Positive photoresist
BCC  Basal Cell Carcinoma
BOE  Buffered Oxide Etchant
cm  Centimeters
CMOS  Complementary Metal-Oxide Semiconductor
C₆H₈O₇·H₂O₂  Citric Acid/Hydrogen-Peroxide
Cr  Chromium
Cr/Au  Chromium and Gold
CST-MWS-TS  Computer Simulation Technology Microwave Studio Transient Solver
CW  Continuous Wave
dBi  Decibels isotropic
DC  Direct Current
DDDA  Deep Donor Deep Acceptor
DDSA  Deep Donors Shallow Acceptors
DI  Deionized water
DUT  Device Under Test
e-field  THz electric field
Eg  Energy gap
EL2  Electrically active defect No. 2
EM  Electromagnetic
EOTPR  Electro Optical Terahertz Pulse Reflectometry
Eₜₜₜ(t)  Terahertz electric field time dependence
eV  Electron volt
far-IF  Far infrared
FeCl₃  Ferric chloride etchant
FFT  Fast Fourier Transform
FIB  Focused Ion Beam
FR4  International grade for Fiberglass
fs  Femtoseconds
FWHM  Full Width at Half Maximum
GaAs  Gallium Arsenide
HF  Hydrogen Fluoride
HF:HNO₃:H₂O  Hydrogen Fluoride, Nitric acid, and DI water
IC  Integrated Circuit
in  Inches
i-line  Ultra-violet light at 365 nm wavelength
InGaAs  Indium Gallium Arsenide
J(t)  Time derivative of photocurrent
LDA  Linear Discriminant Analysis
LTG-GaAs  Low temperature Grown Gallium Arsenide
LTG-GaAs\AlAs\SI-GaAs  Low temperature Grown Gallium Arsenide/Aluminum-Arsenide/Semi-Insulating Gallium Arsenide
MBE  Molecular Beam Epitaxial
min  Minutes
MIF-319  Developer
mm  Millimeters
MMIC  Monolithic Microwave Integrated Circuit
MRI  Magnetic Resonance Imaging
ƞ(t)  Density of the photo-carriers time dependence
ƞair  Air refractive index
near-IF  Near infrared
nm  Nano-meters
NR9  Negative image photoresist
O₂  Oxygen
PCA  Photoconductive Antenna
PCB  Printed Circuit Boards
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>Chemical remover</td>
</tr>
<tr>
<td>PG-101A</td>
<td>Chemical developer</td>
</tr>
<tr>
<td>PoP</td>
<td>Package on Package</td>
</tr>
<tr>
<td>ps</td>
<td>Pico-seconds</td>
</tr>
<tr>
<td>QCLs</td>
<td>Quantum Cascade Lasers</td>
</tr>
<tr>
<td>R</td>
<td>Reflection coefficient</td>
</tr>
<tr>
<td>RD-SOS</td>
<td>Radiation damage Silicon on sapphire</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RF\MW</td>
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<td>SMA</td>
<td>Sub-Miniature version A connector</td>
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<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<td>Scattering parameter</td>
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<td>Transparent polymer protective coating</td>
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<td>Technology Computer Aided Design</td>
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<td>TCE</td>
<td>Trichloroethylene</td>
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<td>Time Domain Reflectometry</td>
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<td>THz Continuous Wave</td>
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<td>THz Time Domain Spectroscopy</td>
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<td>TPI</td>
<td>Terahertz Pulsed Imaging</td>
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<td>TPS</td>
<td>Terahertz Pulsed Spectral</td>
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<td>Dc bias voltage</td>
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<td>van derWaals</td>
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<td>Vector Network Analyzer</td>
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<td>Z_S</td>
<td>Source Impedance</td>
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1. THz electromagnetic spectrum, THz sources and THz applications

1.1. Introduction

The invention of the photoconductive switch is attributed to Auston, who in the 1980s pioneered the switching technique. *Auston et al.* [1] demonstrated a sampling technique by using a transmission line structure and amorphous Si film on fused silica substrate as a photoconductor. *Mouro et al.* [2] in 1981 and *Heidemann et al.* [3] in 1983 used photoconductive switching to drive their antennas and the emitted ps microwave transients in free space. But it was not until 1988 that Smith, Auston, and Nuss [4] reported the first antenna structure with the photoconductive dipole on RD-SOS where carrier lifetime is controlled by ion implantation to enhance the generation of electromagnetic waves radiation.

Different types of electromagnetic wave radiations are grouped together according to their decreasing values of wavelength (or increasing values of frequency) to form the electromagnetic spectrum, as illustrated in Figure 1. For instance, the visible light which lies between the near-IF and ultraviolet frequencies can be detected by human eyes. Different members of the electromagnetic spectrum can be utilized to perform a variety of tasks. The X-rays can penetrate human skin to capture a picture of the bone structure, but is harmful to human tissues due to its high ionization energy level. The THz band, as illustrated in Figure 1, is located between the high microwave frequencies and the low far-IF frequencies. The THz technology has applications in different areas including security screening [5, 6], medical science [7, 8],
pharmaceutical industry [9, 10], industrial non-destructive semiconductor evaluation [11, 12], biology [13, 14], global environmental monitoring [15], astronomy and basic science [16], non-destructive evaluation of mural paintings [17, 18], quality control of industrial processes and products in the plastics industry [19], food and agriculture inspections [20], among others. As data rate is increased, THz technology also benefits information and communications technology [21, 22], such as ultra-fast computing, wireless communications, high-speed data processing, radio astronomy, vehicle compact radar, and satellite communication, to mention some.

THz is a technology that could allow anyone to see through opaque surfaces without the exposure to harmful x-rays. This technology could give us the ability to detect harmful chemicals and bio-agents from a safe distance. In addition, it could enable scientists to peer so deeply into space that they could better understand the formation of the universe.

THz spectrum was called for a long time THz-gap due to the difficulty in bridging the electronics and the optics technologies. During the last decade, these two technologies have been closing the THz spectrum through the effort of building suitable sources and detectors. The generation of THz sources is a mutual cooperation between the two dissimilar technologies aforementioned. Therefore, the THz electromagnetic band does not have a standard definition yet. There is a debate among researchers defining the standard THz band, some define the THz band between 0.1THz to 10THz and others between 0.3THz to 30THz. Consequently, researchers find that the THz band range of 10-30THz exceeds the far-IF band from the well-defined optical technology. In this dissertation, the standard definition for the THz electromagnetic band is established between 0.1 to 10THz, as illustrated in Figure 1.
The THz electromagnetic spectrum has very low photon energy of 0.41meV at 0.1THz and 41meV at 10THz. The X-ray, on the other hand, possesses energy levels of about $1.24 \times 10^4$ eV, which is capable of photo-ionizing the human skin with the possibility of causing a molecular modification to the human tissue.

Figure 1. The electromagnetic spectrum. The THz spectral regime gives birth to the development of numerous efficient emitter-detector sources.

Tremendous effort has been made to fill in the THz gap. Nevertheless, technological advances in optics and electronics have resulted in many different types of THz sources and sensors [16, 23-26]. The lack of suitable and efficient signal sources limit applications to a number of areas that demand highly reliable performance. Researchers have been looking at the world in a new way since the advent of the Time-Domain THz spectroscopy, leading to a widespread potential for THz sources and sensors for multiple applications. In the last few years, new technologies and new tools have been developed in order to understand and utilize the THz principle more effectively. The creation of the new technologies and tools has opened up the
road to ways of developing efficient, compact coherent THz sources that work at room temperature in the range of 0.1 to 10THz for first time.

The only pure electronic device based source is the resonant tunneling diode (RTD) [27, 28]. It can provide an output power of micro-watt at 1.0 THz at room temperature, but shows difficulties in reaching levels of milli-watt radiation. As such, different optical strategies have been widely explored for the realization of efficient and coherent THz sources. They include THz QCLs [29-32], THz gas lasers [33, 34], nonlinear parametric generations [35], THz CW [36, 37], and pulsed THz PCAs [38, 39]. Among these approaches, pulsed THz PCAs supply simple operation, compactness, and can work at room temperature, while the others are bulky and require temperature cooling system. Also, pulsed THz PCAs can be furthermore fused with other semiconductor laser sources offering the smallest stand-alone system. For instance, an integrated semiconductor-based mode-locked laser that generates femtosecond optical pulse trains can supply an optical signal to the THz PCAs. Whereas, frequency beating signal from two integrated semiconductor lasers can supply THz CW emission through the photo-mixer antennas. For many of the future THz applications that require high performance, compactness, mobility, and inexpensiveness, semiconductor-based PCAs will be the ideal choice.

1.2. Terahertz applications

THz PCA sources have been the subject of boundless amounts of experimental procedures to prove their functionality as effective THz wave transmitters and detectors, but they
are bulky and expensive. The opportunity to manufacture THz PCAs on semiconductor materials with optical capabilities makes them very enthralling for several real world applications. Some of the applications of THz technology are described below:

1.2.1. Security screening

THz sensing is empowering technology for detection of mines, explosives, and chemical hazardous agents to provide security in buildings and airports. Screening people with THz radiation is safe, while still capable of penetrating clothes. This makes it a decisive tool for searching objects hidden in the human body. Nevertheless, THz detection features an important characteristic of being non-invasive as it does not reveal intimate areas of the human body. THz imaging saves any unnecessary waiting time arising from the screening procedures as it can be performed efficiently on moving objects. This technology is completely safe to use on pregnant women and on anyone regardless of age or gender. Figure 2 illustrates an actual THz imaging of a concealed weapon hidden under the clothes of a person as they walk through a building.
1.2.2. Medical THz imaging

THz imaging systems for high-efficiency sources and detectors have been developed for medical applications. Consequently, the most recent achievements in the field of medical imaging gave dramatic enhancement to the early detection and treatment of many pathological conditions. THz imaging systems can help detect the early stages of cancer before it is visible.
and not sensitive to any other identification means. The latest research aimed at examining THz properties on carcinoma tissues discovered that refractive index and absorption coefficient of the tumor tissues are higher in comparison to the healthy tissues. Because the disease tissue structure in carcinomas produces increased protein density in affected cells, their higher water content can make a viable distinction in the THz regime. THz imaging is highly sensitive to disease tissues due to the water concentration attenuation. Therefore, soft tissues present evidence of water absorption with the THz measurements, resulting in a contrast distinction between adipose tissue and muscle. Consequently, THz imaging can be able to map tumors in early stages by distinguishing healthy tissues from basal cell carcinoma. The most promising approaches are those non-invasive THz imaging procedures, such as THz-TDS [41], THz pulsed imaging, THz CW [42], and any other THz emitter-detection generation.

1.2.2.1. Breast cancer ex-vivo and in-vivo

Cancer is an important public health concern in the United States and worldwide. To provide an up to date perspective on the occurrence of cancer, the American Cancer Society presents an overview of breast cancer frequency statistics [43-45]. Approximately 39,900 cases of breast carcinoma were diagnosed in 1999 [43]. Approximately 56,900 cases of breast carcinoma were diagnosed in 2000 [45]. Approximately 234,190 cases of breast carcinoma were diagnosed in 2015 [44]. According to these statistics, the incidence rates of breast cancer is dramatically increasing and becoming a significant public health concern. Breast cancer is the most common cancer among women, both in developed and developing countries. Consequently,
breast cancer in women is the second most frequently diagnosed cancer after lung cancer. On the other hand, it is far less common for men.

THz imaging systems ensure the enhancement in the detection of swelling tissues that can lead to the detection of cancer by obtaining information in the frequency and Time-Domain from its coherent technique. THz imaging can provide not only sharp images but also molecular fingerprinting of the diseased area. Due to the uncertain, erroneous, or negligent conventional detection, diagnoses are not always impeccable. As a result, each year thousands of millions of biopsies of breast tissues worldwide are required to be compensated for insufficient or lack of diagnoses and incorrect treatment.

THz imaging systems have been recently utilized to conduct breast cancer research in ex-vivo and in-vivo breast tissue programs for carcinomas using the recently introduced TPS device [41, 46]. The TPS device uses broadband sources of pulsed radiation typically 0.1THz to 3THz with the resolution between 40µm to 50µm [46]. The TPS radiation penetrates much deeper in healthy breast tissue because it is composed mostly of adipose tissue rather than water content [46] as in skin tissues.

The research program shows that 60% of women diagnosed with breast cancer underwent breast preserving surgery [41]. In light of histology information, inability to remove the whole disease with a sufficient margin of normal tissue happens in about 15-20% of cases and leads an increased risk of a second operation [41]. Consequently, the second surgery increases even further the potential of bigger injury causing a risk of wound infection and psychological trauma to the patient with increasing the cost of health care.
The fibrous tissue and cancer can be differentiated by examining the THz pulse integral and the FWHM [47]. THz imaging system has demonstrated a sensitivity of 90% and a specificity of 8% for ex-vivo breast cancer tissue [47]. As a result of specimens analyzed, healthy tissues were diagnosed from diseased tissues with an excellent accuracy of 98% [47]. Subsequently, surgeons can rely on the THz imaging system performance for patient diagnosis and treatment with a reduced likelihood of a second operation.

Figure 3 illustrates the actual THz imaging for the breast cancer ex-vivo and its histology. THz images with a dark color represent the THz radiation absorbed by water content in the tissue. On the other hand, the red color contrast represents the actually diseased region of the human tissue, which is perfectly reflected in the histology image.

Figure 3. Clinical images of the ex-vivo breast carcinoma followed by the histology. In the Emax image, all tissue is shown tumor and surrounding adipose tissue. In Emax/Emin, only the tumor is visible and correlates well with the tumor as shown in the histology image [41].

1.2.2.2. Skin cancer ex-vivo, in-vivo, and in-vitro
Skin cancer is an equally harmful variety and shows an increasing trend. To provide an up to date perspective on the occurrence of skin cancer, the American Cancer Society presents an overview of skin cancer frequency statistics [43-45]. Approximately 54,000 cases of basal and squamous carcinoma, 44,200 melanoma carcinomas, and 9,800 other non-epithelial skin carcinomas were identified in 1999 [43]. Approximately 56,900 cases of basal and squamous carcinoma, 47,700 melanoma carcinoma, and 9,200 other non-epithelial skin carcinomas occurred in 2000 [45]. Approximately 80,100 cases of basal and squamous carcinoma, 73,870 melanoma carcinomas, and 6,230 other non-epithelial skin carcinomas were diagnosed in 2015 [44]. According to these statistics, the incidence of basal and squamous carcinoma, as well as melanoma carcinoma, is increasing dramatically. The other non-related epithelial skin cancer is relatively decreasing.

THz imaging systems have also focused on the research of skin carcinomas [46]. The image of diseased skin is exhibited by the THz spectrum that sits in the far IF range.

Light-skinned populations suffer from higher risk of developing skin cancer BCC [48], the most common skin cancer worldwide. According to the aforementioned statistics from the American Cancer Society, the incidence of BCC has doubled in the USA from 1999 to 2015. The diagnoses of the BCC are always based on visual evaluation in which a margin of error can be introduced by naked eye diagnosis. When a suspicious superficial BCC tumor with the size of 15 mm is present [7], the surgeon simply removes the BCC tumor by surgical procedure [7, 48, 49]. The pathologist decides whether or not the section of the tumor is clear. This technique is, therefore, time consuming and expensive [7]. Consequently, the THz imaging system is capable
of identifying areas of BCC tumors below the skin surface with an accuracy of 98% that is not visible to the naked eye and not sensitive to other techniques.

A research program was conducted with 18 BCC volunteers ex-vivo [48] and 20 volunteers in-vivo [8], where the diseased region was scanned with a TPI system [48]. A 3-D image of the diseased region was created from the reflected THz pulses during the scanned procedure [8, 48, 50]. As a result, healthy as well as diseased tissues from the same patient were analyzed within the same scanned procedure [8, 48]. The resulted analysis showed a tremendous difference between the healthy and diseased tissues [48]. Those tissues that did not show any contrast with the THz imaging system were histologically analyzed and proven to be healthy.
tissues [48]. Also, analyzes in-vitro were conducted in 15 BCC specimens to investigate any contrast between the healthy and diseased tissues [7].

Figure 5 shows an actual analysis of in-vivo and in-vitro skin carcinomas with the THz images showing a major source of contrast (blue color) due to water THz absorption [48].

Figure 5. (a) THz TPI system. (b) Clinical images of the in-vivo and in-vitro skin carcinomas followed by the THz images. In the THz images, the diseased region is shown in red and the THz radiation absorbed by the water content is represented by the blue background [48, 50].

1.2.3. Monitoring and spectroscopy in pharmaceutical

Pharmaceutical pill coatings control the release of API [51] to ensure the biocompatibility, safety, and efficacy of the drug product. The most critical attribute for pills in
the pharmaceutical industry is their ability to maintain optimum hardness level [51]. This can be related to their predisposition to fracture and ability to survive further processing by their disintegration and dissolution properties. During the scale-up and fabrication process for the successfully finished dosage form, it requires constant monitoring [51]. Consequently, current techniques for pill hardness measurement are destructive without any method of the pill failure identification [51]. The most often technique for hardness measurement is based on diametric compression testers [52]. This measurement technique results in many inconsistencies especially in the measurements of unusual asymmetric pills [51]. In order to overcome these limitations, near-IF spectroscopy technique [51] is utilized, but it relies on pill surface reflectance. On the other hand, a TPS [51] system can be employed as a non-destructive means of pill hardness measurement that can identify possible causes of failure with the TPI [53].

THz imaging system [53] has been used during pill tests to identify any signs of pill failure occurring throughout the pill core with non-destructive 3D images. TPI system can also determine thickness [53], uniformity, distribution, and coverage of simple and complex pill coating.

The THz pulsed spectroscopy can also be used to investigate solid state properties of API’s, especially in the field of polymorph [54] and quantification. Therefore, TPS system has been utilized to investigate amorphous to crystalline transformations as well as dryness of medicine molecules [54]. This is because the TPS probe intermolecular vibration effect is more sensitive to the crystalline state of materials [54]. Due to low photon energy, the THz radiation source ensures non-destructive action to the chemical bond [53] and no thermal effect because of low average power. The risk of solid state phase changes can, therefore, be minimized because of the THz source low average power.
It is also potentially possible to investigate falsified medicine by utilizing the THz-TDS [55] due to the implications associated with the active ingredient’s toxicity. Differences in the active ingredients of the adhesive substances of the falsified medicine make a tremendous threat to customers due to the toxicity of the pharmacology [55].

TPI system, Figure 6(a), can reveal cracks, dislocations, and determination in single as well as in multilayer cores [51]. In the THz wave, Figure 6(b), the letter “a” corresponds to the air pill surface interface, while the letter “b” indicates the interface between film coat and pill core [51]. The image Figure 6(c) represents the cross-sectional depth profile of the pill structure where the arrow specifies the interface between film coat and pill core [51]. The image in Figure 6(d) represents a false color image of the spatial distribution of coating layer thickness given in µm color bar. The histology graph in Figure 6(e) is the layer thickness of the outer coating x-axis in µm [51].
1.2.4. Semiconductor industry

THz system in the semiconductor has been successfully developed as an innovative TDR system [56, 57]. The THz TDR system was introduced to isolate faults in advanced IC packages. The THz TDR system is also utilized for non-destructive identification for both 2D and 2.5D [58] with TSV structure of flip-flop packages. The experimental results demonstrated high accuracy of the THz TDR system in determining the defected distance compared to the traditional TDR
system [57, 59]. The TDR system was the traditional technique to isolate faults in IC packages for many years [60]. It became a useful instrument used to determine the majority of the dead open and resistive open failures at the package level [58]. The THz TDR system based on the electro-optical THz pulse reflectometry system uses photoconductive THz pulse generation and detection technology. In contrast to the traditional TDR system, the THz TDR system provides high measurement bandwidth, low time base jitter and high time resolution. The injected THz pulse reflects off faults within the DUT locating the position with an accuracy of 10μm compared to the TDR with 500μm [61]. The unit is used to identify and quickly isolate faults on advanced packages, such as Flip chips, PoP, and TSV[61].

The THz TDR pulses are then launched into the DUT and portions of the pulse are reflected back. Portions of the pulses from the THz on the DUT are reflected back encountering changes in impedance as open or short circuit within the integrated circuit. The reflected waveforms are recorded as a function of time. A failed device impedance profile is compared by using a comparative mode of a good device and bare substrate as two reference impedance profiles.

Figure 7(a) depicts the actual photograph of the IC board. THz TDR distance to defect generates a measurement with actual integrated circuits. The measurement shows the generating failed device impedance profile by using a comparative mode from the faulty DUT distance, Figure 7(b).
Figure 7. (a) THz TDR system. (b) Interconnect integrity in advance IC package. Device A and B both have a FIB cut in an identical trace. (c) The position of the cut is separated by 89 um in the device [62].

1.3. Summary

Many THz sources [63] have been supporting a wide variety of applications, among them, security screening, medical THz imaging, monitoring and spectroscopy in the pharmaceutical, and semiconductor industry, but they are bulky and need a temperature cooling system to operate at room temperature. Therefore, they cannot be integrated with CMOS [64] platform. CMOS technology is based on silicon signal processor components such as pre-amplifier, the lock-in amplifier, and even analog to digital converters. Nevertheless, the scaling of CMOS with other Si-based devices does not result in increased device performance. In
addition, the frequency performance of the CMOS technology degrades with frequencies higher than 712GHz [65] with rapidly falling power [66] as well. In order to overcome the aforementioned constraints presented with the CMOS technology, the III–V semiconductor-based components are introduced to the CMOS platform to offer superior performance where application requirements cannot be achieved with a Si-based platform. Therefore, the III–V semiconductor materials provide the CMOS platform with superior frequency response, gain, SNR, and power performance for all THz applications.

Integrating LTG-GaAs thin film devices on bow-tie PCAs patterned on a silicon host substrates are feasible for integrated on-chip THz source systems. Therefore, integrated THz emitter-detector PCA sources for on-chip THz sources bring tremendous size compactness and cost reduction difficult to obtain with traditional conventional bulk THz sources.

1.4. Scope of the dissertation

The advent of the integrated THz PCA sources will benefit all applications that rely on conventional bulk THz [67] sources for their generation and detection of THz wave radiation. The efficient integrated THz system developed in this dissertation will provide enhancement to the SNR, advantages in compactness, performance, complexity, and cost reduction difficult to realize in conventional bulk THz sources.

Section 1 showed several applications utilizing the THz imaging system in the homeland security and screening, in the medical field, in the pharmaceutical industry, and in the semiconductor industry.
Section 2 introduces the physical dimensions of the bow-tie PCA’s design challenges with an elaborate mathematical model. The PCA’s design is incorporated with four main components. The first component is created with a pair of rectangular electrode tips attached to a second component, the bow-tie radiating shape. The radiating bow-tie structure is designed to keep a flare angle at 90° for better performance in order to maintain its radiation spreading gradually outward. At this point, a mathematical model was developed to relate the resonance frequency with its length. Subsequently, a third component is created as a pair of DC bias transmission lines attached to the radiating bow-tie structure at each lateral side. Each transmission line is then connected to a pair of circular pads that serve to bind the wires, as the fourth component. Finally, a thin film known as LTG-GaAs is designed with a pair of rectangular micro contacts on the back side of the film. The designed rectangular micro contact pairs are separated from each other for connectivity to the rectangular electrode tips on the bow-tie antenna structure.

Section 3 presents the bow-tie PCA’s simulation challenges performed based on the computer simulation CST-MWS-TS to analyze its performance. This analysis is based on the S-parameters, Smith Chart, impedance magnitude analysis, 3D radiation pattern, 2D directivity, and, e-field distribution. Comsol Multiphysics is utilized for the static electric field simulation on the semiconductor platform. The TCAD is engaged to obtain a numerical simulation on the semiconductors for the integrated as well as for the conventional PCA devices.

Section 4 introduces the bow-tie PCA device patterned on a SiO\textsubscript{2}/Si host substrate and its integration with the LTG-GaAs thin film manufactured using sequential fabrication steps. First, the LTG-GaAs thin film devices are obtained with standard photolithography, thermal evaporation of metal contact layers, and with selective wet etching processes. The AlAs layer is
etched selectively to separate the LTG-GaAs thin film layer from its native SI-GaAs substrate. Second, the bow-tie emitter-detector antennas are patterned on a SiO₂\Si host substrate with photolithography, thermal evaporation with metal layers, and lift-off process. Finally, the LTG-GaAs thin film devices are heterogeneously integrated on the bow-tie emitter-detector antenna electrodes. The wafer-scale manufacturing method needs a precise automatic alignment of thin-film devices on assigned integration locations. Consequently, a thin-film device arrangement has been optimized in the silicon host substrate which does not interfere with a post layer by layer process. The thin film device arrangements provide the best performance of both the thin-film devices and the silicon-based electronics.

Section 5 explains two types of PCBs designed and fabricated in order to mount the bowtie-tie emitter-detector antennas. The designed PCB with no space to carry a hyper-hemispherical Si lens is assigned to the bow-tie emitter antenna. Alternatively, the bow-tie detector PCB is designed in a circular shape fashion to use an X-Y mounting stage able to carry a hyper-hemispherical Si lens for SNR boost. In order to facilitate the testing and the THz characterization, the emitter and detector antennas are assembled with the designed PCBs to bond wires using an ultrasonic wire bonding for connectivity to the subminiature connectors.

Section 6 shows the bow-tie PCA packaging and wire bonding for the emitter-detector antennas. The packaging is performed on each of the designed PCBs and then wires are bonded to each PCAs mounted on the PCBs.

Section 7 presents the photoconductive antenna and the RF/MW setup and the discussion on their dissimilar technique in generating electromagnetic waves. It is also presented how the THz radiation from the fabricated THz emitted-detector antennas are characterized using a pump
and a probe THz TDS configuration. The integrated bow-tie and the conventional bow-tie antennas are compared based on design and fabrication using dissimilar techniques. In the integrated bowtie antenna patterned on a SiO₂\Si host substrate, the incident optical pump beam excites the back side of the LTG-GaAs thin film device. On the other hand, the conventional bow-tie patterned on a bulk GaAs substrate is excited with the incident optical pump beam between the rectangular electrode tips on the same bulk GaAs substrate. Applying DC bias voltages of 5V, 15V, 25V, and 35V on both bow-tie antennas with dissimilar fabrication techniques allow the evaluation of the THz wave radiation. The static electric field effect from the voltage variation is then analyzed in both antennas based on their structure performance.

Section 8 presents the results obtained by measuring the dark current and photocurrent of the integrated bow-tie PCA. It is also shown the THz radiation obtained from the TDS characterization and the Fast Fourier power spectrum. The THz wave radiations are obtained by measuring the DC bias voltage variations. On the other hand, the Fast Fourier power spectrums are obtained from the THz wave radiations.

Section 9 presents the conclusion and future research work.

Finally, Appendix and references are presented in Section 10.

2. **Bow-tie PCA structure design, LTG-GaAs thin film design, integration method design, dissimilar optically active semiconductors, and modeling**

2.1. **Introduction**
The resonance frequency response and the influence of the permittivity of the semiconductor substrate dictate the length of the antenna device. On the other hand, the antenna width is determined by the geometric parameters of the bow-tie PCA structure described by a mathematical model, illustrated in Section 2.2. The antenna frequency response and the carrier lifetime of the photoconductive medium determine the ultimate performance of the PCAs, discussed in Section 2.5 and Section 2.6.

Antennas are devices to optimize and control the emitted radiation into free space by coupling the electrical energy from the input circuit (photo-absorption medium). The system must be designed such that the generated THz wave from the photo-absorption of the ultrafast photoconductor medium can be coupled to a radiating metallic planar antenna. The antenna consists of two metallic planar parts forming a small gap at the feed point. However, the design of this kind of antenna has some challenges with impedance matching between photoconductor medium (source) and antenna. The intrinsic LTG-GaAs photoconductor medium demonstrates much higher values of impedance around 10kΩ [68] compared to 65.5Ω measured in the metallic antennas [69]. Preu et al [37] have demonstrated that a typical antenna impedance range is between 20 Ω to 100 Ω at 1 THz.

Because of the low impedance of the metallic patterns, the antenna becomes more sensitive to low frequencies rather than high frequencies [70]. For this reason, impedance matching at THz regime for maximum power transfer is unachievable between the high resistive LTG-GaAs thin film source and the low resistive antenna [71, 72]. As a result of impedance mismatch, the antenna performance directly impacts the performance of the photoconductive medium causing limitations in the radiated THz power. The DC bias voltage and the incident optical pump power also impact the THz photocurrent generation, which limits the THz radiation
power as well. A coherent single cycle of emission of THz radiation from a small gap antenna is similar to a Hertzian dipole antenna [73].

2.2. The bow-tie emitter-detector PCA radiating metallic planar medium design

The design of the antenna starts by establishing several important parameters to determine the dimensions of the structure. The effective length ($W_l$) of the integrated bow-tie PCA is designed with an effective half wavelength ($\frac{\lambda_{eff}}{2}$) patterned directly on the dielectric substrate. The effective antenna wavelength ($\lambda_{eff}$) is given by $\frac{v_{eff}}{f_r}$, where $v_{eff}$ is the propagating phase velocity on the antenna’s surface due to the induced current and $f_r$ is the resonant frequency. Therefore, the effective propagating phase velocity is expressed by $\left(\frac{c}{\sqrt{\varepsilon_{eff}}}\right)$, where $c$ is the speed of light in vacuum and $\varepsilon_{eff}$ is the effective permittivity of the antenna, in a half dielectric substrate ($\frac{\varepsilon_{sub}}{2}$) and in a half free-space ($\frac{\varepsilon_{air}}{2}$). Consequently, the effective permittivity ($\varepsilon_{eff}$) [74, 75] is given by $\frac{\varepsilon_r + \varepsilon_{air}}{2}$, ($\varepsilon_{sub}, \varepsilon_r$: 11.68 for silicon) and ($\varepsilon_{air}$: 1 for air). Finally, the effective bow-tie PCA length ($W_l$) is calculated based on the empirical equation, which is derived by using the expressions of the above mentioned parameters [67]:

$$W_l = \frac{\lambda_{eff}}{2} = \frac{1}{2} \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}}$$

(1)

$$\varepsilon_{eff} = \frac{\varepsilon_{sub} + \varepsilon_{air}}{2} \left\{ \begin{array}{l} \varepsilon_{sub} = \varepsilon_r \\ \varepsilon_{air} = 1 \end{array} \right.$$ 

(2)
\[ WL = \frac{c}{2 \ast f_r \ast \sqrt{\varepsilon_r + 1}} \]  \hspace{1cm} (3)

In general, the THz power decreases dramatically between the values of 1-2 THz region [76]. Again, bow tie PCAs demonstrate higher sensitivities around 0.5 THz [77]. Thus, the bow-tie PCA in this dissertation is designed to operate with a resonance frequency of 0.30THz in order to take into account its sensitivity. As such, the effective antenna length (WL) is calculated based on the expression given by Equation (3), resulting in a value of 200\textmu m patterned on a silicon host substrate (\(\varepsilon_r\):11.68). Three important parameters should be taken into consideration, small thickness, height resistivity, and low permittivity, for any chosen arbitrary host substrate to perform efficiently in the THz region. The resistivity measurement of the Si is discussed in Section 4.2.1.

Subsequently, based on the bow-tie PCA geometry relationship shown in Figure 8, the antenna width (Ww) is then calculated from the mathematical model illustrated in Equation (4).

\[ W_w = WL \tan\left(\frac{\varphi}{2}\right) - \left[\left(2W_{tip} + W_{gl}\right)\tan\left(\frac{\varphi}{2}\right) - W_{gw}\right] \]  \hspace{1cm} (4)

Where (\(\varphi\)) is the flare angle with 90°, Wtip is the electrode tip length with 20\textmu m, Wgl is the photoconductive gap with 20\textmu m, and Wgw is the electrode tip width 10\textmu m. Then all previous data are substituted in Equation (4) to obtained the bow-tie PCA width (Ww) with a value of 150\textmu m.
2.3. The LTG-GaAs thin film design

The bow-tie PCA’s electrode tips are incorporated in the design with fixed dimension values of 10µm width (Wgw) and 20µm length (Wtip). The flare angle of 90° is maintained during the design. The 20µm (Wgl) gap between the bow-tie electrode tips is designed to match the dimension of the electrical micro contacts on the LTG-GaAs thin film device, Figure 9. The length (Wl) and the width (Ww) values of 200µm and 150µm, respectively, Figure 8, are obtained in Section 2.2.

Figure 9 shows the schematic of the individual designed LTG-GaAs thin film mesa device. The dimension of the LTG-GaAs thin film mesa device is 30µm width (TW) by
60µm length (TL) with a thickness of 2.0µm. It has a pair of electric micro contacts with a dimension of 20µm by 15µm separated from each other by 20µm.

![Diagram showing the LTG-GaAs thin film structure](image)

Figure 9. The LTG-GaAs thin film pictographic illustration of the designed structure with metal micro contacts of 20µm by 15µm separated from each other by 20µm.

### 2.4. Integrating the LTG-GaAs thin film on a bow-tie PCA structure and the SI-GaAs bow-tie PCA structure

During the LTG-GaAs thin film mesa device integration [39], the electrical connection has to be achieved through gold metal to metal bonding between the LTG-GaAs thin film mesa device’s metal micro contacts and the bow-tie antenna’s metal rectangular electrode tips. In order to apply a DC-biasing voltage to the bow-tie emitter-detector PCAs, two lateral circular terminals of 100µm (Td) in diameter are connected to each lateral biasing transmission line of 201µm (Lpd) in length and 6µm width (Wpd), respectively, Figure 10(b). During the integration process, the LTG-GaAs thin film mesa device is inverted so
that the electrical micro contact pads from the LTG-GaAs thin film device are bonded to the bow-tie emitter-detector PCAs’ rectangular electrode tips. The bow-tie antenna is patterned on any host substrate. A schematic of the front side of the integrated bow-tie PCA with the LTG-GaAs thin film mesa device is shown in Figure 10(c).

![Figure 10](image.png)

**Figure 10.** The pictographic view illustrating the integrated bow-tie PCA structure. (a) LTG-GaAs thin film mesa device with a pair of micro contacts. (b) Coplanar bow-tie PCA with rectangular electrode tips connected to lateral transmission lines and circular terminals. (c) Integrated bow-tie PCA patterned on a SiO₂\Si host substrate.

On the other hand, the same bow-tie antenna shape design, Figure 11(b), is also utilized to be patterned on the conventional GaAs substrate. The conventional GaAs substrate is composed of three layers the LTG-GaAs\AlAs\SI-GaAs with thickness 2.5µm\0.25µm\497µm, as shown in Figure 11(b) and Figure 12.
Figure 11. The pictographic view illustrates the bow-tie PCA structure on the conventional GaAs substrate. (a) Coplanar bow-tie PCA with rectangular electrode tips connected to lateral transmission lines and circular terminals. (b) The bow-tie PCA patterned on the conventional GaAs substrate.

2.5. Comparative study of the LTG-GaAs thin film epitaxial layer and the conventional bulk GaAs semiconductor

2.5.1. LTG-GaAs thin film epitaxial layer

The LTG-GaAs epitaxial layer is GaAs grown at a temperature of 200 °C-300°C, usually with a slight excess of Arsenic. The temperature of 200°C-300°C can substantially reduce back-gating, side-gating, and light sensitivity in metal-semiconductor field effect [78]. The properties of the LTG-GaAs depend on the degree of post growth annealing. It can be produced with high resistivity [79] and with sub-picosecond carrier-life time making this ideal for ultrafast photodetectors that are based on displacement current. Moreover, the response time is limited by
the recombination life-time of photo-generated carriers [78]. The important property of the LTG-GaAs is its specific resistivity which increases tremendously after an anneal at 600°C for 10 minutes by about 5 orders of magnitude [78]. The As grown material has the resistivity of 10-10^2Ωcm, which increases as a function of the anneal temperature aforementioned. Annealed LTG-GaAs has the resistivity of 10^6 - 10^7Ωcm compared to about 10Ωcm for normal grown GaAs and 10^5Ωcm for the SI-GaAs substrate [78]. During the annealing step, the excess arsenic is coalescing to precipitate. The material relaxes and the lattice constant recovers to the value of normal MBE grown GaAs. In annealed LTG-GaAs, metal-like clusters of arsenic act like buried Schottky barriers [78]. When the number of these precipitates is high enough, the depletion region will overlap and the material in between the As clusters becomes highly resistive [78, 79]. The LTG-GaAs material contains deep defects with concentrations as high as mid-gap 10^19cm^-3 [78].

The other important characteristic of the LTG-GaAs material is the sub-picosecond carrier lifetime. This characteristic of LTG-GaAs material has a strong impact on the fabrication of ultrafast MSM type photodetectors. The carrier lifetime of the LTG-GaAs is obtained by measuring the transient reflectivity [80]. The time decreases with decreasing growth temperature [80]. When the LTG-GaAs material is grown above 300°C, the carrier lifetime strongly increases towards the radiative carrier lifetime of normal GaAs of 1ns. The carrier lifetime below 300°C is about 0.25-0.3ps [80].

In the integration device, the AlAs layer is etched away selectively to separate the LTG-GaAs thin film epitaxial layer from the native SI-GaAs substrate. The optically active LTG-GaAs thin film is around 2.0µm thick epitaxial layer. So, in order to investigate the antenna
device integration technique, the 2.0µm thick LTG-GaAs thin film epitaxial layer will be discussed in Section 4.

2.5.2. Conventional bulk GaAs semiconductor

It was already mentioned in Section 2.5.1 that the resistivity of the normal grown GaAs and the conventional bulk GaAs substrate are 10Ωcm and 10⁵Ωcm, respectively. The conventional bulk GaAs substrate layered with LTG-GaAs/AlAs/SL-GaAs substrate and thickness of 2.5µm/0.25µm/497µm is the material used in the photo switching, illustrated in Figure 12. The conventional bulk GaAs exhibits crystal defects, due to the presence of dangling bonds at interfaces or due to the presence of impurities in the substrate [81, 82]. The EL2 defect is the dominant deep donor in undoped GaAs crystals, which are grown under As-rich condition. At low temperature and illuminated with a white light at 1.18eV, the deep EL2 level disappears. Therefore, the defect was no longer detected by any experimental method [83, 84]. Heating the sample to the temperature higher than 140 K brings the defect and its deep level back in full concentration [85]. Optically or thermally inducible defect metastabilities have been well known for years [86]. The best understood metastable centers are iron-acceptor pairs [85]. If EL2 is present in the conventional bulk GaAs, the semi-insulating behavior can be obtained. The EL2 energy is an electron trap found in the conventional bulk GaAs [87]. It was commonly assumed that the only defect of any importance in compensation considerations was EL2. However, with the advent of increasingly pure materials, it has become clear that even shallow defects must be now included in any realistic compensation model. Moreover, high-temperature processing,
which is necessary to improve material uniformity or to make devices, can cause important modifications in the types and numbers of these shallow defects and can thus drastically affect the resistivity. Many impurities levels have been positively identified in GaAs.

There are three compensation structures in SI-GaAs. They are DDSA [88], SDDA [89], and DDDA [89]. The DDSA mechanism for SI-GaAs behavior is the compensation of EL2 by carbon acceptors [90, 91]. This means that a balance is obtained between the deep lying EL2 and the shallow acceptor impurity. The balance is obtained between Cr deep level acceptors and Si shallow donors in the SDDA compensation structure scheme. The EL2 is compensated by Cr deep level acceptors in DDDA.

Figure 12. The bow-tie antenna patterned on the conventional bulk GaAs substrate with layered thickness.
2.6. Modeling the bow-tie PCA on a conventional bulk GaAs substrate and the LTG-GaAs thin film integrated on the bow-tie PCA

2.6.1. Introduction

The conventional RF/MW and the THz PCAs technologies rely on different techniques to generate and transmit electromagnetic waves, which are utilized to understand the difference from each other. The summary is presented in Table 2.

In the conventional RF/MW technology, the resistance of the transmission line has a constant value and it is considered as the source resistance for the antenna. The input $V_{in}$ is commonly transferred to the antenna through the transmission line, as illustrated in Figure 13(a).

In the THz PCA technology, the photo-absorption medium with impedance $Z_s$ acts as the current source for the PCA. The $V_b$ generates DC electric field to provide kinetic energy to the electrons. Because of the time varying behavior of optical source and the photo-absorption medium response, the source impedance is time-varying. The related equivalent circuit of the THz PCA is illustrated in Figure 13(b). Thus, source impedance is one of the major differences between the conventional RF/MW antenna and the THz PCA, Figure 13.
Figure 13. (a) The conventional RF/MW antenna model representation. (b) The THz PCA representation.

Table 1 describes briefly the difference between the two dissimilar technologies for the electronic side and the THz PCA side.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RF/MW antennas</th>
<th>THz PC antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation source/feeding</td>
<td>Transmission line</td>
<td>Optical laser pulse</td>
</tr>
<tr>
<td>DC biased voltage</td>
<td>Unbiased</td>
<td>Emitter: Biased</td>
</tr>
<tr>
<td></td>
<td>Unbiased</td>
<td>Receiver: Unbiased</td>
</tr>
<tr>
<td>Substrate material</td>
<td>Low loss dielectric</td>
<td>High resistive semiconductor</td>
</tr>
<tr>
<td>Antenna material</td>
<td>High conductive metals</td>
<td>Au/Cr, Au/Ti</td>
</tr>
<tr>
<td>Current type</td>
<td>Conduction current</td>
<td>Drift and displacement currents</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Small and large facilities</td>
<td>Expensive and sophisticated</td>
</tr>
<tr>
<td>Computer aid design</td>
<td>Available</td>
<td>No in one package</td>
</tr>
</tbody>
</table>

Table 1. Illustrates the overview of the two dissimilar techniques.
The physical basis for the proposed pulsed THz system is electron-hole pair generation by photo-absorption in the LTG-GaAs thin film epitaxial layer and the SI-GaAs substrate, respectively. Table 2 shows the material properties between the LTG-GaAs thin film epitaxial layer and the SI-GaAs substrate.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value for LTG-GaAs thin film</th>
<th>Value for SI-GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature, $T_o$</td>
<td>300 °K</td>
<td>300 °K</td>
</tr>
<tr>
<td>Laser central wavelength, $\lambda$</td>
<td>800nm</td>
<td>800nm</td>
</tr>
<tr>
<td>Optical average power density, $I_o$</td>
<td>0.25 W/mm$^2$</td>
<td>0.25 W/mm$^2$</td>
</tr>
<tr>
<td>Absorption coefficient, $\alpha$</td>
<td>10000 cm$^{-1}$</td>
<td>10000 cm$^{-1}$</td>
</tr>
<tr>
<td>Electron lifetime, $\tau_{ne}$</td>
<td>0.1 ps [92]</td>
<td>100 ps [93]</td>
</tr>
<tr>
<td>Hole lifetime, $\tau_{np}$</td>
<td>0.4 ps [92]</td>
<td>100 ps [93]</td>
</tr>
<tr>
<td>Electron velocity, $v_{ne}$</td>
<td>4x10$^4$ m/s</td>
<td>4x10$^4$ m/s</td>
</tr>
<tr>
<td>Mobility, $\mu$</td>
<td>200 cm$^2$/Vs [67]</td>
<td>8500 cm$^2$/Vs [94]</td>
</tr>
<tr>
<td>Resistivity, $\Omega$ cm</td>
<td>$&gt;10^7$ $\Omega$ cm [95]</td>
<td>$\approx 10^7$ $\Omega$ cm [96]</td>
</tr>
<tr>
<td>Relative permittivity, $\varepsilon_r$</td>
<td>13.18</td>
<td>13.18</td>
</tr>
<tr>
<td>Laser power, mW</td>
<td>20mW/10mW</td>
<td>20mW/10mW</td>
</tr>
<tr>
<td>Biased voltage, V</td>
<td>20V</td>
<td>20V</td>
</tr>
<tr>
<td>Gap size, $g$</td>
<td>20$\mu$m</td>
<td>20$\mu$m</td>
</tr>
<tr>
<td>Antenna thickness</td>
<td>0.2$\mu$m</td>
<td>0.2$\mu$m</td>
</tr>
<tr>
<td>Antenna length, $L$</td>
<td>200$\mu$m</td>
<td>200$\mu$m</td>
</tr>
<tr>
<td>Antenna width, $w$</td>
<td>150$\mu$m</td>
<td>150$\mu$m</td>
</tr>
<tr>
<td>Substrate thickness, $t$</td>
<td>2$\mu$m</td>
<td>2.5$\mu$m/0.25$\mu$m/497$\mu$m</td>
</tr>
</tbody>
</table>

Table 2. Physical parameters of the modeled LTG-GaAs and SI-GaAs pulsed THz [67, 92-98].

Jepsen et al. [73] have proposed a simple model based on the Drude–Lorentz theory using small dipole aperture in order to derive the radiated ultrashort THz pulses. In the model, accelerated carriers are included due to the influence of the space charges field driven by the bias field.
Usually, the dimension of the photoconductive switch is much smaller than the wavelength of the generated THz electrical pulses in small antennas. Therefore, the photoconductive switch can be modeled by an equivalent element circuit [99] operating in the THz frequency range, as illustrated in Figure 14. The modeled circuit is utilized in Section 2.6.2 with the LTG-GaAs thin film epitaxial layer and in Section 2.6.3 with the SI-GaAs substrate.

2.6.2. THz analysis based on the carrier density from the LTG-GaAs thin film epitaxial layer
The free carrier lifetime in a photoconductive antenna based on the LTG-GaAs thin film epitaxial layer can be approximately as equal to the carrier trapping time. This is because the trapping time in the mid-gap states is much shorter than the recombination time between electrons and holes [100].

The layers of electrons are assumed to account for the absorption of the light in the LTG-GaAs thin film epitaxial layer. The layers are assumed to have the same mobility and the same recombination time. The carrier lifetime in the LTG-GaAs epitaxial thin film is shorter by about 1ps [93].

The carrier density \( n(x,t) \) [92] behavior in time for the LTG-GaAs epitaxial layer can be calculated by:

\[
\frac{\partial n_{LTG-GaAs}(x,t)}{\partial t} = - \frac{1}{\hbar \nu} \frac{\partial I_{opt}(x,t)}{\partial x} - \frac{n_{LTG-GaAs}(x,t)}{\tau_{r,LTG-GaAs}}
\]  (5)

The first part of Equation (5) has the following terms: \( R \) is the reflection coefficient at the photoconductive surface, \( \hbar \nu \) is the excitation photon energy which, greater than the GaAs room temperature band gap energy of 1.42eV, \( I_{opt}(x,t) \), is the total incident laser power exciting the active photo gap, and \( x \) is the distance from the semiconductor surface. This part of the equation represents the absorption of the light which leads the generation of electron and hole pairs.

The second part of Equation (5) has the following terms: \( n_{LTG-GaAs}(x,t)/\tau_{r,LTG-GaAs} \) represents the electrons and holes recombination rate, and \( \tau_{r,LTG-GaAs} \) is the recombination/trap
lifetime of electrons in the semiconductor substrates. The second term indicates the removal of electrons from the conduction band through recombination or trapping.

Therefore, the sheet electron concentration in the LTG-GaAs epitaxial layer can be written as:

$$n_{LTG-GaAs}(t) = \int_{0}^{l} n_{LTG-GaAs}(x,t) dx$$

(6)

The thickness of the LTG-GaAs epitaxial layer is represented by the letter $l$.

Subsequently, Equation (5) with Equation (6) can be integrated [92] to yield:

$$\frac{\partial n_{LTG-GaAs}(t)}{\partial t} = -\frac{(1 - R)}{h\nu} \{ I_{opt}(l,t) - I_{opt}(0,t)\} - \frac{n_{LTG-GaAs}(t)}{\tau_{r,LTG-GaAs}}$$

(7)

$$\frac{\partial n_{LTG-GaAs}(t)}{\partial t} = \frac{(1 - R)}{h\nu} I_{opt}(0,t)\{1 - e^{-\alpha l}\} - \frac{n_{LTG-GaAs}(t)}{\tau_{r,LTG-GaAs}}$$

(8)

The linear absorption coefficient of the pump laser optical beam is $\alpha$. The other terms were aforementioned.

From the Drude-Lorentz model developed by Jepsen et al. [73], the photocurrent density and carrier dynamics are explained in three coupled differential equations describing the relation of the free carrier density, the carrier velocity, and polarization. The polarization is caused by separation of the carriers under the influence of the bias field. The equations are presented as follow:
\[
\frac{dn(t)}{dt} = - \frac{dn(t)}{dt} + G(t) \tag{9}
\]

\[
\frac{dv(t)}{dt} = - \frac{v(t)}{\tau_s} + \frac{q}{m^*} E \tag{10}
\]

\[
E = E_b - \frac{P_{SC}}{\zeta \varepsilon_r} \tag{11}
\]

\[
\frac{dP_{SC}}{dt} = - \frac{P_{SC}}{\tau_r} + J_{pc}(t) \tag{12}
\]

The carrier trapping time is \(\tau_r\) or also carrier lifetime mentioned previously. This is the average time that excess free electrons survive before falling into an energy level caused by the presence of a defect or traps. The \(q\) is the charge of the carriers. The momentum relaxation time is \(\tau_s\), also known as the carrier scattering time. This carrier scattering time is defined as the average time of electrons to move from trapping stage to an empty valence band state [101]. \(G(t)\) represents the generation rate of carriers by laser pulses. The \(m^*\) is the effective mass. \(E\) represents the electric field in the photoconductive gap. \(E_b\) represents the DC bias applied voltage between antenna electrodes. \(P_{SC}\) is the space charge polarization created by the carriers separated in the field. Finally, \(\zeta\) represents a geometrical factor [73], which is equal to three for an isotropic dielectric material.

Under laser illumination within the photo gap, the photocurrent is generated because of the movement of electrons from the valence band promoted into the conduction band. Therefore, \(n(t)\) is assumed to be the electron or free carrier density promoted into the conduction band. Subsequently, \(v(t)\) represents the velocity of carriers and \(J_{pc}(t)\) is the photocurrent (pc) density given by [102].
\[ J_{pc}(t) = -q \cdot n(t) \cdot v(t) \] (13)

The electron charge is represented by \( q \). The hole is a positive charge with an effective mass much greater than the electron, therefore, the contribution from hole to the THz current and radiation is small for which the hole is neglected in this analysis \[102\].

A coherent single cycle of emission of THz radiation from a small gap antenna is similar to a Hertzian dipole antenna. The radiated electric field from the antenna is proportional to the time derivative of the current, \( I_{pc}(t) \), or equivalently, it is proportional to the photocurrent density, \( J_{pc}(t) \) \[103, 104\].

\[
E_{THz}(t) \propto \frac{\partial I_{pc}(t)}{\partial t} \propto \frac{\partial J_{pc}(t)}{\partial t} 
\] (14)

\[
E_{THz}(t) \propto \frac{\partial J_{pc}(t)}{\partial t} = q \cdot \frac{\partial n(t)}{\partial t} \cdot v(t) + q \cdot n(t) \cdot \frac{\partial v(t)}{\partial t} 
\] (15)

\[
E_{THz}(t) = q \cdot \frac{\partial n_{LTG-GaAs}(t)}{\partial t} \cdot v_{LTG-GaAs}(t) + q \cdot n_{LTG-GaAs}(t) \cdot \frac{\partial v_{LTG-GaAs}(t)}{\partial t} 
\] (16)

THz far-field radiation \( E_{THz}(t) \) is the result of the occurrences of two events happening together, the ultrafast variation from the carrier density and the acceleration of photo-carriers. In order to enhance THz radiation from the aforementioned events, the incident power and DC bias field can be increased with limitation from the antenna device saturation.
2.6.3. THz analysis based on the carrier density from the SI-GaAs semiconductor

The layers of electrons are assumed to account for the absorption light in the SI-GaAs substrate. They are assumed to have the same mobility and the same recombination time. The SI-GaAs substrate has longer carrier lifetime of about 100ps [93] than in the LTG-GaAs thin film layer.

The carrier density \( n(x,t) \) [92] behavior in time by the SI-GaAs substrate can be calculated by:

\[
\frac{\partial n_{SI-GaAs}(x,t)}{\partial t} = -\frac{(1 - R)}{h\nu} \frac{\partial I_{opt}(x,t)}{\partial x} - \frac{n_{SI-GaAs}(x,t)}{\tau_{r,SI-GaAs}} \tag{17}
\]

The first part of Equation (17) has the following terms: \( R \) is the reflection coefficient at the photoconductive surface, \( h\nu \) is the excitation photon energy, which is greater than the GaAs room temperature band gap energy of 1.42eV, \( I_{opt}(x,t) \), is the total incident laser power exciting the active photo gap, and \( x \) is the distance from the semiconductor surface. This part of the equations represents the absorption of the light, which leads the generation of electron and hole pairs.

The second part of Equation (17) has the following terms: \( n_{SI-GaAs}(x,t)/\tau_{r,SI-GaAs} \) represents the electrons and holes recombination rate, and \( \tau_{r,SI-GaAs} \) is the recombination/trap lifetime of electrons in the semiconductor substrates. Therefore, the terms signify the removal of electrons from the conduction band through recombination.
As such, the sheet electron concentration in the SI-GaAs substrate can be written as:

\[ n_{SI-GaAs}(t) = \int_{l}^{\infty} n_{SI-GaAs}(x, t) \, dx \]  

(18)

The thickness of the SI-GaAs substrate is represented by the letter \( l \). Subsequently, Equation (17) with can be integrated \[92\] Equation (18) to yield:

\[
\frac{\partial n_{SI-GaAs}(t)}{\partial t} = -\frac{(1 - R)}{h\nu} \{ I_{opt}(l, t) \} - \frac{n_{SI-GaAs}(t)}{\tau_{r,SI-GaAs}} \]  

(19)

\[
\frac{\partial n_{SI-GaAs}(t)}{\partial t} = \frac{(1 - R)}{h\nu} I_{opt}(0, t) e^{-\propto l} - \frac{n_{SI-GaAs}(t)}{\tau_{r,SI-GaAs}} \]  

(20)

The linear absorption coefficient of the pump laser optical beam is \( \propto \). The other terms were aforementioned.

All derived equations for the SI-GaAs substrate have been similar derived as for the LTG-GaAs thin film epitaxial layer in Section 2.6.3. Therefore, only the last two resulted equations are shown without any derivation as follows:

\[
E_{THz}(t) \propto \frac{\partial J_{PC}(t)}{\partial t} = q \cdot \frac{\partial n(t)}{\partial t} \cdot v(t) + q \cdot n(t) \cdot \frac{\partial v(t)}{\partial t} \]  

(21)

\[
E_{THz}(t) = q \cdot \frac{\partial n_{SI-GaAs}(t)}{\partial t} \cdot v_{SI-GaAs}(t) + q \cdot n_{SI-GaAs}(t) \cdot \frac{\partial v_{SI-GaAs}(t)}{\partial t} \]  

(22)
$E_{THz}(t)$ is the far-field radiation.

2.7. Summary

The LTG-GaAs thin film epitaxial layer has short carrier lifetime than the SI-GaAs. The LTG-GaAs thin film epitaxial layer responds much faster (in the picoseconds or even in the subpicoseconds), shown in Equation (8), than in the SI-GaAs, shown in Equation (20). Therefore, the THz wave radiation is enhanced in the LTG-GaAs thin film epitaxial layer, shown in Equation (16), than in the SI-GaAs), shown in Equation (22). The LTG-GaAs properties are shown in Table 2 as well as for the SI-GaAs semiconductors.

3. Integrated bow-tie PCA patterned on a silicon host substrate and conventional bulky bow-tie PCA simulation

3.1. Introduction

The CST-MWT-TS package software is engaged in simulating the antenna structure in order to obtain the S-parameter in conjunction with the Smith Chart representation, antenna impedance magnitude, the 3D radiation pattern, the 2D far-field directivity, and the e-field distribution radiation. The resulted S-parameter value measured in dB should be small as possible to obtain optimal condition that indicates how well the radiation is channeled in both directions to the front and back side of the antenna with minimum lateral scattering. Most radiators emit stronger radiation in one direction that in another, known as anisotropic;
otherwise, the radiation is isotropic [105]. The 3D radiation pattern and the 2D far-field directivity can provide information whether the radiation pattern is anisotropic or isotropic. The 3D radiation pattern and the 2D far-field directivity allow seeing any presence of undesired lateral side lobes generated on the main lobe. Consequently, the presence of undesired lateral side lobes can impact tremendous the main lobe radiation power. The 2D far-field directivity also provides information about the radiation direction of the antenna. Subsequently, in order to investigate the behavior of the e-field radiation on the integrated bow-tie PCA and on the conventional bulk bow-tie PCA, the e-field simulation is performed to analyze the distribution radiation at the resonance frequency where the bow-tie PCA is optimized. The static electric field distribution in the LTG-GaAs thin film and in the conventional bulk GaAs semiconductors is represented hypothetically by pictorial views. The pictorial views allow a better understanding of the behavior of the static electric field distribution in each of the aforementioned dissimilar semiconductor materials. Comsol Multiphysics is employed to simulate the static electric field distribution to facilitate the generation of the THz radiation in both dissimilar semiconductor materials. Finally, the TCAD is engaged to obtain a numerical simulation on the semiconductors for the integrated as well as for the conventional PCA devices.

3.2. S-parameter simulation based on the antenna length variations

The S-parameter investigation begins with the analysis of the antenna length variations performed with the CST-MWT-TS simulation, as illustrated in Figure 15. This study is
accomplished in order to achieve the lowest possible S-parameter value for the optimally integrated bow-tie PCA performance, as illustrated in Figure 15(a). The lowest obtained value for the S-parameter can avoid lateral scattering direction channeling most of the THz radiation to the back and to the front side of the antenna. Therefore, the lowest obtained value for the S-parameter represents the maximum power transfer that the integrated bow-tie PCA can receive and radiate.

In order to find the optimal condition for the integrated bow-tie PCA, simulations for each antenna length variations are performed. Figure 15(1-3) illustrate the integrated bow-tie PCAs with variations in lengths for comparative analysis with the conventional bulk bow-tie PCA, Figure 15(4). The integrated bow-tie PCA length variation values are 80μm in Figure 15(1), 120μm in Figure 15(2), 160μm in Figure 15(3), and 200μm for the conventional bulk bow-tie PCA in Figure 15(4). The antenna width is kept constant at 150μm for the S-parameter analysis. The integrated bow-tie PCA with length values of 80μm, 120μm, and 160μm show frequencies response values of 0.4534THz, 0.3588THz, and 0.3296THz. Therefore, the S-parameter values are obtained at -26.787dB, -19.036dB, and -15.001dB, respectively. The integrated bow-tie PCA with the length of 80μm shows higher frequency response than for the integrated bow-tie PCA with 160μm in length. Therefore, the optimal frequency response value of 0.2349THz with the optimal S-parameter value of -32.043dB are achieved when the integrated PCA length is at 200μm, illustrated in Figure 15(a) marked with the number 4. On the other hand, the S-parameter value for the bow-tie PCA patterned on the surface of the conventional bulk GaAs substrate is obtained at -19.684dB with a frequency response of 0.21615THz. The bow-tie PCA on the conventional bulk GaAs substrate shows much higher S-parameter (not a good result) than with the optimally integrated bow-tie PCA. The integrated bow-tie PCA and
the conventional bulk bow-tie PCA are simulated with the same antenna dimensions to obtain the lowest S-parameter for optimal results, illustrated in Figure 15(a).

Figure 15(b) illustrates the directivity for the integrated bow-tie PCA length values of 80μm (right-hand side), 120μm (middle side), and 160μm (left-hand side). The directivity provides information about the radiation direction of the antenna. The integrated bow-tie PCA with the length value of 80μm shows strong lateral scattering radiation at ±50° and ±130° with a weak radiation channeled to the front (180°) and back (0°) sides of the antenna. The integrated bow-tie PCA with the length value of 120μm shows stronger lateral scattering radiation at ±90° with a weak radiation channeled to the front (180°) and back (0°) sides of the antenna. The integrated bow-tie PCA with the length value of 160μm shows stronger lateral scattering radiation at ±90°, ±30°, and ±150° with a weak radiation channeled to the front (180°) and back (0°) sides of the antenna. Therefore, the directivity for the integrated bow-tie PCA with lengths of 80μm, 120μm, and 160μm did not show any efficient radiation channeled to the front (180°) and back (0°) sides of the antenna. Once the integrated bow-tie PCA reaches the length of 200μm, the antenna achieves an efficient radiation channeled to the front (180°) and back (0°) sides of the integrated bow-tie PCA without lateral scattering side-lobes. The 3D radiation patterns, as well as the directivities for the integrated bow-tie PCA and the conventional bulk bow-tie PCA for their optimal condition values, are presented in Section 3.7.
Figure 15. The Integrated bow-tie PCAs with length variations of 80μm, 120μm, 160μm, and the conventional bulk bow-tie antenna with the length of 200μm having a constant width at 150μm. (a) The S-parameter analysis. The optimal condition is achieved for the integrated antenna with a length of 200μm, indicated in red with a marker number 4. (b) The antenna directivities with lateral scattering radiations for the antennas (left, middle, right).
### 3.3. Smith Chart simulation based the antenna length variations

Antennas are devices to optimize and control the emitted radiation into free space by coupling the electrical energy from the input circuit (photoconductor semiconductor substrate) to the antenna device. The system must be designed such that the generated THz wave from the photo-absorption of the ultrafast photoconductor medium can be coupled to a radiating metallic planar antenna. However, the design of this kind of antenna has some challenges associated with impedance matching between photoconductor material (source) and the antenna pads. The LTG-GaAs photoconductor material impedance possesses higher impedance value of 10kΩ than the based metallic planar antenna with impedance in the order of 50Ω. As a result of impedance mismatch, the photoconductor medium directly impacts the performance of the antenna pads causing limitations in the THz radiated power. Therefore, the antenna becomes more sensitive to low frequencies rather than high frequencies due to its low impedance value. Consequently, impedance matching at THz regime for maximum power transfer is unachievable between the high resistivity of the LTG-GaAs thin film source and the low resistivity of the antenna pads. In the CST-MWT-TS simulation, a discrete port excitation represents the photoconductor medium with an assigned impedance value of 50Ω. The matching impedance between the photoconductor medium and the antenna pads is achievable with the CST-MWT-TS simulation. The mismatch between the photoconductor medium and the antenna pads will be represented within the Smith Chart graph, as illustrated in Figure 16(a).

Figure 16(1-3) illustrate the integrated bow-tie PCAs with variations in lengths to compare the results with the conventional bulk bow-tie PCA, as illustrated in Figure 16(4). The integrated bow-tie PCA length variation values are 80μm in Figure 16(1), 120μm in Figure
16(2), 160µm in Figure 16(3), and 200µm for the conventional bulk bow-tie PCA in Figure 16(4). The antenna width is kept constant at 150µm with the length variations in each of the integrated bow-tie PCAs for the Smith Chart representation. This investigation is performed with the Smith Chart representation in order to analyze the impedance mismatch between the semiconductor and the antenna pads for the optimally integrated bow-tie PCA performance, as illustrated in Figure 16(a).

On the right-hand side of the Smith Chart representation in Figure 16(a) illustrates all variation lengths from each of the integrated bow-tie PCAs. The number 1 located in the center of the Smith Chart represents the normalized impedance \( z = \frac{Z_{\text{ant}}}{Z_s} \) for maximum power transfer. The \( Z_{\text{ant}} \) is the antenna impedance and \( Z_s \) is the source (semiconductor material) impedance. The marker with the number 4 located near the Smith Chart center represents the integrated bow-tie PCA optimal condition. The matching impedance for the integrated bow-tie PCA optimal condition could be as much as 50Ω as illustrated with the impedance magnitude simulation in Section 3.6. The integrated bow-tie PCAs marked with numbers 1, 2, and 3, as illustrated in the right-hand side of Figure 16(a), exhibit mismatch impedances that are reflected with strong lateral scattering radiation, as shown in Section 3.2.

The Smith Chart representation demonstrates that the optimal condition is achieved by the integrated bow-tie PCA with a length of 200µm. On the other hand, the conventional bulk bow-tie PCA exhibits the higher mismatch impedance, illustrated with the marker indicated with the number 5 on the right-hand side of Figure 16(a). The impedance matching optimal condition indicates the maximum power transfer the PCA can receive and radiate.
Figure 16. Integrated bow-tie antennas with length variations of 80µm, 120µm, 160µm, 200µm, and the bulk bow-tie antenna with 200µm having a constant width at 150µm (a) Smith Chart analysis with a magnified center view (right). The optimal condition is achieved with an integrated bow-tie antenna with 200µm in length and a flare angle of 90°, indicated in red with a marker number 4.
3.4. S-parameter simulation based on the antenna flare angle variations

The S-parameter investigation begins with the analysis of the antenna flare angles variations performed with the CST-MWT-TS simulation, as illustrated in Figure 17. Figure 17(1-3) illustrate the integrated bow-tie PCAs with variations in flare angles for comparative analysis with the conventional bulk bow-tie PCA, Figure 17(4). The integrated bow-tie PCA flare angle variation values are 50° in Figure 17(1), 90° in Figure 17(2), 130° in Figure 17(3), and the 90° for the conventional bulk bow-tie PCA in Figure 17(4). The antenna length is kept constant at 200μm with flare angle variations in each of the integrated bow-tie PCAs for the S-parameter analysis. The S-parameter optimal condition helps to channel the radiation within an appropriate direction as mentioned Section 3.2.

In order to find the optimal condition for the integrated bow-tie PCA, simulations with antenna flare angle variations are performed. The integrated bow-tie PCA with flare angle values of 50°, 90°, and 130° show frequencies response values of 0.2368THz, 0.2349THz, and 0.233THz. Therefore, the S-parameter values are obtained at -19.635dB, -32.043dB, and -22.46dB, respectively. The integrated bow-tie PCA with 50° flare angle, in Figure 17(1), shows a lower S-parameter value than the integrated bow-tie PCA with 130° flare angle, in Figure 17(3). Therefore, the optimal S-parameter value of -32.043dB and the optimal frequency response value of 0.2349THz are achieved when the integrated PCA flare angle is at 90°, illustrated with a marker number 2 in Figure 17(a). On the other hand, the S-parameter value for the bow-tie PCA patterned on the surface of the conventional bulk GaAs substrate is obtained at -19.684dB with a frequency response of 0.21615THz. The bow-tie PCA on the conventional bulk substrate shows much higher S-parameter than the optimally integrated bow-tie PCA. The integrated bow-tie
PCA and the conventional bulk bow-tie PCA are simulated with the same antenna dimensions to obtain the optimal S-parameter results.

Figure 17(b) illustrates the directivity for the integrated bow-tie PCA flare angle values of 50° (on the right-hand side) and 130° (on the left-hand side). The directivity provides information about the radiation direction of the antenna. The integrated bow-tie PCA with flare angle value of 50° shows strong scattering lateral radiation at ±90° with no radiation channeled to the front (180°) and back (0°) sides of the antenna. The integrated bow-tie PCA with the flare angle value of 130° shows stronger scattering lateral radiation at ±90° with a weak radiation channeled to the front (180°) and back (0°) sides of the antenna. Therefore, the directivity for the integrated bow-tie PCA with flare angles of 50° and 130° did not show any efficient radiation channeled to the front (180°) and back (0°) sides of the antenna. Once the integrated bow-tie PCA reaches the flare angles of 90°, the antenna achieves an efficient radiation to the front and back sides of the integrated bow-tie PCA. The 3D radiation and directivity for the integrated bow-tie PCA and the conventional bulk bow-tie PCA with the optimal values are presented in Section 3.7.
Figure 17. The integrated bow-tie antennas with flare angle variations of 50°, 90°, 130°, and the bulk bow-tie PCA with flare angle of 90° having a constant length at 200μm. (a) The S-parameter analysis. The optimal condition is achieved with a flare angle of 90° for an integrated bow-tie antenna, indicated in red with a marker number 2. (b) The antenna directivities with lateral scattering radiation for antennas (l-right, 3-left).
3.5. Smith Chart simulation based on the antenna flare angle variations

The antenna structure is a device to couple the generated electromagnetic waves from the photo-absorption medium to the metallic planar antenna. Due to the high impedance of the photo-absorption medium, the matching impedance between the photo-absorption medium and the antenna is not possible, aforementioned in Section 3.3. Therefore, the photo-absorption medium is represented with the CST-MWT-TS simulation as a discreet port with 50Ω impedance for matching impedance compatibility with the metallic planar antenna impedance. The mismatch between the photo-absorption medium and the antenna will be represented within the Smith Chart graph, illustrated in Figure 18(b).

Figure 18(1-3) illustrates the integrated bow-tie PCAs with variation in flare angles to compare the results with the conventional bulk bow-tie PCA, Figure 18(4). The integrated bow-tie PCA flare angle variation values are 50° in Figure 18(1), 90° in Figure 18(2), 130° in Figure 18(3), and the 90° for the bulk bow-tie PCA in Figure 18(4). The antenna length is kept constant at 200μm with the flare angle variations in each of the integrated bow-tie PCAs for the Smith Chart representation. This investigation is performed with the Smith Chart representation in order to analyze the impedance mismatch between the photo-absorption medium and the antenna pads for the optimally integrated bow-tie PCA performance, as illustrated in Figure 18(a).

The Smith Chart in the right-hand side of Figure 18(a) illustrates all variation flare angles from each of the integrated bow-tie antennas positioned near the center. The number 1 located in the center of the Smith Chart (indicated with a red circle) represents the normalized impedance \( z = \frac{Z_{ant}}{Z_0} \) for maximum power transfer, aforementioned in Section 3.3. The integrated bow-tie
PCA marked with the number 2, positioned near the Smith Chart center, indicates the optimal condition. The matching impedance for the integrated bow-tie PCA optimal condition could be as much as 50Ω as illustrated with the impedance magnitude simulation in Section 3.6. The integrated bow-tie PCAs marked with numbers 1 and 3, as illustrated in the right-hand side of Figure 18(a), exhibit mismatch impedance reflected with strong lateral scattering radiation, as illustrated in Figure 17(b). The Smith Chart representation demonstrates that the optimal condition is achieved with the integrated bow-tie PCA with a flare angle of 90°, as illustrated by the marker number 2 on the right-hand side of Figure 18(a). On the other hand, the conventional bulk bow-tie PCA exhibits the higher mismatch, illustrated by the marker number 4 on the right-hand side of Figure 18(a). The impedance matching optimal condition represents the maximum power transfer the PCA can receive and radiate.
Figure 18. The integrated bow-tie antennas with flare angle variations of 50°, 90°, 130°, and the bulk bow-tie antenna with flare angle of 90° having a constant length at 200μm. (a) Smith Chart analysis with a magnified center view (right). The optimal condition is achieved with the integrated bow-tie antenna with the length of 200μm and flare angle of 90°, indicated in red with a marker number 2.
The integrated antenna has been simulated not only with length variations with constant width, but also with flare angle variations with constant length. Therefore, the integrated antenna with the length of 200μm and flare angle of 90° has exhibited excellent results making it the achieved optimal PCA device.

3.6. Antenna impedance magnitude simulation based on the flare angle variations

The THz circuit model, shown in Figure 19, will allow the derivation of the formula for the impedance magnitude to represent the impedance magnitude values for the integrate bow-tie PCA.

Figure 19. THz circuit model for the antenna impedance magnitude formulation.
Assumption to be considered for the calculation of the total impedance magnitude:

The source reactance \(X_S\) must be equal to the reactance complex conjugate \((-X_{ant}^*)\) of the antenna or vice versa, expressed as:

\[
X_S = -X_{ant}^* \quad \text{or} \quad X_{ant} = -X_S^*
\]  \hfill (23)

The source resistance \(R_s\) must be equal to the antenna resistance \(R_{ant}\) for maximum power transfer, expressed as:

\[
R_s = R_{ant}
\]  \hfill (24)

\[
Z = R_s + R_{ant} + jX_S + jX_{ant}
\]  \hfill (25)

\[
|Z| = \sqrt{(R_s + R_{ant})^2 + (X_S + X_{ant})^2}
\]  \hfill (26)

By substituting Equation (23) in Equation (26), the reactance components are canceled out leaving only a pure source and antenna resistive components, expressed as:

\[
|Z| = \sqrt{(R_s + R_{ant})^2}
\]  \hfill (27)

According to Equation (27), the maximum power transfer between the source resistance \(R_s\) and the antenna resistance \(R_{ant}\) can occur when they are both equal. However, it is not achievable when using the semiconductor in THz frequency regime \([72]\). This is because the semiconductor impedance is huge compared to the low impedance value of the antenna. In the
simulation with CST-MWS-TS, the semiconductor is represented by the discrete port value of 50Ω for matching impedance analysis with the bow-tie antenna.

Equation (28) illustrates the expression needed to calculate the antenna impedance having the antenna resistive and the reactive antenna components:

\[ Z_{ant} = R_{ant} + jX_{ant} \]  \hspace{1cm} (28)

\[ |Z_{ant}| = \sqrt{R_{ant}^2 + X_{ant}^2} \]  \hspace{1cm} (29)

Therefore, the antenna impedance magnitude becomes equal to the antenna resistance \( R_{ant} \) when the reactance antenna component \( X_{ant} \) becomes zero, Equation (29). The antenna reactance \( X_{ant} \) has the antenna capacitance reactance associated with the antenna inductance reactance that becomes zero at a particular THz resonance frequency.

According to the impedance magnitude graph shown in Figure 20(a), the integrated bow-tie PCA presents the matching impedance value of 48.573 Ω. Therefore, the integrated bow-tie PCA has achieved the maximum power transfer not achievable with the conventional bulk bow-tie PCA having a high resistance magnitude of 131.23 Ω. The matching impedance is based on the discrete port impedance value of 50 Ω representing the semiconductor (photo-absorption) medium. Therefore, the normalized factor \( z \) for the integrated bow-tie PCA is 0.97146, very close to 1 at the center point of the Smith Chart, but the conventional bulk bow-tie PCA has a factor of 2.6246 with a huge mismatch impedance value.
Figure 20. (a) Impedance magnitude obtained for the integrated bow-tie antenna with flare angle variations of 130°, 50°, 90°, and bulk bow-tie antenna 90° keeping constant the length of 200µm.

As it was earlier demonstrated, the integrated bow-tie PCA has shown much better impedance matching than the conventional bulk bow-tie PCA. For that reason, the impedance magnitude graph has demonstrated maximum power transfer results with the integrated bow-tie PCA not achievable with the conventional bulk bowtie PCA.
3.7.3D radiation pattern and 2D far-field directivity simulation

Based on the already elaborated investigation with the S-parameter and Smith Chart analysis, the 3D-THz radiation can also be employed to further investigate the integrated device as well as the conventional bulk device.

The 3D-radiation and directivity are both generated by the CST-MSTS on both PCAs patterned on dissimilar semiconductor materials. Figure 21(a,d) illustrate the 3D radiation pattern images of the integrated and conventional bow-tie antennas with a maximum illumination radiation (in red). The THz radiation is perpendicular to the antenna surface on both and opposite directions. The THz wave radiation that is passing through the substrate thickness is indicated with 0°, and the front side THz wave radiation on the path of the incoming optical laser excitation beam is indicated with 180°, as illustrated in Figure 21(b,e). The 2D far-field directivity represents the fundamental antenna parameter which provides information about the radiation direction of the antenna, as illustrated in Figure 21(c,f).

The THz wave radiation is mostly directed into the substrate at 0° direction, as illustrated in Figure 21(c,f), which is desirable in case a silicon lens is utilized to enhance substrate-air coupling efficiency. Most radiators emit stronger radiation in one direction than in other directions, which is known as anisotropic; otherwise, the radiation is isotropic [105] in which the radiation is uniformly provided in all directions from a point source. To determine the far-field directivity dBi unit, isotropic radiator is used as a reference; even so this kind of radiation is not achievable. Consequently, they can both be used to determine whether or not undesired side lobes are developed on either side of the main lobe. The presence of side lobes can affect the
overall main lobe radiation. The 2D far-field directivity provides information about the radiation direction of the antenna, as illustrated in Figure 21(c,f).

According to Figure 21(c,f), the integrated bow-tie PCA has strong directivity at 5.82dBi compared with the bulk PCA with 5.07dBi. As a result, the directivity in both PCAs does not exhibit any side lobes that can impact the overall radiation power. Subsequently, the e-field radiation on a coplanar bow-tie PCA will be investigated in the next section for the analysis behavior in both dissimilar devices.

![Figure 21](image_url)

Figure 21. (a,d) The 3D PCAs radiation patterns. (b,e) The 3D radiation patterns top view. (c,f) The PCA directivities are obtained at frequencies of 0.2349THz for the integrated device and 0.2162THz for the conventional bulk device with optimal conditions.
3.8. Bow-tie PCA e-field distribution simulation

In order to investigate the impact of the e-field radiation on both the integrated and the conventional bow-tie PCAs, the e-field radiation simulation is performed by the CST-MSTS program, as illustrated in Figure 22. The e-field distribution effect is observed to be mostly concentrated on the lateral side edges of the bow-tie electrodes. This exhibits an exponential decay motion toward the lateral flare side of the radiating pads. Once the e-field starts intensifying to the maximum value, the e-field intensity decays exponentially on both lateral edges of the flare radiating pads. The e-field radiation follows a simultaneous and symmetric motion on both lateral flare radiating pads, without reaching the antenna ends.

Figure 22 shows that there is not much radiation inside the antenna surface, which also decreases exponentially toward the end of the radiating pads. The maximum e-field distribution effect is observed to have significant intensity with the integrated antenna and weak intensity with the conventional bulk antenna, as illustrated in Figure 22(a,b). The integrated bow-tie PCA demonstrates significant radiation at the simulated resonant frequency of 0.2349THz, as illustrated in Figure 22(a). On the other hand, the bulk PCA does not show significant radiation at the resonance frequency of 0.21615THz, as illustrated in Figure 22(b). This performance is investigated in more detail by discussing the static electric field in dissimilar semiconductors as well as with the TCAD simulation.
Figure 22. The e-field distribution at THz frequency regime in both THz PCA devices. (a) The strong e-field radiation generated at a resonance frequency of 0.2349THz for the integrated device. (b) The weak e-field radiation generated at a resonance frequency of 0.21615THz for the conventional bulk device.
3.9. **Metal thickness for evaporation based on the skin effect analysis**

A very thin layer beneath the surface of the antenna conductor carries most of the current due to its high frequency. As a result, the thin layered conductor causes very high current losses in the THz region [106]. At very high frequency regime, the current and magnetic flux are confined near the antenna surface [107] due to the electromagnetic induction [108]. In addition, the e-field amplitude decays exponentially from the surface, $e^{-z/\delta}$ [109]. Consequently, the skin depth has a dependency of the angular frequency ($\omega$), relative magnetic permeability ($\mu_r$), resistivity ($\rho$), the permeability of the free space ($\mu_0$), a constant factor pi ($\pi$), and frequency ($f$), as shown in Equation (30) [109].

$$\delta = \frac{1}{K} = \frac{2}{\omega \mu \sigma} = \frac{1}{\pi f \mu_r \mu_o \sigma}$$

One of the best available conductor and lossless material that can carry both current and magnetic flux in antennas is silver. However, silver oxidizes very easily. Gold is used instead because it is an inert material. Moreover, an adhesion layer containing chromium and titanium is used at the interface with the selected silicon host substrate to provide bonding firmness between the surface of the silicon substrate and gold antenna pads. Equation (30) is used to calculate the skin depth for the gold needed in the evaporation process. The resonance frequency of 0.30 THz obtained in Section 2.2 provides a skin depth of 137.5 nm. The integrated PCA resonance frequency of 0.2349 THz obtained in Section 3.2 produces a skin depth of 155.4 nm, while the conventional bulk PCA is 162nm at the resonance frequency of 0.21615THz. Therefore, as the
frequency increases, the skin depth decreases. A layer of 200 nm thickness of gold is then evaporated accounting for the skin depth effect in the outcome of reaching lower frequencies.

3.10. Static electric field simulation in the dissimilar semiconductors

DC bias voltage is applied to the bow-tie PCA electrodes to create a static electric field in the photo gap between the bow-tie PCA electrodes in order to increase the kinetic energy of generated mobile carriers in the photoconductor medium. The electron-hole pairs are created in the photoconductor medium by illuminating the bow-tie PCA photo gap with an optical pump laser beam from a femtosecond pulse known as the Ti: sapphire laser. Both the DC biased voltage and the optical laser beam are required to switch the bow-tie PCA photo gap to generate the THz wave radiation by coupling the generated electron-hole pairs with the antenna pads. The bandwidth of the generated THz wave depends on the light absorption strength, the carrier mobility and the recombination time in the LTG-GaAs layer, and the pulse duration of the femtosecond pump laser. The pulse duration must be short in order to have many spectrum frequencies within the wideband where one of the frequencies will oscillate in the bow-tie PCA pads. It is, therefore, imperative to investigate how the static electric field is distributed on the LTG-GaAs thin film epitaxial layer and on the conventional bulk GaAs substrate. Consequently, the static electric field distribution investigation can lead to a further explanation of the generation of the THz wave radiation on both PCA structures patterned on dissimilar semiconductor materials.
Figure 23(a) illustrates a perspective pictorial view of the incident optical pump laser beam exciting the 2.0µm thick LTG-GaAs epitaxial thin film device in conjunction with the applied DC bias voltage. Figure 23(b) depicts the perspective pictorial view showing how the LTG-GaAs epitaxial thin film device can hypothetically confine the static electric field distribution inside the semiconductor material. Figure 23(c) is the front side of the pictorial view showing the hypothetically static electric field distribution confinement inside the LTG-GaAs epitaxial thin film device. The 0.3µm air gap between the LTG-GaAs epitaxial thin film device and the SiO₂\Si substrate does not affect the THz radiation. The wavelength for the 0.2349 THz frequency is 1.277µm indicating no resonance effect within the semiconductor-air-semiconductor interface. The static electric field distribution inside the SiO₂\Si substrate does not have any effect on the generation of the THz-wave radiation. The only effect is the THz-wave radiation absorption passing through the semiconductor medium on the way to the detector PCA. High resistivity SiO₂\Si host substrate is suitable for THz radiation due to its transparency in THz regime.

On the other hand, Figure 23(d) illustrates the perspective pictorial view of the incident optical pump laser beam exciting directly the photo gap of the conventional bulk bow-tie PCA device in conjunction with the applied DC bias voltage. Figure 23(e) also depicts a perspective pictorial view showing a hypothetically extended static electric field distribution inside the conventional bulk GaAs substrate. Figure 23(f) is the front side view illustrating a hypothetically extended static electric field distribution inside the conventional bulk GaAs substrate dying exponentially.
Figure 23. (a-c) The integrated bow-tie PCA excited with the incident optical pump laser beam (red) and the applied DC bias voltage generating the perspective view of the hypothetically confined static electric field. (d-f) The conventional bulk bow-tie PCA excited with the incident optical pump laser beam (red) and the applied DC bias voltage generating the perspective view of the hypothetically extended static electric field.

Figure 24(a) illustrates the static electric field confinement on the integrated bow-tie PCA cross-sectional area simulated with COMSOL Multiphysics software. The electron-hole pairs gain kinetic energy because of the static electric field confinement built up inside the LTG-GaAs thin film epitaxial layer. When the optical laser beam excites the LTG-GaAs thin film epitaxial layer with no metallic antenna electrodes on the surface, huge amount of electron-hole pairs are accelerated generating a strong THz wave radiation through the bow-tie PCA.

Figure 24(b) illustrates the static electric field extension on the conventional bulk bow-tie PCA cross-sectional area simulated with COMSOL Multiphysics software. The electron-hole
pairs gain kinetic energy because of the static electric field extended inside the conventional bulk GaAs semiconductor. The static electric field is also extended inside the SI-GaAs substrate with no significant effect to the acceleration of the electron-hole pairs. When the optical laser beam excites the LTG-GaAs thin film epitaxial layer area between the antenna metallic electrode tips on the surface, the small amount of electron-hole pairs are accelerated generating a weak THz wave radiation. The antenna metallic electrode tips create a shadow effect beneath the semiconductor medium avoiding the generation of strong THz radiation.
Figure 24. (a) The integrated bow-tie PCA with a 2.0µm LTG-GaAs thin film epitaxial layer illustrates the confinement of the static electric field distribution on the semiconductor cross-sectional area. (b) The conventional bulk bow-tie PCA substrate illustrates the extended static electric field distribution on the semiconductor cross-sectional area.

3.11. Electric field effect on dissimilar semiconductors based on electron-hole pairs under optical illumination with a numerical simulation
To understand the physical origin of the performance difference between thin-film based PCA and conventional bulk PCA, further investigation is conducted by a numerical simulation TCAD software to analyze the electric field distribution based on the electron-hole pairs in each of the semiconductors under laser illumination.

Figure 25(a,b) depict the device configuration for the integrated bow-tie PCA and the conventional bulk bow-tie PCA with their configuration of the pump beam path. When a static bias voltage is applied to the antenna electrodes, a considerable static electric field is built up in the gap region between the two electrodes. Electrons will gain enough kinetic energy under the static bias voltage to be accelerated by the influence of the pump beam excitation. This region is emphasized by the pump beam excitation within the electrode gap where the photoconduction takes place. The potential distribution is calculated based on an applied bias voltage of 25V. The LTG-GaAs sample shows a resistivity of approximately $1.05 \times 10^7 \, \Omega\cdot\text{cm}$ based on four-point probe measurement. Based on this measurement, it is assumed that the carrier concentration of LTG-GaAs epitaxial layer is around $1.2 \times 10^8 \, \text{cm}^{-3}$, which generates a Schottky metallization region based on the Cr/Au metal layers, Figure 25(c,d). Near to one of the electrodes, an expected strong electric field is built up and, therefore, it increases according to the increment of the applied bias voltage. Once the optical pump beam excites the LTG-GaAs layer, electron-hole pairs are generated. The illumination configuration is the same as the ones illustrated in Figure 25 (a,c). The Gaussian optical pulse with 100 fs temporal duration illuminates the semiconductor material. The carrier lifetime of LTG-GaAs is assumed at 1ps. It is expected that the optically generated short lifetime carriers in the region of the LTG-GaAs semiconductor material with the reasonable electric field will contribute to the photocurrent and consequently THz radiation is
generated through the bow-tie PCA. As a result of exciting the back site of the LTG-GaAs thin film layer with the pump optical beam, the electrodes are not creating a shadow effect, Figure 25(a). In contrast, the electrodes of the conventional bulk GaAs PCA, Figure 25(b), are on the path of the pump optical beam blocking an important area of the optical semiconductor material. Consequently, in the case of the bow-tie PCA integrated with the LTG-GaAs thin film, the calculated potential has a great range distribution than in the case of the conventional bulk bow-tie PCA with the same applied bias voltage. Therefore, the higher THz radiation power is observed to have more contribution to the LTG-GaAs thin film than with the conventional bulk PCA device, illustrated in Figure 25(e).

Since the majority of photo-generated carriers are on the surface of thin-film LTG-GaAs and the PCA electrodes are located on the bottom of the LTG-GaAs thin-film, the transient pulse response of the LTG-GaAs thin-film PCA shows a unique pulse response with two peaks. The first narrow peak pulse is due to faster electron current and the following broaden pulse is due to slower hole current. However, for a conventional bulk LTG-GaAs PCA configuration, the majority of the photo-generated carriers on the surface are collected immediately by the surface electrodes. Therefore, electron and hole currents are combined as shown in Figure 25(e). While the final THz radiation is affected by both the transient photocurrent at the gap of the PCA and the implemented antenna structure, the peak intensity of the THz radiation is expected to be proportional to the photocurrent intensity.
Figure 25. The integrated based PCA shows the high contribution of THz radiation power than with the conventional bulk PCA.
3.12. Mechanisms to improve THz wave radiation power

3.12.1. Introduction

Both the substrate thickness reduction and the glass substrate can be employed to enhance the THz wave radiation power in a stand-alone antenna. The reduction of the substrate thickness is performed with the CST-MWT-TS software to investigate the effect of the THz radiation power enhancement. The glass substrate can also be investigated with the simulation software to demonstrate the THz radiation power enhancement.

3.12.2. THz radiation power effect based on substrate thickness variations

Di et al. [110] has demonstrated that reducing substrate thickness minimizes substrate radiation effects and therefore radiation power can be greatly improved.

A high resistivity silicon substrate used to pattern the photoconductive antenna is investigated based on thickness variations from its three thickness values of 500μm, 400μm, and 300μm. The thickness variations will give a clear analysis of the thickness effect on the THz radiation power profile. In order to pursue this investigation, CST-MWS-TS package is engaged to perform the simulation.

Figure 26(a-c) illustrate the silicon substrate thickness variation data with the S-parameter and their pattern radiation directivity, as illustrated in Figure 26(d). The silicon host substrate employed to fabricate the PCA has a thickness of 500μm with a simulated frequency of
0.2349THz having a directional radiation at $0^\circ$ and $180^\circ$ (back/front direction), as illustrated in Figure 26(d). When the thickness is reduced from 500µm to 400µm, the frequency response shows an increment from 0.2349THz to 1.006THz. The S-parameter decreases from -32.043dB to -41.618dB improving not only in THz radiation power, but also in return lost factor. When the thickness is further decreased from 400µm to 300µm, the frequency response shows an increment from 1.006THz to 1.23THz. Therefore, the S-parameter shows a slight increment from -41.618dB to -40.814dB, without much change in return lost factor. When the thickness decreases, the frequency conversely increases, confirming that reducing substrate thickness minimizes substrate radiation effect and radiation power can be greatly improved. After obtaining the optimal conditions in substrate thickness, the antenna parameter must be optimized to find the resonance frequency that probably falls again into the results given by the simulation, as illustrated in Figure 26 (a), and the one given in the experimental result.
Figure 26. (a-c) Illustrates the S-parameter for the silicon substrate thickness variations from 500µm down to 300µm. (d) Illustrates the radiation patterns for silicon substrate thickness variations.

3.12.3. THz radiation power effect based on dissimilar substrates

Another way to improve the THz wave radiation power is by using glass (Pyrex), which has a relative dielectric constant ($\varepsilon_r$) of about 4.7, a refractive index ($\eta$) of about 1.47, and a high
resistivity [111]. On the other hand, the silicon substrate is considered for a comparative analysis with the glass substrate. Silicon substrate has a relative dielectric constant \((\varepsilon_r)\) of about 11.68 with a refractive index \((\eta)\) of about 3.7 and a high resistivity as well [112]. Glass possesses the great advantage over silicon material limited for some applications, even though both are transparent in THz regime because of their high resistivity. The CST-MWS-TS package is utilized to simulate the silicon as well as the glass (Pyrex) substrates. Figure 27(a) illustrates S-parameter simulation for the 500\(\mu\)m thick silicon substrate with the S-parameter value of -32.043dB at a frequency of 0.2349THz. Figure 27(b) illustrates the S-parameter simulation for the 1,000\(\mu\)m thick glass with a value of -44.372dB at a frequency of 1.4129THz. Figure 27(c) illustrates the resulted directivity for silicon and glass in which the glass substrate exhibits a lower S-parameter value with higher THz frequency power, as previously mentioned. The simulation results demonstrate that glass substrate can be potentially utilized for THz sensing applications, but it cannot be integrated with CMOS platform.
Figure 27. (a) Illustrates the S-parameter for the silicon substrate. (b) Illustrates the S-parameter for the glass substrate. (c) Illustrates the radiation patterns for silicon and glass substrates.

4. Integrated bow-tie PCA patterned on a silicon host substrate and the conventional bulk bow-tie PCA fabrication

4.1. Introduction

LTG-GaAs is the material of choice as the optically active medium for high-speed photoconductor switching. It presents a high resistivity in the order of $3.5 \times 10^8 \Omega \cdot \text{cm}$ [113], a high electron mobility, a carrier lifetime less than 1.0 ps, and a high dielectric breakdown [114]. The high-speed photoconductive performance of the material is assessed by fabricating the LTG-GaAs thin film mesa devices integrated on a bow-tie emitter-detector PCAs patterned on any arbitrary host substrate. This material is usually grown by MBE at low temperature around
200°C [80]. The LTG-GaAs material used in this study is the epitaxial grown layer of 2.5μm (optically active medium) with the 0.25μm AlAs etching stop layer sandwiched between the optically active layer and the SI-GaAs substrate.

A highly selective wet chemical etching process for mesa small vertical indented areas of LTG-GaAs thin film is developed and discussed in detail. The fabrication process for the LTG-GaAs thin film mesa array device is performed in three steps. The first step is the fabrication of electrical metallic micro contacts on the LTG-GaAs layer of the conventional bulk GaAs substrate discussed in Section 4.2.2. The second step is the rectangular mesa array definitions fabricated on the LTG-GaAs layer of the conventional bulk GaAs substrate discussed in Section 4.2.3. Finally, the third step introduces the LTG-GaAs thin film mesa array lift-off process discussed in Section 4.2.4.

4.2. Mylar film diaphragm and LTG-GaAs thin film mesa array fabrication

4.2.1. Mylar transparent film diaphragm fabrication

The transfer Mylar transparent diaphragm for storing mesa devices is made by wet-etching a through-hole on a silicon wafer and then attaching the Mylar thin film diaphragm on the silicon wafer surface.

The fabrication of the Mylar diaphragm starts by mixing the HF:HN0₃:H₂O. The HF:HN0₃:H₂O solution is based on a 6:2:1 rate prepared in a teflon beaker, as illustrated in Figure 28(a). A silicon sample size of about 4.0 in² is prepared for the etching process with the
HF:HN\textsubscript{3}:H\textsubscript{2}O. The Apiezon W wax pellet of about 3.0cm is dissolved with TCE solution to evenly spread out on both silicon wafer surfaces leaving enough space at the center for the etching process. The silicon wafer sample is placed with a pair of teflon tweezers inside the teflon beaker containing the etchant solution for about 20 minutes. The AZ4620 solution is used to spread out around the center opening area evenly, as illustrated in Figure 28(b). The acrylic diaphragm is cut to fit the size of the silicon sample and then firmly placed on the surface, as illustrated Figure 28(c). Finally, in order to have the AZ4620 solution dry out, the silicon wafer is placed in the oven at 113\textdegree C for about 20 minutes.
4.2.2. LTG- GaAs thin film epitaxial layer with metallic micro contact array

The bulk GaAs substrate is the chosen semiconductor layered with the 2.5μm-LTG-
GaAs/0.25μm-AlAs/497.25μm-SI-GaAs substrate, as illustrated in Figure 29(a). The conventional bulk GaAs substrate is cleaned with acetone to remove organic impurities, methanol to remove the contaminated acetone, then rinsed in isopropanol to remove the remaining contaminations from previous solvents avoiding striations. A light sensitive tone negative-positive photoresist bi-layer process is utilized. The conventional bulk GaAs substrate is bi-layer photoresist spin-coated, as illustrated in Figure 29(b), with 1.0μm thick positive SF-11 at 3,500 RPM and with 1.0μm thick negative NR9-1500PY (or positive AZ5214 imaging reversal) at 6,000 RPM. Hot plate bi-layer resist pre-exposure bake (soft-bake) at 170°C for 5.0min and at 150°C for 1.0min plays a very critical role in photo-imaging due to the fact that the coated photoresist becomes photosensitive. Pre-exposure bake (soft-bake) minimizes the solvent concentration in order to prevent bubbling, improve resist adhesion, and to prevent dissolving one resist layer by a following multiple coating.

The bi-layer photoresist film is exposed to two different UV wavelengths one after the other for each layer at a time. The NR9-1500PY top layer is exposed with the photolithography i-line delineating the geometrical shape with high-resolution capability, and the SF-11 bottom layer is exposed to the flood short waves (265nm wavelength) defining the undercut of the SF-11 resist layer, Figure 29(c).

Photolithography exposes the NR9-1500PY layer for 20sec to image the mask pattern with 20μm by 15μm rectangular micro contact array separated by 20μm to account for the photoconductor gap. A hot plate post exposure bake at 100°C for 1.0min completes a photoreaction initiated during photolithography exposure, and then RD6 imaging developer for 9sec reveals the rectangular micro contact array openings in the NR9-1500PY layer. A hot plate post development bake or hardbake at 150°C for 1.0min hardened the photoresist to
increase thermal, chemical, and physical stability for subsequent processes. The SF-11 layer is flood-exposed with short waves for 10min. This exposure procedure is repeated four times in order to ensure good undercut at the interface between NR9-1500PY and SF-11 increasing with development time. The SF-11 photoresist is developed by the PG-101A imaging developer for 1.0min, Figure 29(c). Figure 29(d) illustrates the actual microscope top view image of the bi-layer photoresist showing in yellow the undercut rectangles of SF-11 photoresist areas beneath the transparent NR9-1500PY photoresist.

Thermal metal evaporation is performed with layers of 200nm-Au/100nm-Ni/20nm-Cr, as illustrated in Figure 29(e). Figure 29(f) illustrates the actual microscope top view image of the evaporated Au layer on the surface of the conventional bulk GaAs substrate. Finally, the metal lift-off process is accomplished with PG remover pre-warmed for 5min at around 70°. Samples were left submerged for several minutes and rinsed with acetone to get rid of the excess of metal from the surface of the conventional bulk GaAs substrate, as illustrated in Figure 29(g). Figure 29(h) illustrates the resulted conventional bulk GaAs substrate profile layers of the final process. Figure 29(i) is an actual microscope top view image of the evaporated Au layer defining the 20µm by 15µm rectangular micro contacts, separated by 20µm to account for the photoconductor gap.
Figure 29. Hierarchical micro contacts fabrication process performed on the conventional bulk GaAs substrate. (a) Conventional Bulk GaAs substrate. (b) Spin-coated bi-layer photoresist, (c) Photolithography and development, (d) Actual microscopy top view image of the bi-layer photoresist, (e) Thermal metal evaporation, (f) Actual microscope top view image of metal evaporation, (g) Metal lift-off process, (h) Conventional bulk GaAs substrate profile layers. (i) Actual microscope top view image of the micro contacts array for the mesa devices.

4.2.3. LTG-GaAs epitaxial thin film layer with rectangular mesa definition
Hereafter, defining the rectangular LTG-GaAs thin film mesa array device by solvent cleaning, spin-coating photoresist, and mask alignment photolithography processes are performed accordingly in the similar fashion as outlined in Section 4.2.2, but thermal evaporation and metal lift-off processes are not needed for the further process.

Metallic micro contacts on the conventional bulk GaAs substrate are already evaporated in Section 4.2.2, as illustrated in Figure 30(a). It is then spin-coated with 0.75µm thick positive S-1805 high-resolution photoresist, at the speed of 3,000RPM. A hot plate pre-exposure bake is set at 105°C for 1.0min, as illustrated in Figure 30(b).

This section differs from Section 4.2.2 in the way that the manual mask alignment photolithography is performed. This technique is one of the most important, difficult, and critical steps in the photolithography process. In this case, the photomask marks are aligned with the evaporated metal marks created on the conventional bulk GaAs substrate surface. The mask-aligner UV light during the exposition passes through the negative metallic photomask array pattern to expose the positive S-1805 photoresist to define the rectangular array shape. The positive S-1805 photoresist is exposed for 4.0sec defining the 60µm by 30µm rectangle array shape through the aligned negative metallic photomask array pattern, as illustrated in Figure 30(c). Immersing the conventional bulk GaAs substrate in the MIF-319 imaging developer for 30sec reveals the rectangle array shape separated by 5.0µm from each other, as illustrated in Figure 30(c).

A cleaned 22x22-mm² micro cover glass is placed on a hot plate at 120°C to melt a small Apiezon W wax pellet. At 120°C, the pellet keeps its viscosity high enough to inhibit the Apiezon W wax from melting uncontrollably. The bottom surface of the conventional bulk GaAs
substrate is then glued on the surface of the micro cover glass with the already melted Apiezon W wax.

Subsequently, three arbitrary reference points are measured in advance with the VEECO-DEKTAK-150 profilometer to obtained the profile thickness between the S-1805 photoresist thickness and the conventional bulk GaAs substrate surface. The S-1805 photoresist layer on the top of the conventional bulk GaAs substrate surface is exposed to the chemical etching agent, illustrated in Figure 30(d). The three reference points are used to control the vertical etching process of the LTG-GaAs thin film thickness toward the AlAs sacrificial interface layer. The etching treatment is carried out in a bath with a mixture of 4:1 ratio of C₆H₈O₇:H₂O₂ at room temperature with the vertical etching rate of 0.5µm/min. During the vertical etching progression, the LTG-GaAs thin film thickness is measured every 1.0min with the profilometer in conjunction with a microscope for visual inspections to determine whether or not the 2.0µm thickness is achieved. The etching of 2.0µm LTG-GaAs thickness is completed during a time period of 5.0min through the S-1805 photoresist rectangular openings separated from each other by 5.0µm, as illustrated by the actual microscope top view image in Figure 30(e). This procedure must be done very carefully in order to preserve a high yield fabrication device.

The etching process delineates the 60µm by 30µm rectangular array shape maintaining the metallic micro contacts aligned on the surface of the obtained rectangular array shape, as illustrated in the actual photograph in Figure 30(e). The remaining 0.50µm thickness of the LTG-GaAs thin film is left provisional and intentional to prevent etching onto the AlAs interface sacrificial layer, so that the HF can etch it off. The remaining 0.50µm thickness is accomplished in Section 4.2.4 after etching off the AlAs layer.
Dissolving the Apiezon W wax with TCE solution releases the conventional bulk GaAs substrate from the 22x22-mm² micro cover glass. The S-1805 photoresist layer is resistant to the TCE solution. The S-1805 photoresist layer protects the mesa devices’ micro contacts during the etching process as well as from diluted black wax contaminations. Figure 30(e) is an actual microscope top view illustrating the fringe green color patterns in the S-1805 photoresist layer. It is important to inspect the lateral surfaces for any wax and photoresist particles inadvertently left behind on the 0.25µm thick AlAs sacrificial layer, so that the HF acid can etch it off. Finally, the released conventional bulk GaAs substrate is cleaned with solvents and dried with a nitrogen gun for next process.
Figure 30. Hierarchical rectangular array shape fabrication procedure for LTG-GaAs thin film mesa array device. (a) Evaporated metal on LT-GaAs Bulk substrate. (b) Spin-coated S-1805 photo-resist. (c) Photolithography and S-1805 photoresist development. (d) LTG-GaAs thin film mesa array device etching process. (e) Actual microscope top view image of the rectangular array shape for mesa devices.

4.2.4. LTG-GaAs thin film mesa array fabrication and storing on a Mylar transparent film diaphragm for integration and future use

The bulk GaAs substrate on a 22x22mm² micro cover glass is heated up on a hot plate at
120°C to melt the Apiezon W wax. The Apiezon W wax is utilized to give some mechanical firmness and handling capabilities to the LTG-GaAs thin film mesa devices, after lift-off from its native GaAs substrate. One supportive Apiezon W wax pellet of 1.0mm thick is melted with a slightly domed shape on the top of the S-1805 photoresist, entrenching the 4.5x4.5mm² conventional bulk GaAs substrate area. A teflon rod is placed along the upper side of the dome melted wax for substrate handling purposes, as illustrated in Figure 31(a). Figure 31(b) illustrates the actual microscope image of the conventional bulk GaAs substrate small size attached to a teflon rod.

Hereafter, the LTG-GaAs thin film epitaxial layer lift-off by selectively undercutting the AlAs is discussed. The AlAs sacrificial interface layer from the conventional bulk GaAs substrate with layers of LTG-GaAs\AlAs\SI-GaAs is selectively etched in a 10% isotropic aqueous dilution of HF. This process is carried out in a bath at room temperature with a lateral undercutting rate of 5.0µm\min, as illustrated in Figure 31(c). Then, the conventional bulk GaAs substrate small size with layers of GaAs\AlAs\SI-GaAs is left for seven hours in a plastic bottle with HF solution to continue etching the sacrificial AlAs layer and to make the SI-GaAs substrate float away, as illustrated in Figure 31(c).

The remaining LTG-GaAs thin film thickness of 0.50µm is etched off by the chemical agent approach aforementioned in Section 4.2.3, as illustrated in Figure 31(d). Figure 31(e) shows an actual microscope top view image revealing the Apiezon W wax surface among the LTG-GaAs thin film mesa array after etching off the remaining 0.50µm thin film layer. This etching process is performed in a short period of time, less than 0.50sec at a time until the Apiezon W wax surface is revealed. The rectangular structure of the LTG-GaAs thin film mesa devices is separated by 5.0µm from each other. The rectangular mesa shape has been adopted
instead of square for easy identification purposes at the time of mesa device integration on the antenna gap.

By means of a blade, the LTG-GaAs thin film array device is detached from the teflon rod, storing and bonding it on a transparent and mechanically tough Mylar film diaphragm, Figure 31(f). Afterward, the TCE solution dissolves the supported Apiezon W wax, releasing the LTG-GaAs thin film mesa devices on the transparent Mylar thin film diaphragm surface, Figure 31(g). Finally, the LTG-GaAs thin film mesa devices are carefully cleaned with methanol and isopropanol to remove the S-1805 photoresist film. The Mylar thin film diaphragm is kept tilted around 5° to allow the dissolvent drains away. A high yield of LTG-GaAs thin film mesa devices from the etching process to the lift-off process is successfully obtained. A few mesa devices are flushed away from the stack devices due to irregular solvent pressure during the cleaning, but they are maintained within the large surface of the Mylar thin film diaphragm area, as illustrated in Figure 31(h). The LTG-GaAs thin film mesa devices are very well bonded by the vdW forces [115, 116] on the Mylar film diaphragm surface. E. Yablonovitch et al. [115] have demonstrated a similar lift-off technique for epitaxial mesa films of 2.0cm by 4.0cm, storing them in isopropanol. In contrast, in our approach, rectangular micro-mesa devices are defined by vertical selective chemical etching and stored in a transparent Mylar film diaphragm.

The total of 7,075 LTG-GaAs thin film mesa devices are obtained from a 4.5x4.5mm² LTG-GaAs substrate area. 6,500 LTG-GaAs thin film mesa devices are estimated to be achieved from the time of etching to the time of lifting-off with a 92% yield.
Figure 31. Hierarchical fabrication process performed for the LTG-GaAs thin film mesa devices. 
(a) Teflon rod and Apiezon wax embedded in the LTG-GaAs thin film mesa array. (b) Actual 
microscope image of teflon rod holding the LTG-GaAs thin film mesa array device. (c) Mesa 
etching process and lift-off. (d) Etching of the remained LTG-GaAs thin film thickness to 
separate the mesa array. (e) Actual microscope view image of LTG-GaAs thin film mesa array 
embedded in Apiezon W wax. (f) LTG-GaAs thin film array on Mylar thin film diaphragm. (g) 
Apiezon W wax and S-1805 cleaning and the profile layers (h) Actual photograph top view 
image of the LTG-GaAs thin film mesa array bonded on the Mylar thin film diaphragm.
4.3. Bow-tie PCA electrode pads patterned on a Si substrate fabrication

Hereafter, the bow-tie PCA patterned on silicon host substrate (but not limited) is fabricated in two steps. The first step discusses the measurement of the resistivity of the SiO₂/ Si host substrate, which is a very important parameter for the THz performance. The second step is the patterning of the bow-tie PCA with electrode tips on the SiO₂/ Si host substrate with the dimensions already discussed in Section 2.

4.3.1. Silicon host substrate resistivity measurement

The SiO₂/ Si substrate with a thickness of 5µm/495µm is utilized as the host substrate to pattern the bow-tie PCA. The BOE with a rate of 0.2µm/min is used to selectively etch away the 5µm SiO₂ layer in order to measure the Si substrate resistivity. The Si resistivity is measured by a four point probe technique [117, 118]. The resistance of the Si substrate is measured and then the resistivity ρ (Ω*cm) is calculated using the following expressions:

\[ g = \frac{1}{\pi} \ln \left[ \frac{\sinh \left( \frac{t}{s} \right)}{\sinh \left( \frac{t}{2s} \right)} \right] \]  \hspace{1cm} (31)

\[ \rho = \frac{R \times t}{g} \]  \hspace{1cm} (32)

Where \( t \) is the thickness of the Si substrate with 495µm, \( s \) is the probe space separation with 1.0mm, \( R \) is the 702.389KΩ measured resistance with the four point probe device, and \( g \) is the factor with a value of 0.230286897775 from Equation (31) that accounts for how much current is squished in the layer. The current flows between the distances of the two outer probes. Therefore, the Si substrate resistivity (ρ) is calculated with Equation (32) given a value of
0.151 MΩ.cm indicated to be a suitable semiconductor material in the THz frequency regime. Finally, the bow-tie antenna is prepared for metal evaporation process.

4.3.2. Bow-tie PCA electrode pads patterned on a silicon host substrate

SiO₂\Si host substrate, Figure 32(a); spin-coating bi-layer photoresist, Figure 32(b); photolithography, Figure 32(c) (these two processes are discussed in detail in Section 4.2.2); metal evaporation, Figure 32(d); and metal lift-off processes, Figure 32(e). The bow-tie PCA patterned on a SiO₂\Si substrate is defined with thickness and metal layers of 200nm-Au/20nm-Cr by the thermal evaporation process, as illustrated in Figure 32(e). Finally, the metal lift-off process is accomplished with PG remover pre-warmed for 5 minutes at around 70°. Samples are left submerged for several minutes and rinsed with acetone to get rid of the excess of metal from the sample surface, Figure 32(e). Figure 32(f) shows an actual microscope top view image of the fabricated bow-tie PCA with electrode tips and flare radiating pads deposited on a SiO₂\Si host substrate with thicknesses of 5.0μm/495μm.
Figure 32. Bow-tie antenna is fabricated on a SiO$_2$\Si host substrate. (a) SiO$_2$\Si host substrate. (b) Spin-coated bi-layer photoresists. (c) Photolithography and development process. (d) Thermal evaporation. (e) Metal lift-off process. (f) Actual microscope top view image of the bow-tie antenna with rectangular electrode tips and flare pads deposited on SiO$_2$\Si host substrate.

**4.3.3. LTG-GaAs thin film mesa integration on the bow-tie PCA electrode tips patterned on a silicon host substrate process**

Initially, a micro-needle probe is employed to weaken bonding the LTG-GaAs thin film mesa device that is then transferred between the two Mylar thin film diaphragm surfaces. The
back side of the Mylar thin film diaphragm carrying the mesa device is pressed to approach the LTG-GaAs thin film mesa device into the tiny DI droplet water. Due to the effect of vdW \cite{115, 116} forces, the LTG-GaAs thin film mesa device is pulled down and temporally bonded on the Mylar thin film diaphragm surface, Figure 33(a). The LTG-GaAs thin film mesa device’s metallic micro contacts are facing down towards the Mylar thin film diaphragm surface, which are not suitable for integration. The metallic micro contacts on the LTG-GaAs thin film mesa device are not placed in the appropriate position for the integration step yet, so it has to be transferred once again in order to position the metallic micro contacts on the Mylar diaphragm surface facing upwards. Therefore, the Mylar thin film diaphragm carrying the mesa device is inverted to initiate the transferring process, as illustrated in Figure 33(b). Once the transferring process between the two Mylar thin diaphragm films is accomplished, as discussed in the step for Figure 33(a), the metallic micro contacts are finally facing upwards, as illustrated in Figure 33(d). The tiny DI droplet water left behind is dried out at room temperature. Subsequently, the Mylar thin film diaphragm is again inverted to prepare the LTG-GaAs thin film mesa device for the integration process on the bow-tie PCA electrode tips, Figure 33(e).

Once the LTG-GaAs thin film mesa device and the bow-tie PCA are positioned under the microscope, the transferring mesa device takes place, Figure 33(f). The transferring technique is the same as discussed in Figure 33(a) and Figure 33(c). However, two motion controller stages with two micro-needles in each of them are utilized for the thin film mesa device final alignment. The micro-needles align the LTG-GaAs thin film mesa device between the electrode tips after being positioned by magnetic forces.

The motion controllers are provided with three axes that can gradually align the mesa device with excellent accuracy as shown with a magnified microscope top view image of the
integrated mesa on the antenna, as illustrated in Figure 33(h). The integrated bow-tie PCA with the LTG-GaAs thin film mesa device is depicted by a microscope top view image in Figure 33(i). E. Yablonovitch et al. [115] have demonstrated a similar technique using a vacuum tool to pick up and to align a mesa sample size of 2.0cm by 4.0cm. In contrast, the manual technique of picking up and ensuring alignment of mesa device by utilizing DI water, magnetic forces, and micro-needle probes to integrate the mesa sample on a micro-scale technique is hereby demonstrated.

In addition, the SU8-2 transparent polymer is used to protect and provide mechanical metal to metal bonding support between the micro contacts on the surface of the LTG-GaAs thin film mesa device and the bow-tie PCA electrode tips, which is discussed in Section 4.3.4.
Figure 33. LTG-GaAs thin film mesa device integration on bow-tie PCA process: (a) Transferring LTG-GaAs thin film mesa with DI water. (b) Inverting the LTG-GaAs thin film mesa device. (c) Transferring LTG-GaAs thin film mesa with DI water and needle. (d) LTG-GaAs thin film mesa device transferred. (e) Inverting LTG-GaAs thin film mesa device. (f) Integrating LTG-GaAs thin film mesa on the bow-tie PCA. (g) LTG-GaAs thin film mesa device aligned on the bow-tie PCA. (h-i) Microscope top view image of the integrated bow-tie PCA.

Figure 34(a) shows an actual photograph of the LTG-GaAs thin film mesa device transferring process between the two Mylar thin film diaphragms. Figure 34(b) shows an actual microscope back side image of the LTG-GaAs thin film mesa devices temporally bonded on a Mylar thin film diaphragm, which is captured through the transparent back side thin film diaphragm. Air fringe patterns on some devices indicate weak bonding of the LTG-GaAs thin film devices on the diaphragm surface.
4.3.4. SU8-2 transparent polymer for mechanical support between the LTG-GaAs thin film mesa and the bow-tie PCA process

The integrated LTG-GaAs thin film device is directly bonded by vdW surface tension effect on the surface of the bow-tie antenna metal rectangular electrode tips patterned on a silicon host substrate, Figure 35(a). Subsequently, four hours of oven annealing at 200 °C is performed to ensure stable metal to metal bonding between the metallic micro contacts on the surface of the LTG-GaAs thin film mesa and the bow-tie PCA’s metal rectangular electrode tips, Figure 35(b). Because the LTG-GaAs device is thin, the surface morphology of the integrated substrate is relatively smooth, so further processing is possible on the top of the integrated device.

Figure 36(b) exhibits the LTG-GaAs thin film device heterogeneous integrated [116] onto the bow-tie photoconductive gap between the rectangular electrode tips.
Before starting, apply the SU8-2 transparent polymer coating onto the bow-tie PCA patterned on the SiO$_2$Si host substrate integrated with the LTG-GaAs mesa thin film. The SiO$_2$Si host substrate undergoes a plasma etching operation to change the surface characteristic from hydrophobic to hydrophilic. However, the plasma is performed with O$_2$ at 15 sccm and 90W of RF power for 5sec.

In the current integrated device for the LTG-GaAs based THz PCAs, the SU8-2 transparent polymer is defined on the LTG-GaAs thin film device front side by spin coating and photolithography process.

The SU8-2 transparent polymer layer serves as a protective coating layer for the LTG-GaAs thin film mesa device integrated on the front site of the bow-tie PCA’s rectangular electrode tips, Figure 35(b). Figure 35(c) shows an actual microscope top view image to the protective SU8-2 transparent polymer coated layer on the front side of the integrated bow-tie PCA patterned on a SiO$_2$Si host substrate.

The SU8-2 polymer is highly transparent at the 800nm wavelength of the pump-probe optical laser excitation beam. The emitted THz wave radiation coming out from the back side of the bow-tie emitter PCA is collected and collimated by a pair of silver coated off-axis parabolic mirrors onto the back side of the bow-tie detector PCA. Consequently, the THz wave radiation from the emitter to the detector does not interact with the SU8-2 transparent polymer layer. On the contrary, The THz wave radiation interacts only through the host substrate thickness, which is affected based on the material resistivity. The higher the resistivity of the substrate material, the more it becomes transparent in the THz frequency regime resulting in higher THz wave radiation performance.
Figure 35. (a) A bow-tie antenna patterned on a SiO₂/Si host substrate. (b) A bow-tie antenna with an integrated LTG-GaAs thin-film. (c) A bow-tie antenna with an integrated LTG-GaAs thin-film protected with a coated SU8-2 polymer layer.

4.4. Bow-tie PCA electrode pads patterned on a conventional bulk GaAs substrate fabrication

The total thickness for the bulk GaAs is 500µm consisting of LTG-GaAs\AlAs\SI-GaAs with thickness layers of 2.5µm\0.25µm\497.25µm. The bulk GaAs resistivity is about 3.5×10⁸Ω.cm [113]. The bow-tie antenna metals are defined by photolithography, thermal evaporation, and lift-off processes on the LTG-GaAs\AlAs\SI-GaAs substrate. A similar process is covered in Section 4.3 for the silicon substrate.

5. Printed circuit board fabrication

5.1. Introduction
The PCB for the integrated bow-tie PCA emitter is fabricated under commercial automatic PCB machinery with the dimension of 2.8cmx2.8cm using a double sided copper board. One side of the double sided copper board is the back side for the ground plane and the other side is the front side for the positive plane to avoid short circuit connectivity from each other. The PCB for the bow-tie PCA emitter is not designed to use a hyper-hemispherical Si lens because the small size substrate can scratch the lens surface during displacement adjustments. On the other hand, a second PCB is custom designed for the integrated bow-tie PCA detector with a 4.8cm diameter to fit the X-Y mounting stage circular shape with a cavity located at the center to accommodate a hyper-hemispherical Si lens.

5.2. PCB for the emitter bow-tie PCA

The ProtoMaster SA62 is a machine able to fabricate PCBs automatically [119]. The ProtoMaster SA62 counts with a user interface BoardMaster program to control speed, drill selection from the panel, and X-Y displacement directions.

The PCB patterns are designed in advance by using the Multisim Board layout, which is loaded into the computer via BoardMaster, as illustrated in Figure 36(b). The BoardMaster program recognizes Gerber format done in Multisim Board layout. The Gerber format is a standard 2D binary vector imaging file format used by printed circuit board industry software. Finally, the 2.8mmx2.8mm PCB is fabricated for the bow-tie PCA emitter, as illustrated in Figure 36(d). This type of PCB is not able to accommodate a hyper-hemispherical Si lens due to its small size.
Figure 36. (a) ProtoMaster S62 with the vacuum hose, machining head, movable table to fix based material, and a drill panel. (b) The computer BoardMaster user surface. (c) The PCBs printed on the fixed based material. (d) The PCBs with a centered opening to fit the PCA.

5.3. PCB for the detector bow-tie PCA

Initially, the copper board is cleaned with dishwasher soap and a Scotch green sponge on both sides, if the board is double sided copper, and then dried with paper. The detector designed PCB circular shape is printed with a toner printer on glossy photo paper. The PCB circular shape
is aligned and transferred onto a copper board surface by using an iron heated to maximum for better results. Successively, the iron is hard pressed with back and forth movements for about 5 minutes. The printed shaped on the copper board is then submerged into a boiled water pod for about 30 min. Subsequently, the copper board is removed from the water and the paper layers peeled off. Once the printed shape is revealed on the copper surface, the printed shape is inspected for any uncovered critical areas that can be fixed with a permanent marker pen. FeCl₃ is used with a Maria’s bath to maintain a temperature at 70°C in order to expedite its etching rate process. The etching process is done in a ventilated room because of its toxicity. Once the process is done, the PCB board is rinsed with cold water to remove excess of ferric chloride left behind. The resulted emitter PCB is a circular shape with 4.8 cm in diameter, as illustrated in Figure 37, able to use the hyper-hemispherical Si lens in conjunction with the X-Y mounting stage.
Figure 37. The photograph illustrates the PCB for the PCA detector able to accommodate the hyper-hemispherical Si lens to enhance the THz signal SNR.

6. **Bow-tie PCA packaging and bonding wires**

6.1. **Bow-tie PCA emitter**

In order to facilitate THz characterizations from the integrated emitter bow-tie PCA, the integrated bow-tie emitter PCA needs to be mounted on the fabricated PCBs, Figure 38(a). The SMA connectors are attached to the PCBs and the integrated bow-tie PCA patterned on the Si substrate are mounted, Figure 38(b). The emitter bow-tie PCAs’ circular
terminal pads with 201µm lateral transmission lines are wire-bonded and placed on the mounting stage to enable connection to an external SMA connector, Figure 38(c). The two microscope close up views through the PCB open center of the integrated and conventional bulk bow-tie PCAs with the bonded wires on the circular pads are illustrated in Figure 38(d,e). The DC biased voltage is applied to the bow-tie emitter PCA through the SMA connector to establish static electric field needed for the switching and enhancement of the THz wave radiation strength during the device TDS characterizations, Figure 38(f).

6.2. Bow-tie PCA detector
Figure 39(a) illustrates the back side of the X-Y mounting stage with the hyper-hemispherical Si lens located at the center. The integrated bow-tie PCA is patterned on the surface of the Si substrate with dimensions of about 2.5cm x 1.5cm and mounted on the back side of the circular PCB, as illustrated in Figure 39(b). The hyper-hemispherical Si lens is able to slide on the back side surface of the 2.5cm x 1.5cm silicon wafer without the worries of being scratched, as illustrated in Figure 39(b). The lateral pads of the bow-tie PCA are bonded with wires to the PCB using a wire of 25.4μm diameter alloy aluminum with 10% silicon, as illustrated in Figure 39(c). The positive and negative terminals from the front side of the PCB are connected to the SMA connector, as illustrated in Figure 39(c,d). The DC bias voltage can be provided through the SMA connector to the integrated bow-tie PCA, as illustrated in Figure 39(c,d). The mounting stage is provided with two knobs to control the X-Y axes for the hyper-hemispherical Si lens alignment, as illustrated in Figure 39(d). The main reason to provide a hyper-hemispherical Si lens to the integrated bow-tie PCA detector is to increase the THz dynamic range of the SNR signal.
7. Experimental set up

7.1. Introduction
The integrated conventional bulk bow-tie PCAs and the commercial RF\MW antennas setup are discussed to understand the different characteristics between these two dissimilar technologies able to generate electromagnetic waves.

7.2. Comparative analysis of the THz photoconductive antennas and the RF\MW antennas

THz photoconductive antennas and commercially RF\MW antennas are dissimilar from different perspectives, such as designed frequencies, semiconductor characteristic, antenna structure, feeding technique, conduction current, manufacturing facility, test, and measurement facility, as illustrated in Figure 40(a,b).

THz antennas are designed based on THz frequencies in the order of $10^{12}$Hz and are patterned on photoconductor materials with certain energy bandgap (for instance, GaAs 1.43eV). Moreover, the photoconductor mediums are very complex materials from the manufacturing point of view in order to reunite high mobility, high resistivity, and fast response time in the order of picoseconds or even sub-picoseconds, among others. As a result, the three layered semiconductor material, LTG-GaAs\AlAs\SI-GaAs, with the thickness of 2.5µm\0.25µm\497µm is very expensive to produce due to the involved complex material process of growing the LTG-GaAs optically active layer.

THz antennas are designed with length less than the working wavelength in the micro-scale to obtain reasonable operating frequency. Metallization is based on photolithography and evaporation techniques with expensive metals, usually chromium and gold. The feeding technique is based on ultra-fast femtosecond laser where its photons possess higher energy than
the bandgap energy of the semiconductor medium in order to be excited. The photoconductive antennas are fabricated in very expensive and sophisticated facilities equipped with state of the art machinery.

In a laboratory facility, all optical components require very precise alignment without physical connectivity to each other for testing and measurements known as the THz-TDS, as illustrated in Figure 40(a). The process of generating THz wave radiation with a TDS setup is briefly explained as follows: THz wave radiation from the photoconductive antennas \([120]\) (in the order of micrometers) is generated from the transient electric current that is produced into the semiconductor medium. The dislodged free carriers (electrons-hole pairs) on the surface of the photoconductor medium \([121]\) illuminated by the infrared pump optical beam are separated and accelerated by the DC bias electric field. Then, the THz wave is radiated due to the resonance of the transient electric currents coupled into the metallic planar antenna. The conduction current is the result of two mechanisms, generation of electron-hole pairs under the electric field known as drift current and the displacement current due to second order nonlinear optical characteristic of the semiconductor medium. The THz wave is then collected, collimated, and focused onto the detector PCA by a pair of off-axis parabolic mirrors. The THz wave and probe optical beam (on the path of the delay line) meet each other onto the detector PCA, where a lock-in-amplifier collects the THz data. This is explained in more detail in Section 7.3. The THz wave pulse is mapped out by sampling and moving the delay line. The optical alignment has to be done with high precision because the misalignment between the antennas (emitter-detector) and the optical sources (pump-probe) can affect the THz wave generation and detection.
THz PCAs are mostly used in THz sources operating at room temperature. Due to PCA strong THz wave generation and detection capabilities, they are used in pulsed as well as CW THz systems that are now commercially available.

On the other hand, the RF\MW antennas are designed based on Mega\Gigahertz frequencies on the order of $10^6 - 10^9$Hz with the wavelength in the range from meters to millimeters [122]. In addition, the RF\MW antennas are excited by coaxial cables. RF\MW antennas are usually patterned with highly conductive metal such as copper. The substrate in RF\MW antennas is low-loss dielectric material usually FR4 which consists of fiberglass reinforced epoxy laminated sheet. In the MMIC [123], the substrate is GaAs where its transmission lines are patterned with gold. The conduction current in the RF\MW antennas is due to the motion of conduction electrons. During testing and measurement, the RF\MW antennas, both Tx and Rx antennas, are connected to a vector analyzer to determine various parameters of the antenna. The laboratory facility utilizes commonly anechoic (non-reflective, echo free) and reverberation measurements chamber facilities, illustrated in Figure 40(b). There are anechoic chamber facilities able to accommodate large test machines, such as spacecraft mockups with antennas mounted on them [124]. The microwave materials that cover the wall and door surfaces absorb electromagnetic energy, thereby allowing the anechoic chamber to simulate a space environment. The far-field chamber facility has the capability to accommodate lower frequencies, down to 200MHz, under testing in an effort to bring indoors all testing with frequencies ranging from 200MHz to 40 GHz. The near-field facility within the anechoic chamber expands the testing and measurement capabilities of this facility by providing a means of analyzing radiating elements in cases where far-field measurements are impractical due to the range length requirements [124], as illustrated in Figure 40(b).
The test measurement in small facilities consist of an anechoic chamber vector with a VNA (frequency limitation up to 100 GHz) attached to the antenna under testing and held by a custom sample holder. The size of the anechoic chamber space in which the antenna is placed is 140cmx120cmx120cm [125], as illustrated in Figure 40(b).
Figure 40. THz photoconductive antennas and RF/MW antennas characterization techniques. (a) Shows the TDS setup with all optical components not connected to each other in which misalignment between optical components is critical. (b) Shows the RF/MW antennas setup with all components connected to each other with no component misalignment.
7.3. TDS for THz signal characterization

THz pulses can be generated by different methods such as illuminating the PCAs, semiconductor surfaces, or the quantum structure [126] with fs optical pulses. Among these methods, the generation and emission from THz-pulsed PCA are a crucial and fundamental one, as illustrated in Figure 41. The semiconductor medium for the fabrication of THz PCA sources needs to reunite excellent properties like short carrier lifetime, high mobility, high breakdown voltage, and high resistivity. As a result, the conventional bulk GaAs semiconductor material that presents the aforementioned characteristics is utilized to fabricate the THz emitter-detector PCA sources. The active optical medium to fabricate the integrated bow-tie PCA is the LTG-GaAs epitaxial layer that it is separated from the native SI-GaAs, as illustrated in Figure 41(a). On the other hand, the conventional bulk GaAs semiconductors are utilized as a whole optically active medium to fabricate the bow-tie PCAs, as illustrated in Figure 41(b).

Figure 41. Illustrates the perspective pictorial view of the standard THz pulse emission (in green) generated from the DC-biased voltage (battery) and the optical pump laser beam (in blue). (a) Shows the integrated bow-tie PCA with the LTG-GaAs thin film technique. (b) Shows the conventional bulk GaAs bow-tie PCA technique.
Two identical integrated bow-tie PCAs are prepared. One is used as a THz PCA emitter and the other is used as the THz PCA detector with a hyper-hemispherical Si lens. A Mode-locked Ti: Sapphire laser with 80fs ultra-short pulses of 800nm wavelength with 85-MHz repetition rate is used as the excitation optical source. The 2.0mm diameter optical laser beam with an average power of 375mW is divided by an optical beam splitter in two optical laser beams. One is a reflected 200mW optical laser beam onto the spectrometer detector to monitor the laser mode-locking state of the Gaussian profile. The other is a transmitted 175mW main optical laser beam arriving into the 60/40 beam splitter to divide the optical laser beam in the 70mW pump and 105mW probe optical laser beam paths.

The half wave plate and Gran-Taylor polarizer prism on the path of the pump optical laser beam adjust the optical power from 70mW to 30mW. The pump optical laser beam falls in the mechanical chopper’s rotating disc to modulate the pump optical beam at a frequency of 1.86 KHz to increase the dynamic SNR. The optical chopper on the way of the pump optical laser beam path reduces the power by 50%. The 15mW incident pump optical laser beam is collimated onto a lens, which focuses the optical beam onto the biased integrated bow-tie PCA emitter to generate electrons-holes pairs. The free carriers gain enough kinetic energy by the 20V applied DC bias voltage (battery). The carriers are accelerated by the pump optical beam to a maximum value. Then, they decay exponentially with a time constant determined by the carrier lifetime (typically 430fs), resulting in a pulsed (transient) photocurrent in the gap of the PCA. Current modulation occurs in the subpicosecond regime and thus emits a subpicosecond transient EM wave as a coherent THz wave radiation, illustrated in Figure 42(a,b) indicated in green.

The emitted THz pulse passing through the semiconductor thickness, Figure 42(a,b) illustrated in green, is collected and collimated by a silver coated off-axis parabolic mirror,
Figure 42(c). Moreover, the collimated THz beam is reflected onto another silver-coated off-axis parabolic mirror that focuses the THz beam onto the hyper-hemispherical-Si-lens, which further focuses it onto the PCA detector with no pre-amplifier. The hyper-hemispherical Si lens reduces the loss caused by the reflected and refracted radiation at the surface/air interface and also enhances the THz dynamic SNR signal.

On the other hand, the femtosecond optical probe pulses on the path of the optical time-delay line gate the integrated bow-tie PCA detector. The induced transient photocurrent component from the incident THz field on the bow-tie PCA detector is measured with an ammeter connected to a low-noise amplifier. By delaying the timing between the gating pump pulses (that generates the THz pulses) and the probe pulses (that gates the bow-tie PCA detector), the waveform profile of the THz pulses are obtained. The time resolution is limited by the repetition rate of the pump/probe pulses from the Titanium: Sapphire femtosecond laser. The output signal of the current is fed into a lock-in amplifier without pre-amplifier, illustrated by a box beneath the computer in Figure 42(c). The THz characterization is performed at room temperature without a vacuum-tight purged box with nitrogen gas.

In order to map out the average electromagnetic THz radiation as a function of time, the retro-reflector scans up to 55mm distance in steps of 0.01mm increments with a delay time of 1.0sec in each interval. Finally, the time-domain measurement of the THz emission from the integrated bow-tie emitter-detector PCAs is characterized.
Figure 42. (a,b) Illustrate the actual THz-TDS setup to characterize the THz wave signals. (c) Illustrates the pictorial view of THz-TDS setup.
7.4. Summary

The experimental setup for THz characterization remains bulky, but it can potentially be furthermore fused with other integrated CMOS platforms. For example, mode-locked laser on-chip [127], semiconductor lock-in amplifier (signal processing on chip) [128], waveguide, and integrated PCA for future THz on-chip sensing.

8. Results and discussions

8.1. Dark current and photocurrent signals

Keithley 2400 source measurement unit is utilized to perform the electrical characterization on the bow-tie PCA integrated with a LTG-GaAs thin film. An optical single mode fiber is employed to couple a laser light at 846nm wavelength vertically onto a LTG-GaAs thin film optical device integrated on the bow-tie PCA device. Both the Newport 1930-C and Newport 918-SL are utilized to calibrate the output optical power of the fiber. The Newport 1930-C is a power meter and the Newport 918-SL is a calibrated PD.

No breakdown current was observed when measuring the dark current and photocurrent as a function of applied voltage up to 60 V, as illustrated in Figure 43. A dark current of 1.72nA at 60V applied DC-biasing voltage was observed with no direct excited light onto the LTG-GaAs thin film mesa, integrated on the bow-tie PCA device showing a high resistivity suitable for THz PCAs. In addition, a light from a single mode fiber laser at 846nm wavelength with the optical power of 64.2mW illuminating the LTG-GaAs thin film device exhibits the higher photoconductive current of 300nA at 60V applied DC biasing voltage resulting in sufficient
efficiency with low resistivity, as illustrated in Figure 43.

![Graph showing dark and photocurrents for the integrated bow-tie PCA.](image)

Figure 43. Dark and photocurrents for the integrated bow-tie PCA.

8.2. THz signal

Figure 44 shows the characterized Time-Domain THz pulse generated and detected from the integrated bow-tie emitter-detector PCAs. The measured THz signal peak to peak voltage is 6.1mV and its full width at half maximum (FWHM) is 0.35ps. The resulted THz signal from the integrated bow-tie emitter-detector PCAs is obtained with a detector equipped with a pre-amplifier in order to enhance the THz signal strength before feeding it into a lock-in amplifier. L. Desplanque et al. [129] have demonstrated THz pulses using post-bonding of LTG-GaAs film.
Figure 44. A temporal THz wave generated and detected from the integrated bow-tie emitter-detector PCAs.

The corresponding frequency spectrum distribution of the time-domain signal obtained by the FFT exhibits its maximum energy concentration up to 0.6 THz, as illustrated in Figure 45. The spectral THz bandwidth is about 2.0 THz and its frequency spectrum distribution is extended up to 8.0 THz before the signal level drops closer to the noise floor.

The THz signal is fundamentally restricted by its SNR, which is limited specifically by the ratio between the THz power signal and the detector noise obtained with the THz emitter.
blocked. In order to calculate the SNR at a frequency of about 0.37 THz, two values are obtained from the THz spectral power magnitude: one is from the FFT spectral power signal with 0.1799 and the other is from the optical probe beam noise with 8.363E-05, as illustrated in Figure 45. The SNR value resulted from the dynamic range ratio of 3.333 decades is 66.65dB. The noise floor contribution comes mainly from the optical probe beam not from the optical pump beam.

Figure 45. The FFT exhibits maximum energy concentrated up to 0.6 THz with a bandwidth of about 2.0 THz and the FFT spectrum distribution extended up to 8 THz before the signal level drops closer to the noise floor.
8.3. Integrated PCA and conventional bulk PCA under voltage variations

The magnitude of the $E_{THz}(t)$ emitter is proportional to the time derivative of the photocurrent $J(t)$. Therefore, the $E_{THz}(t)$ [130, 131] can be expressed as:

$$E_{THz}(t) \propto \frac{\partial J(t)}{\partial t}$$  \hspace{1cm} (33)

The peak value of $J(t)$ is a function of the density of the photo-carriers time dependence [n(t)], which is determined by the laser pulse shape and carrier lifetime. Since photocurrent generates electromagnetic pulses due to its variation in time, the $E_{THz}(t)$ can also be expressed as:

$$E_{THz}(t) = V_b \left( \frac{q\mu A}{4\pi \varepsilon_o c^2 z} \right) \frac{\partial n(t)}{\partial t}$$  \hspace{1cm} (34)

The $q$ denotes the elementary charges, $\mu$ is the mobility of electrons, $V_b$ is the applied DC bias electric field in between the photoconductive gap, $\varepsilon_o$ is the vacuum permittivity, $c$ is the speed of light in a vacuum, $z$ is the distance between the field point and the THz source, and $A$ is the incident optical pump laser beam effective area at the Gaussian waist, which is 314.16µm$^2$ with 10mW of pump power.

Therefore, the applied $V_b$ is increased with values of 5V, 15V, 25V, and 35V, as illustrated in Figure 46(a-b). The carrier density [n(t)] for the integrated and the conventional bulk PCA devices is discussed in Sections 2.6.2 and 2.6.3.
The free carriers are driven by the $V_b$ field across the photoconductive gap and produce the photocurrent density. The $E_{\text{THz}}(t)$ scales up basically with the variation of the $V_b$, as illustrated in Equation (34). Subsequently, the analysis has been limited basically to the SNR that is mainly affected by the variation of the $V_b$.

The THz wave signals scaling up stronger in the integrated bow-tie PCA, as illustrated in Figure 46(a), than in the conventional bulk bow-tie PCA, as illustrated in Figure 46(b). The THz wave signal magnitude increases as the $V_b$ is gradually increased, so the energy of the $E_{\text{THz}}(t)$ stored in the photoconductive gap increases as well.

Multiple ripples are observed in the measured THz radiations shown in Figure 46 (a,b) may be due to the interface reflections between air and substrates in PCA emitter and receiver, which needs more investigations.
Figure 46. (a) THz wave signals from $V_b$ variations with values of 5V, 15V, 25V, and 35V in the integrated bow-tie PCA. (b) The conventional bulk GaAs bow-tie PCA with the same conditions as before.
The spectral power amplitude in the integrated bow-tie PCA shows a higher SNR enhancement response when the voltage increases without touching the noise levels as the THz signal continues to 8 THz, as illustrated in Figure 47(a). On the other hand, the conventional bulk GaAs bow-tie PCA shows negligible SNR enhancement response and overlapping with the noise floor as the THz signal increases to the frequency of 8 THz, as illustrated in Figure 47(b). Conventional GaAs bow-tie PCA shows high attenuation at high THz frequencies than the integrated bow-tie PCA, as illustrated in Figure 47(b).
Figure 47. The spectral power amplitude for (a) the integrated bow-tie PCA and for (b) the bulk GaAs bow-tie PCA under variations of applied DC bias voltages of 5V, 15V, 25V, and 35V. SNR enhancement is obtained with the integrated bow-tie PCA than with the bulk bow-tie PCA.
All measurement condition was identical and average optical pump power excited onto the PCAs was measured at 10mW. Figure 48 shows the extracted peak-to-peak value of the measured THz signal as a function of applied bias voltage. The THz peak to peak voltage profile from the applied DC bias voltage variations demonstrates that the integrated bow-tie PCA increases faster than in the conventional bulk bow-tie PCA. This fast voltage increment behavior in the integrated bow-tie PCA is due to no shadow effect is observed allowing much higher electron-hole pairs generation than in the conventional bow-tie PCA, explained in Section 3.11. Therefore, the integrated bow-tie PCA gets higher THz peak voltage values reaching saturation level much faster than the conventional bulk bow-tie PCA, as illustrated in Figure 48(a,b). As expected, the measured THz signal is increased as the bias voltage is increased. It was also observed that LTG-GaAs thin-film PCAs show higher THz peak power at the similar bias voltage. The integrated bow-tie PCA, therefore, generates higher THz radiation power than the conventional bulk bow-tie PCA.
Figure 48. Illustrates the THz peak-to-peak sensitivity with the integrated bow-tie PCA (indicated with dash lines) and the bulk bow-tie PCA (indicated by a solid line).

8.4. Summary

In the photoconductor medium, the epitaxial lift-off method allows the use of LTG-GaAs thin films on arbitrary carrier substrates with enhanced transmission properties at optical and THz frequencies. The conventional bulk GaAs, on the other hand, is known to exhibit considerable attenuation and dispersion at THz frequencies [71].

9. Conclusion and Future research work
The bow-tie THz PCA patterned on a silicon substrate heterogeneously integrated with the LTG-GaAs thin film mesa and bow-tie THz PCA patterned on the conventional bulk GaAs substrate have been successfully designed, fabricated, characterized, and analyzed. The benefits of using the LTG-GaAs thin film mesa devices for device integration of on-chip THz sources have been discussed in detail. The integrated bow-tie PCA THz wave emission and detection have been performed by using pump-probe THz TDS measurements. The possibility of THz functional devices based on the heterogeneous integration approach that can be individually optimized and integrated into any technology platform (including electrical circuits and microfluidic systems) has been demonstrated. The cost effectiveness of using the thin-film based PCAs for integrated on-chip THz source systems has been successfully illustrated. Consequently, this will greatly broaden THz technologies to many practical applications within the industry and from the scientific research point of view.

The THz wave signal strength dependency on DC bias voltage for both LTG-GaAs thin film and conventional bulk GaAs based THz PCAs has been studied, analyzed and experimentally tested. The LTG-GaAs thin film based THz PCA has shown better performance than its conventional bulky counterpart. The integrated LTG-GaAs thin film bow-tie PCA exhibits larger dynamic range SNR signal than the conventional GaAs bow-tie PCA at the same DC bias voltage and optical excitation conditions. In other words, the integrated PCAs generate higher THz radiation power compared to the conventional bulk PCAs with the same optical pump power. Moreover, the integration approach permits multi-material integration when using the LTG-GaAs thin film mesa and the silicon-based host substrate. The integration of the LTG-GaAs thin film method was proven to have a great potential interest in the forthcoming
development of on-chip THz based microsystems, which combines the optics, electronics, and THz on-chip scale components or package for many multidisciplinary applications.

9.1. Future research work

The introduced integrated bow-tie PCA THz source can be patterned on any host substrate with the high coherent transmission in THz frequency regime, unlike the conventional bulk GaAs substrate based PCA. The conventional bulk GaAs substrate has demonstrated, at different DC bias voltage levels in Section 8.3, considerable THz signal attenuation and dispersion than the silicon substrate at THz frequency regime. In addition to the compactness of its on-chip scale, the integrated bow-tie PCA with a LTG-GaAs thin film patterned on any host substrate has a huge potential advantage in terms of cost effectiveness. For instance, a THz liquid-gas sensor can be utilized as a stand-alone device that is patterned on a glass substrate due to its high transparency in the visible spectrum for easy device alignment purpose and its high transmission properties in the THz frequency regime.

9.2. THz sensor for liquids and gasses measurement

The THz material spectral absorption fingerprint features can be efficiently utilized in liquid and gas identification. THz dielectric permittivity in liquids and gasses are correlated with their constituent weak intramolecular and intermolecular interaction which can be probed and easily identified at the THz frequency regime. The liquid/gas based THz sensor sensitivity is
limited by THz wave radiation strength and liquid/gas sample effective interaction pad length, which can benefit from the introduced and discussed high efficient on-chip THz source. This type of sensor is not limited to liquid/gas characterization, but it can also be extended to measure protein, DNA, cells, to mention a few.

Figure 49 represents a pictographic view of a liquid/gas based THz sensor featuring two similar bow-tie PCAs patterned on 1.0mm thick glass. An air-tight sealed acrylic box is built with a liquid/gas chamber with inlet and outlet plastic tubing. A lens focuses the optical pump beam onto the LTG-GaAs thin film THz emitter that generates THz wave radiation, which propagates through the sensor gap to the back side of the integrated detector. The collimating silver coated off-axis parabolic mirrors are not needed in this device topology because the THz emitter and detector are closely spaced. This has an advantage of not having the extra dedicated optic component alignments, which can introduce insufficient optical alignment between emitter-detector PCAs.

Due to the high resistivity and low refractive index of the glass substrate, it promises to be an excellent candidate to transmit a higher THz signal power than the silicon based platform.
Figure 49. THz sensor composed of the integrated bow-tie emitter-detector PCAs patterned on a 1.0mm glass. The two PCAs are mounted on an acrylic box with two apertures to connect the liquid/gas chamber input-output tubing lines.
APPENDIX A
PROCESS SEQUENCES

A.1. Mylar transparent thin film diaphragm process

This part of the appendix contains the detailed process sequence used for the Mylar diaphragm fabrication used for the integration process and for the thin film devices storage.

1. The proper safety equipment must be used, trionic gloves, apron, goggles, and face shield.
2. Prepare a teflon beaker and teflon tweezers.
3. A solution base of HF:HN03:H2O with a rate of 6:2:1 is prepared to etch the silicon wafer.
4. The Apiezon W wax pellet is melted with TCE to protect areas not exposed to the silicon etchant.
5. A silicon wafer sample with a size of about 3inx3in.
6. The silicon sample is submerged into the etchant solution.
7. After finishing the silicon etching process, the AZ4620 photoresist is spread around the center opening surface of the silicon.
8. The Mylar diaphragm sheet is placed tightly on the surface of the silicon wafer.
9. Finally, oven at 113°C for about 20 minutes dries the AZ4620 photoresist to firmly tighten the film to the surface of the silicon.
A.2. LTG-GaAs epitaxial layer with metallic micro contact array process

This part of the appendix contains the detailed process sequence used for the metallic micro contact array fabrication on the surface of the LTG-GaAs thin film epitaxial layer from the conventional bulk GaAs substrate.

1. The conventional bulk GaAs substrate is composed of three layers, LTG-GaAs\AlAs\SI-GaAs substrate with a size of 4.5mmx4.5mm.
2. The surface of the conventional bulk GaAs substrate is cleaned with acetone, methanol, isopropanol, and a nitrogen gun.
3. The process is bi-layer photoresist coated with the first layer of a positive photoresist SF-11 at 3,000 RPM for 30sec to get 1.0μm thick.
4. The SF-11 is hot plate baked at 170°C for 5min.
5. The second layer is a negative NR9-1500PY imaging spin-coated at 6,00RPM for 30sec to get a thickness of 1.0μm.
6. The NR9-1500PY is hot plate baked at 150°C for 1.0min.
7. The NR9-1500PY coated layer on the substrate is exposed with i-line by the mask aligner photolithography for 20sec.
8. The NR9-1500PY layer is bake at 100°C for 1.0min.
9. The NR9-1500PY is developed with PG-101A for 6sec.
10. The NR9-1500PY is hot plate baked at 150°C for 1.0min.
11. The SF-11 is exposed to the first flood short wave at 265nm wavelength for 10min.
12. The SF-11 is developed with PG-101A for 1.0min.
13. The SF-11 is exposed to the second flood short wave at 265nm wavelength for 10min.
14. The SF-11 is developed with PG-101A for 1.0min.
15. The SF-11 is exposed to the third flood short wave at 265nm wavelength for 10min.
16. The SF-11 is developed with PG-101A for 1.0min.
17. The photoresists are hot plate baked at 150°C for 1.0min to dry the both photoresists.
18. Thermal metal evaporation for the thickness at 200nm-Au\0100nm-Ni\020m-Cr.
19. The metal lift-off process with PG remover is pre-warmed at 70°C for 5min.
20. Rinsing with isopropanol and dry with a nitrogen gun.

A.3. LTG-GaAs epitaxial thin film layer with rectangular mesa definition process

This part of the appendix contains the detailed process sequence used for the rectangular LTG-GaAs thin film mesa array creation by photolithography and etching processes.

1. The surface of the bulk GaAs substrate is cleaned with acetone, methanol, isopropanol, and a nitrogen gun.
2. Positive photoresist S-1805 is spin-coated at 3,000RPM for 0.75μm thickness.
3. The S-1805 is hot plate baked at 105°C for 1.0μm.
4. Alignment between marks from the photo-mask and the metal array patterned on the surface of the bulk GaAs are carefully aligned and exposure for 4.0sec.
5. The positive photoresist S-1805 is developed with MIF-319 for 30.0sec.
6. Rinsing with DI water and dry with a nitrogen gun.
7. The S-1805 is hot plate baked at 125°C for 5.0min to harness the S-1805 photoresist.
8. A micro cover glass of 22x22-mm² is cleaned with acetone, methanol, isopropanol, and a nitrogen gun.

9. The sample is glued with an Apiezon W wax pellet melted at 120°C on the micro cover glass surface.

10. Using a DEKTAK profilometer to determine in advance two reference thicknesses from the metal surface to the conventional bulk GaAs surface for the etching process. This procedure is the most decisive step to preserve high yield fabrication mesa devices.

11. C₆H₅O₇:H₂O₂ with 4:1 ratio with an etchant rate of 0.5μm/min is prepared in a glass beaker to define the rectangular shape for the LTG-GaAs thin film mesa devices.

12. The process stops when the etchant reaches the LTG-GaAs thickness of 2.0μm in about 5min before getting closer to the interface sacrificial AlAs layer.

13. The Apiezon W wax is dissolved with TCE solution to release the bulk GaAs substrate from the cover glass.

A.4. LTG-GaAs thin film mesa array fabrication and storage on a Mylar transparent film diaphragm for integration and future use process

This part of the appendix contains the detailed process sequence used for the fabrication of the LTG-GaAs thin film mesa devices. The LTG-GaAs thin film mesa devices have lift-off from the sacrificial AlAs layer under wet etching processes. The remaining 0.5μm thick of LTG-GaAs thin film layer is etched off to create the LTG-GaAs thin film mesa devices to be released on the surface of the Mylar film diaphragm for integration and storage.
1. The Apiezon W wax pellet is melted at 120°C on top of the bulk GaAs substrate surface to protect the LTG-GaAs thin film rectangular array.

2. Edges of the SI-GaAs sample are carefully cleaned with TCE solution for particles of S-1805 and Apiezon W wax left behind.

3. A teflon rod is attached to the melted Apiezon W wax for handling purposes.

4. The bulk GaAs substrate is submerged in a 10% isotropic aqueous dilution of HF with a rate of 5.0μm/min to etch off the AlAs.

5. Once the AlAs layer is etched off, the LTG-GaAs thin film epitaxial layer is separated from the SI-GaAs substrate.

6. The 0.5μm thick LTG-GaAs thin film epitaxial layer left behind is etched off with the C₆H₈O₇:H₂O₂ to create the LTG-GaAs thin film mesa devices.

7. A blade cuts the Apiezon W wax in between the Teflon rod and the LTG-GaAs thin film mesa devices to release the LTG-GaAs thin film mesa devices onto the surface of the Mylar film diaphragm.

8. The Apiezon W wax is melted with the TCE solution to release the LTG-GaAs thin film mesa devices on a transparent Mylar film diaphragm to finish with isopropanol to remove the S-1805 photoresist left behind.

A.5. Preparation for imaging bi-layer photoresist with a negative NR9-1500PY and the SF11 layers process

This part of the appendix contains the detailed process sequence used for the imaging bi-layer photoresist to pattern a bow-tie PCA on a silicon host substrate. In order to make a bi-layer re-entrant photoresist suitable for bi-layer lift-off, the negative NR9-1500PY photoresist is
coated on top of the sacrificial layer SF11 photoresist. Consequently, the re-entrant is provided by the SF11 photoresist and the negative NR9-1500PY provides the printing pattern based on photolithography technique.

1. The SiO₂\Si host substrate is used to pattern the bow-tie PCA.
2. The surface of the SiO₂\Si host substrate is clean by acetone, methanol, isopropanol, and a nitrogen gun.
3. The process is bi-layer photoresist coated with the first layer of a positive photoresist SF-11 at 3,000 RPM for 30sec to get 1.0μm thick.
4. The photoresist is hot plate baked at 170°C for 5min. It is recommended to place the silicon at the edge of the hot plate for 1.0min and then slide the silicon wafer to the hot spot for 5.0min.
5. The second layer is a negative NR9-1500PY imaging photoresist coated at 6,00RPM for 30sec to get a thickness of 1.0μm.
6. The photoresist is hot plate baked at 150°C for 1.0min with the same conditions as in 4.
7. The NR9-1500PY layer is exposure under i-line with the mask aligner photolithography for 20sec.
8. The NR9-1500PY layer is hot plate baked at 100°C for 1.0min.
9. Developed with RD6 for 6sec.
10. Rinsing with DI water and dry with a nitrogen gun.
11. The NR9-1500PY layer is hot plate baked at 150°C for 1.0min.
12. The SF-11 is exposed to the first flood short wave at 265nm wavelength for 10min.
13. The SF-11 is developed with PG-101A for 1.0min.
14. The SF-11 is exposed to the second flood short wave at 265nm wavelength for 10min.

15. The SF-11 is developed with PG-101A for 1.0min.

16. The SF- is exposed to the third flood short wave at 265nm wavelength for 10min.

17. The SF-11 is developed with PG-101A for 1.0min.

18. The photoresists are hot plate baked for 150°C for 1.0min to dry the photoresists.

19. Thermal metal evaporation with the layer of 200nm-Au/20nm-Cr.

20. Metal lift-off process with PG remover pre-warmed for 5min at 70°C to define the bow-tie PCA.

21. Rinsing with acetone and dry with a nitrogen gun.

A.6. Preparation for imaging reversal bi-layer photoresist with a positive AZ5214 and a SF11 layers process

This part of the appendix contains the detailed process sequence used for the imaging reversal bi-layer photoresist to pattern a bow-tie PCA on a silicon host substrate. In order to make a bi-layer re-entrant photoresist suitable for bi-layer lift-off, the positive AZ5214 reversal photoresist is coated on top the sacrificial layer SF11 photoresist. Consequently, the re-entrant is provided by the SF11 photoresist and the positive reversal imaging AZ5214 provides the printing pattern based on photolithography technique.

1. The SiO₂\Si host substrate is used to pattern the bow-tie PCA.

2. The surface of the SiO₂\Si host substrate is clean by acetone, methanol, isopropanol, and a nitrogen gun.
3. The process is bi-layer photoresist coated with the first layer of a positive photoresist SF-11 at 3,000 RPM for 30sec to get 1.0μm thick.

4. The SF-11 is hot plate baked pre-exposure at 170°C for 5min. It is recommended to place the silicon at the edge of the hot plate for 1.0min then sliding the silicon to the hot spot for 5.0min.

5. The second layer is a positive AZ5214 imaging reversal coated at 6,00RPM for 30sec to get a thickness of 1.0μm.

6. The AZ5214 is hot plate baked at 90°C for 1.0min.

7. The positive AZ5214 layer is exposure under i-line with the mask aligner and the photomask for 1.20sec.

8. The positive AZ5214 layer is hot plate baked at 120°C for 45.0sec.

9. The positive AZ5214 layer is exposure with i-line without the photomask for 36.0sec to obtain a reversal imaging negative photoresist.

10. The positive AZ5214 layer is developed with MIF-422 for 1.0min.

11. Rinsing with DI water and dry with a nitrogen gun.

12. The SF-11 is the first flood exposure with a short wave of 265nm wavelength for 10min.

13. The SF-11 is developed with PG-101A for 1.0min.

14. The SF-11 is the second flood exposure with a short wave of 265nm wavelength for 10min.

15. The SF-11 is developed with PG-101A for 1.0min.

16. The SF-11 is the last flood exposure with a short wave of 265nm wavelength for 10min.

17. The SF-11 is developed with PG-101A for 1.0min.

18. The photoresists are hot plate baked at 150°C for 1.0min.
19. Thermal metal evaporation with the layer of 200nm-Au/20nm-Cr.

20. Metal lift-off process with PG remover pre-warmed for 5min at 70°C to define the bow-tie PCA.

21. Rinsing with acetone and dry with a nitrogen gun.

A.7. LTG-GaAs thin film mesa integration on a bow-tie PCA electrode tips with transmission lines patterned on the silicon host substrate process

This part of the appendix contains the detailed process sequence used for the LTG-GaAs thin film mesa integration on the bow-tie PCA electrode pads with transmission lines patterned on the silicon host substrate.

1. Micro-needle probe weakens the bonding of the LTG-GaAs thin film mesa that is transferred to another Mylar transparent diaphragm surface.

2. The LTG-GaAs thin film mesa is flipped to correct position.

3. The LTG-GaAs thin film mesa is placed on tiny DI droplet water on the electrode tips of the bow-tie PCA.

4. Magnetic forces position the LTG-GaAs thin film mesa that is attracted by the surfaces tensions.

5. A pair of micro-needle probes finishes positioning the LTG-GaAs thin film mesa.
A.8. SU8-2 transparent polymer for mechanical support between the LTG-GaAs thin film mesa and the bow-tie electrode tips process

1. Four hours of oven annealing at 200°C is accomplished to perform stable metal-to-metal bonding between LTG-GaAs thin film mesa metallic micro contacts and the bow-tie PCA metallic electrode tips.
2. SiO₂\Si host substrate undergoes plasma etching.
3. The SU8-2 is spin-coated with a gradual spin increase to reach 1,700RPM to avoid thin film fly away.
4. The SU8-2 photoresist is hot plate baked at 95°C for 2.0min.
5. Mask aligner photolithography to expose the SU8-2 with i-line for 10.0sec.
6. The SU8-2 photoresist is hot plate baked at 95°C for 3.0min.
7. The SU8-2 photoresist is developed with the SU-8 developer for 1.0min.
8. Rinsing with isopropanol and dry with a nitrogen gun.

A.9. Silicon layer resistivity measurement process

1. The host substrate is the SiO₂\Si substrate with a thickness of 5µm\495µm.
2. The BOE with a rate of 0.2µm/min is used to selectively etch away the 5µm SiO₂ layer.
3. The silicon without the 5µm layer is measured using a four point probe device.
10. References


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