Chapter 1

Introduction

1.1 Introduction

For several decades, the region covering the wavelengths between 20 μm to 3 mm was considered as Far Infrared Region (FIR). In the initial days, this region was termed a sub-millimeter region but it was not justified since the sub-millimeter region strictly provides a cut-off of 1 mm. Later, in 1978 Blaney suggested a name for this region as short millimeter and sub-millimeter wavelength range (SMSMR) [1], but even this did not get acceptance by the research community. The term Terahertz has become widely accepted by the researchers following its use by J.W. Fleming in a 1974 paper [2]. The main problem associated with the terahertz region is its very high absorption in the earth's atmosphere over a major portion of the frequency range due to vibrational–rotational levels of water vapour. As a result, there are limitations in THz astronomy and research in the upper atmosphere. The terahertz (THz) technology is predicted to be one of the emerging technologies that will revolutionize our planet. The Editors of Technology Review in 2004 listed THz technology as one of the "10 emerging technologies that will transform your life". This chapter provides a brief discussion on the history of research in the THz region. This chapter discusses the THz spectral region, its unique properties, and its applications.

1.1.1 Early 20th Century Research

In 1895, J. C. Bose demonstrated wireless transmission over a mile in front of the public in order to remotely ring a bell and detonate explosives [3]. He used wavelengths between 2.5 cm and 5 mm for the demonstration. This work on millimeter waves has laid the foundation for the research in THz region. The research in the terahertz region started way back in the 1890s by Heinrich Rubens. Over a period from 1892 to 1922, Rubens and his research group published around 150 research papers in the FIR research. In the early FIR area, Rubens contributed about 90 % of the papers published up to his death. Three major discoveries were made during this period. In fact, Ruben was the first one who created THz source, a mercury arc lamp that is prevalent even today [4]. Another discovery made by him and his team is that they formulated an empirical formula to explain the reflectivity of metals in the THz region [5]. His significant achievement includes the development of measurement setup for the absorption of water vapour out to 400 μm without any electronic aids [6]. Rubens and his team were also successful in developing techniques for experimental studies involving wavelengths beyond 50 μm (6 THz).

1.1.2 The Years 1920-1940

In 1923, E.F. Nicholas and J.D. Tear succeeded in connecting the electric wave spectrum to infrared region (IR). Apart from them, Cartwright made detailed investigations on the absorption of materials in the long wavelength region and he was responsible for the design of a liquid oxygen-cooled thermopile that showed a ten-fold increase in responsivity over the same device operated at room temperature [7]. J. D. Strong with the help of Randall made studies on the absorption of gases in the region between 20 μm and 200 μm [8]. He was one of the first persons during this period who pursued the transitions from grating to interference spectroscopy at THz frequencies [9]. There were only marginal improvements in the performances of the sources and the detectors during these decades. The most significant contribution during this period is the detection of ammonia gas over the wavelength range 1-4 cm using a coherent source [10].

1.1.3 The Years 1940-1950

During World War II, there were many developments in the field of high frequency electronic systems. Major inventions during this period include the pneumatic detector (Golay cell) [11] and the cooled bolometer [12]. During World War II, there were also major improvements in spectroscopy systems. The DC record systems were used earlier for all the experiments but from 1945 onwards, detectors were designed with shorter time constants, the incoming radiation was chopped and AC amplification was used. High-frequency radar systems were developed resulting in new magnetron and klystron sources. With the klystron source, the absorption of oxygen was measured at 50 GHz to 60 GHz [13]. Two research groups extended the frequency into IR spectroscopic systems. C. H. Townes and his colleagues had reached frequencies of 270 GHz [14]. W. Gordy and his research group extended microwave spectroscopy into the sub-mm region [15].

1.1.4 The Years 1950-1960

This period laid the foundation for the transition from gratings to Fourier-Transform Spectrometer (FTS), although happened relatively slowly, it went on to revolutionize FIR spectroscopy. The slow transition is due to the limitations of the then-available computers. The major invention during this period was the harmonic analyzer [16] that can be able to derive the spectra by observing the fringe intensity. Michelson and Rayleigh were aware that it is possible to explore the full spectrum through Fourier transformation but they had no way to perform this. Peter Fellgett was the first person to derive the actual spectrum while studying stars in the IR. Prior to the availability of detector arrays until recently, it was possible to study only one frequency at a time [17]. Two more major inventions during this period are the carbon bolometer [18] in 1959 and the same year photoconductive detector that reaches wavelengths longer than 100 μm [19]. During this period foundation was laid for the first backward wave oscillator (BWO) [20]-[21].

1.1.5 The Years 1960-1970

During the 1960s there was great progress in the development of detectors. During this decade, major detectors invented are the n-InSb electron bolometer [22], the Ge bolometer [23], and a tunable FIR detector [24], the extrinsic photoconductor Ge:Ga [25], when stressed this responds out to 200 μm [26]. A helium-cooled detector based on the Josephson effect also belonged to this decade [27]. Another important invention was the so-called honeycomb diode chip design for the Schottky diode mixers [28]. Some of the other discoveries during this period include the THz laser, the water vapour laser in 1964 [29] that led to discovering the long wavelength gas lasers including HCN which provides frequencies close to 1 THz [30]. Another discovery was polymer TPX, a hard plastic that is transparent for most of the FIR [31]. It is very much useful for windows and lenses and it has the same refractive index in both visible and THz regions. In 1968, time-domain spectroscopy evolved but it was limited to the microwave region only [32].

1.1.6 The Years 1970-1980

During this decade, there was a significant progress made in astronomical research due to the availability of high-altitude observatories and efficient receivers. In the 1970s, the presence of carbon monoxide (CO) in the interstellar medium was detected at 115 GHz with a Schottky-diode heterodyne receiver [33]. Later in 1977, the presence of carbon monoxide at 0.345 THz was detected with a heterodyne receiver based on an InSb hot electron bolometric mixer [34]. The researchers in this decade had sensed and pointed out that FIR imaging systems may be developed for various other non-astronomical applications like industry, medical, military etc [35]. During this decade there was significant progress in the Schottky diode optimization [36]. Another important invention during this period was the superconductor-insulator-superconductor mixer (SIS) useful for THz heterodyne systems [37]-[38].

1.1.7 The Years 1980 and beyond

During this period, a p-type Ge laser, a source covering the frequency from 1 THz to above 4 THz was invented [39]-[40]. The primary advantage of this laser is that they can be electrically excited, and the laser require quite low power and can be packaged with a mechanically cooling device [41]. Elias and his team improved the free electron laser (FEL) to operate from 0.3 THz and 0.77 THz with a peak power of 10 kW [42] which has applications in biology including photobiology. In the development of spectroscopy, stable coherent synchrotron radiation (CSR) was used that produced a power increase of 10^5 over the 0.3-1THz range [43]. In 1984, Auston and his colleagues [44] developed the so-called Auston switch to produce high powers that were used to study the transmission and absorption of many materials. A remarkable thermal detector was invented by G. N. Goltsman and his co-workers, known as hot electron bolometer (HEB) [45] followed the same mechanism as the helium-cooled detectors [46]. It is a fast thermal detector that is useful throughout the IR and THz regions.

The major reason for increased interest in the THz region comes primarily from astronomy. This region has enormous scope for research in spectroscopy and imaging applications. Many emission lines and absorption of astrophysical and astrochemical molecules and atoms occur in this part of the spectrum. By 2011, nearly 150 molecules and atoms have been discovered in space. The research in this frequency domain gives a lot of information which were undiscovered in galaxies and outer space. Also, the development of local oscillator (LO) sources has made THz sources with μW to mW output power available up to 2 THz. The invention of Quantum Cascade Lasers (QCL) made it possible to cover most of the THz region [47] that have applications in a variety of fields [48]-[49]. In today's era, the increased need for extra bandwidth for communications had an impact on the THz technology, especially in the low-frequency range where the research applications are approaching 0.3 THz. But another problem associated with THz radiation is its strong absorption in air. Hence it is limited to use only in local networks. Many investigations in the diagnostics of charged particle beams [50], [51] in micro and nanoscale devices are being carried out currently through THz spectroscopy for plasma displays [52]. Of late, THz devices are used for mainly military purposes. TeraView, a company that was founded in 2001 by Michael Pepper and Don Arnone was responsible for the development and commercialization of many commercial THz devices that are available now.

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1.2 Terahertz Spectral Region

The terahertz (THz) spectral region is located between the sub-millimeter wave region and infrared region of the electromagnetic spectrum as shown in Fig.1.1. The electromagnetic radiation emitted in the THz region is termed as the THz radiation or T-rays or T-waves [48]. There are many number of research groups working in the area of terahertz. In general, there are three different definitions available in the literature to define the T-ray band. They are 0.1-10 THz, 0.3-3 THz, and 0.3-30 THz [48]. In this thesis, we considered 0.1-30 THz to be the terahertz region as overlapping of region exists in the electromagnetic spectrum like the definitions of X-rays and gamma rays overlap. It is one of the challenging areas of the electromagnetic spectrum. The invention of the laser [53] has attracted researchers to suddenly jump to the optical region from the electronics region of electromagnetic spectrum leaving behind a large band of frequencies in the spectrum. This might be one of the reasons for the terahertz region remaining unexplored for many years. The gap now is getting filled as the researchers started revisiting this region as it has more potential applications in imaging, astronomy, space etc. As the THz region lies between the two popular domains, the optical (photonics) and the microwave (electronics), expert's perception may differ as they are expressed in terms of wavelength into the far infrared in photonics, and expressed in terms of frequency down to gigahertz (GHz) in radio-electronics respectively. The boundaries of the THz region are not strictly defined. Due to its position in the spectrum, theory and practices from both the domains are employed to utilize THz radiation, but with unique limitations. Presently, no ideal methods exist to generate or detect the THz waves. It is completely based on the types of sources used and detection technologies employed for specific applications. For absorption wavelength of 30 μm (at 10 THz frequency), systems can be designed in such a way that they follow the similar physics employed in the near-IR regions. However, as the wavelengths are longer, to avoid diffraction losses and interference effects, it is necessary to increase the size of the optical components. These issues are overcome in the microwave region by confining radiation to a single mode in a waveguide. Fig.1.1 shows the location of terahertz region in the electromagnetic spectrum.

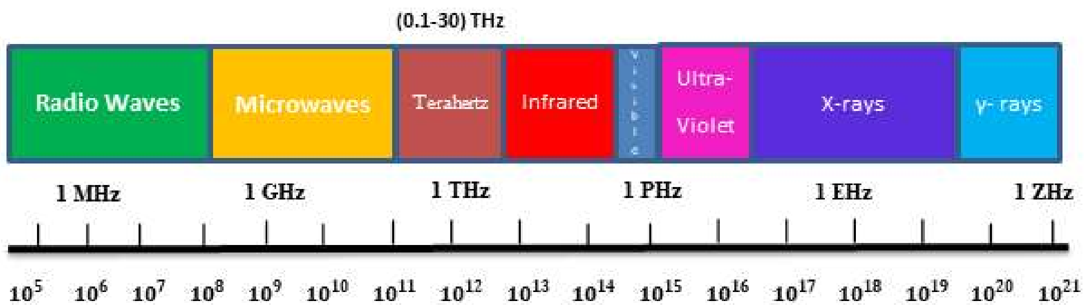

Fig.1.1 The Electromagnetic Spectrum

1.3 Properties of Terahertz Radiation

The THz radiation possesses unique properties and the terahertz band is expected to find application in both non-telecommunication and telecommunication systems. This region has a huge potential for the development of novel devices. A few reference frequencies corresponding wavelengths, energy bandgap and wavenumbers in the terahertz band are listed in Table1.1.

Table1.1 Characteristics of THz radiation

Frequency (THz)	Wavelength (μm)	Energy (meV)	Wavenumber (m^{-1})
0.1	3000	0.4133	333.33
1	300	4.1333	3333.33
10	30	41.3333	33333.33

1.3.1 Non-Ionizing

A very heavy exposure to the radiation with shorter wavelengths (X-rays, γ-rays) may lead to sickness, mutation in humans and sometimes cancer which can lead to death. On the other hand, THz radiation has photon energies of the order of meV that are very much less compared to that of X-rays. This energy is not sufficient to damage the human tissues unlike X-rays. Therefore, the THz radiation is non-ionizing and is very much useful in imaging applications in the medical field.

1.3.2 Penetration

One of the most prominent advantages of the THz radiation is that most of the common materials available in nature are transparent or semi-transparent to it. This list may include some plastics, paper, cardboard, semiconductors, and human and biological tissues [54]. This is the reason why THz research may find its application in imaging. A suitable technology needs to be developed for the production of devices that may compete with existing systems such as X-ray, MRI, etc. The main disadvantage of the THz radiation is that it does not possess the same penetrative power as millimeter wave or X-ray radiation.

1.3.3 Safety

The last few years have seen the power levels of the THz sources increasing at an alarming rate. An extensive study needs to be carried out on the effects caused on humans under exposure to radiation with increased power levels. It is also required to analyze its permissible levels for safety. In the initial days, it seemed that THz radiation is safe as it is considered to be non-ionizing. But this may not be true completely as rigorous testing has not been carried out yet as the technologies associated with them are fairly new. Recently, there are reports of negative impacts on exposure to THz radiation with high power levels like growth enhancements, wound healing, and changes in anxiety levels [55]. More investigations are necessary to determine the limitations of THz radiation power levels. A recent investigation suggests that it is unlikely to cause damage to the human tissues for the power levels below 10 $mWcm^{-2}$[55].

1.3.4 Resolution

At distances less than 1 m, current millimetre wave scanning systems run at roughly 30 GHz and give around 1 mm of spatial resolution. By shifting into the THz domain, not only is the resolution increased but the system's aperture may be reduced. This allows the systems to be more compact, movable, and covert if necessary [6], [56]-[57]. The X-ray systems offer better resolution based on Rayleigh criterion in comparison to the THz as the X-rays have a substantially shorter wavelength. The resolution versus penetration of the radiation, as well as ionising energy concerns, are trade-offs for X-rays against T (terahertz)-rays.

1.3.5 Scattering

The scattering of THz light is less than that of shorter wavelength radiation. The probability of Rayleigh scattering is inversely proportional to the wavelength as λ^4. In comparison to visible light, there is a 10^{12} reduction in scattering for wavelengths of 1 mm (0.3 THz) [54], [58]. This decrease in scattering makes it possible to get a better image. In wireless communication, the THz technology has the potential to establish a reliable communication link in case of bad weather like fog, etc. [60].

1.3.6 Atmospheric Transmission

As discussed earlier, it is very challenging to develop devices in the THz region. Armstrong [60] pointed out that when considering the power levels and distances necessary for establishing a communication system, anything more than 100 metres for wavelengths higher than 1 THz is nearly not feasible, even with a petaWatt of power. This limitation is defined as the THz Wall because no matter how much a signal is boosted to a receiver, nothing gets through beyond 100 meters.

1.4 Applications of THz Region

THz region finds many applications in civil and military situations. Some of the applications have been presented here.

1.4.1 Astronomy

Astronomers were among the first scientists to show interest in THz radiation for a very practical reason. About half of the luminosity and 98% of photons released since the occurrence of the Big Bang reside in the THz portion of the spectrum, specifically the interstellar dust that sits 14-140 K below the ambient background of the earth [61]. Because of this and spectral attenuation, ground-based systems in the THz will always have limited utility. This application is one of the most easily employed areas since the primary limitations of THz radiation are mitigated by putting the sensors in space. In a space vacuum, all the problems with absorption and transmission nearly go away. At longer wavelengths, the rotation spectrum of heavy molecules dominates the gas emissions of interest. This is where a THz detector could be used since the clouds are optically thin. At shorter wavelengths into the infrared, these dust clouds are optically thick, so one cannot see through them to detect the emission lines of interest. By using THz spectroscopy in space to look at these emission lines, scientists can gather the information that can answer many unknown questions regarding the formation of galaxies, stars, and planets. It is also useful for the characterization of the Earth's upper atmosphere, to detect and map ozone holes [61].

1.4.2 Packaging and Quality Control

Industries need a viable technology to monitor the quality of the products manufactured and to find the defects very quickly. In addition, any serious damage like the slightest of cracks in the machines that are not visible to the human eye can be identified with a THz imager [62]. Especially, when shipping fragile items, many shipping and packaging companies would like to be able to look through the box and check the condition of the contents without opening the box for fragile contents. Quality control could potentially be greatly improved with non-contact rapid THz imaging [62]. In the pharmaceutical industry, THz imaging can be used to check the tablet coating uniformity within a single tablet and the entire batch. It is preferable because of its non-destructive nature in comparison to other imaging techniques available. Also, due to the heavy absorption by water in the THz band, damage in fruits and vegetables can be observed.

1.4.3 Security

A continuous monitoring and highly accurate devices are required for security screening in airports, public meetings, sporting events etc. [62]-[63]. Since the THz radiation is transparent to clothes and metals are opaque to the THz, a small camera may be designed and fixed to the security personnel who can screen the people and identify the hidden weapons if any, thus avoiding dangerous situations. Especially at large sporting events, spectators are required to pass through a metal detector to have an entry into the stadium. A system may be installed where people could just walk through a hallway illuminated with THz and a camera could image the people as they walked through to search for weapons [64]. This system may eventually avoid the large waiting times significantly at large crowd events. This type of concept can also be used in airport security screenings. Current airport scanners use millimeter waves to search for hidden weapons, but by switching to a THz (submillimeter) scanner to search would give the Travel Security Agency (TSA) better spatial resolution to scan specific areas if a dangerous item has been detected [62], [64]. This is due to the Rayleigh criterion stating that the minimum resolvable element is proportional to the wavelength. Since many chemicals have spectral features in the THz, it can also be used to screen for dangerous chemicals that can be identified at airport security and sporting events.

1.4.4 Medical Applications

Most of the materials existing in nature are transparent to the THz radiation including the human tissues like the outer layers of human teeth and small layers of skin. Therefore, it is possible to use THz imaging as an alternative to the existing X-ray imaging [61]. Much of the human body is composed of water which quickly absorbs THz radiation. Despite that, in areas like teeth, hands, and feet, it is quite possible to see through the skin to the bones, as they are denser and are opaque to the THz [65]-[66]. Human beings getting exposed to X-rays multiple times for medical reasons is very dangerous as the rays are ionizing in nature [68]. Since the THz radiation is non-ionizing, usage of THz imaging avoids the harmful effects of X-ray imaging. In the THz range, many substances exhibit emission, absorption, and other spectrum properties. To identify specific chemical abundances, this may be used to image a vein or skin in the hand and track changes in the associated spectrum features [68]. This approach might be extended to monitoring certain THz spectrum shifts that correlate with blood glucose levels, allowing diabetics to image via their palms non-invasively without drawing blood to test their blood glucose levels [63], [68]-[69]. THz technology may play a crucial role in the identification of cancer via biopsy and associated surgery as it can precisely identify the areas affected, thereby reducing the number of procedures required for the cure. THz radiation will be very useful for the analysis of burn depth and severity, and the detection of skin cancer [70].

1.4.5 Art and Archaeology

Since the terahertz radiation is non-destructive, it may be used by cultural heritage conservators whose aim is minimizing the disturbance of the objects under investigation. THz radiation provides a better resolution of the images in comparison to other imaging techniques with negligible damage to the object [71].

1.4.6 Material Characterization

THz radiation can able to identify many materials existing in nature like semiconductors and lightweight molecules [72]. It is useful to determine the carrier concentration and mobility of the semiconductors and in superconducting material research.

1.4.7 Wireless Communication

In the last decade, the number of people using the internet increased at an unprecedented rate. Therefore, to provide service to all users, there is a great requirement for large bandwidths for the telecom companies. Currently, 5G technology (beta trials) is already in use in a few cities of India that offer faster data rates (1-10 Gbps) in comparison to the existing 4G technology. 5G technology is still insufficient to meet some applications like holograms and multi-sense communication that are the major frontiers in virtual mode of communication. It is expected that 6G wireless communication offers very high data rates >1Tbps and will come into reality around 2025-2030 [58], [73]-[75]. With the technology revolution in wireless network, Internet of Things (IoT) has become a part of everyone's life. In future-generation wireless communication systems, not only humans are better connected but also intelligent things like home appliances, cars, industrial equipment etc., all are connected. Therefore, 6G wireless communication paves a way for the development in IoT [76]. Thus, the THz frequency band has become a focus of interest as it offers high data rates and larger bandwidths for all the future generation wireless communications. A concept of THz/Free Space Optical (FSO) may be useful for future wireless communication system. In the real time scenario, we can use any of the communication system based on the weather conditions. It is possible to use FSO communication in case of clear weather condition. In case of adverse weather conditions, we may use THz communication as it establishes a reliable communication compared to FSO. Unmanned automotive vehicle (UAV), needs a reliable communication that is provided by the THz like forest fire recognition, emergency search operations, high-vision data delivery for telemedicine [76]-[77].

1.5 Outline of the Thesis

Terahertz science and technology is receiving great attention due to its unique characteristics and wide application prospects. The lack of mature technologies for manufacturing terahertz sources and detectors become the bottleneck in the development of this field. The mercury cadmium telluride (MCT) material system has reached a level of maturity that it can be utilized for the development of detectors that may operate in the THz region but they are presently restricted to the optical domain side of the electromagnetic spectrum. The main objective of this thesis is to have an insight into the MCT-based detectors for the terahertz regime. Since the fabrication and measurement techniques are unavailable currently and very sophisticated set up is necessary for such studies particularly at an absorption wavelength of 30 µm i.e., at a frequency of 10 THz, a sincere effort has been made in this thesis to focus on the detailed analysis of optoelectronic characteristics of the THz detectors through simulation studies.

This thesis comprises seven chapters primarily focused on the history of research in the THz region, and the development of the state-of-the-art devices based on MCT that is carried out during the PhD program. The chapters are organized as follows:

The current chapter presents a general discussion on the Terahertz spectrum, its unique characteristics, historical research in the terahertz region and its applications. It also outlines the scope of the thesis.

Chapter 2 provides a comprehensive review of the terahertz detectors. It discusses the currently available detector technologies. In particular, it presents the state-of-the-art HgCdTe technology and the material properties.

In **Chapter 3** the performance of a $N^{+} - CdTe/\, n^{0} - Hg_{0.824675}Cd_{0.175325}Te\,/p^{+} - Hg_{0.824675}Cd_{0.175325}Te$ n-i-p photodetector with a heavily doped CdTe material as a window for terahertz frequency application has been presented. The detector is designed and studied in respect of electrical and optical characteristics at a temperature of 77 K. A library of MCT properties using analytical and empirical expressions for material parameters has been developed. The chapter also presents an analytical model of the device for operation in the THz region. The results obtained on the basis of the analytical model are compared and contrasted with the results obtained on the basis of ATLAS™ TCAD tool.

In **Chapter 4**, in an attempt to achieve a low dark current and enhanced optoelectronic characteristics, a HgCdTe-based double heterojunction n-i-p photodetector operating at 30 µm has been presented. Based on the design, a comparison has been made between the simulated results from the ATLAS™ TCAD tool with the results obtained from analytical modeling. The double heterojunction photodetector is expected to enhance the optoelectronic properties over a single hetero-junction photodetector while maintaining a low dark current.

Chapter 5 presents a Graphene/n^+ - HgCdTe Schottky barrier diode detector for operation in 30 μm wavelength. The detector designed is expected to exhibit a low dark current in comparison to the p-i-n diodes designed in chapter 3 and chapter 4. It is also expected that the device shall offer an enhanced optical response because of its structural advantages.

Chapter 6 presents an analytical model for a THz wave-controlled graphene-gated semiconductor field-effect transistor (GSFET) operated in the THz regime. The analysis is carried out to explore the effect of illumination on the graphene-gated semiconductor field-effect transistor detector for the determination of drain characteristics, transfer characteristics, and transconductance considering both the photoconductive effect and photovoltaic effect. The analysis aims to examine the potential of Graphene-HgCdTe FET as a high-speed THz detector operating at a significantly low power level.

Chapter 7 summarizes the major conclusions drawn from the work carried out during the PhD. It also highlights the future scope of the work.