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Advances in Terahertz Detectors

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ABSTRACT— Terahertz waves cover a large region of the electromagnetic spectrum that is between the well-established microwave and infrared bands. The significance of this regime lies in the accessibility of both structural and spectroscopic information. Applications of THz imaging and spectroscopy include biomedical imaging, detection of explosives, and non-destructive evaluation tools for the aerospace industry. Development and exploitation of terahertz detectors for both direct and heterodyne detection is an attractive area for research and commercial applications. This paper presents an overview of the features of available terahertz detectors.

KEYWORDS— Terahertz, Golay-cell detectors,bolometers.

I. INTRODUCTION

Terahertz THz detectors play an important role in different areas of human activities e.g., security, biological, drugs and explosions detection, imaging, astronomy applications, etc. Physical quantities corresponding to 1 THz are listed as follows:

Frequency, 1 THz = 10^{12} Hz ; Wavelength, 300 μm; Wavenumber, 33 cm^{-1}; Energy, 4.1 meV; Temperature, 48 K.

Detector development is at the heart of all current research. There exists a large variety of traditional deeply cooled mm and sub−mm wavelength detectors (mainly bolometers) as well as new propositions based on optoelectronic quantum devices, carbon nanotube bolometers, plasma wave detection by field effect transistors, and hot electron room temperature bipolar semiconductor bolometers. Progress in THz detector sensitivity has been evoking admiration in a period of more than half century in the case of bolometers used in far-IR and sub-mm-wave astrophysics. Some uncooled THz wave detectors are Golay cell, Piezoelectric, VOx microbolometers, Bi microbolometer, Nb microbolometer, Ti microbolometer, Ni microbolometer, Schottky diodes, Mott diodes, Si MOSFET, Si FET, Si CMOS, SiN membrane, Micro−Golay cell, HgCdTe HEB.

All radiation detection systems in THz spectral ranges can be divided into two groups:

Incoherent detection systems (with direct detection sensors), that allows only signal amplitude detection and which, as a rule, are broadband detection systems, and

Coherent detection systems, that allows detection of amplitude and phase of the signal. Coherent signal detection systems use heterodyne circuit design. For high radiation frequency range, proper amplifiers do not exist. Basically, these systems are selective (narrow−band) detection systems.

Most common sensors are based on heterodyne detection since the dominant area for terahertz technology was high resolution spectroscopy. However this is changing and more emphasis is put towards direct detection techniques and components.

II.HETERODYNE SEMICONDUCTOR DETECTION

Signal acquisition is done by converting the signal in the terahertz range RF range and then amplified at lower frequency. A Schottky diode mixer is the preferred down converter for the terahertz range. This technique requires a local oscillator (LO) operating at terahertz frequency (narrowband terahertz source - FIR gas or more recently quantum cascade laser - in order to achieve intermediate frequency (IF) in RF range.

III.HETERODYNE SEMICONDUCTOR DETECTION

High sensitivity detectors rely on cryogenic cooling for terahertz operation. Several superconducting detectors have been developed based on the Josephson effect, superconductor - semiconductor barriers (super Schottky), and bolometric devices. However, the superconductor - insulator - superconductor (SIS) tunnel junction mixer has become an equivalent to the Schottky diode down converter in terms of operational frequencies. The advantage of the SIS mixers is their low LO power requirement and high nonlinear VI characteristic.

An alternative to the SIS mixer is the transition-edge or hot electron bolometer (HEB) mixer. Modern HEB mixers are based on micro-bridges of niobium niobium-nitride, niobium-titanium-nitride and more recently aluminum and ytterbium-boride-copper-oxide (Y BCO) based materials that respond thermally to terahertz radiation. Micrometer or even smaller sized HEB devices can operate at very high speeds through fast photon or electron cooling. The LO power requirement is even lower than SIS mixers (range of 1 to 100 nW operating above 5 THz).

IV.DIRECT DETECTORS

Small area GaAs Schottky diodes used as antennas, coupled square-law detectors, conventional bolometers based on direct thermal absorption and change of resistivity, composite bolometers with thermometer or readout integrated with the radiation absorber, micro-bolometers using antenna to couple power to a small thermally absorbing region, and Golay cells.

V.GOLAY DETECTORS

Golay Cell is one of the most efficient devices detecting THz radiation. It has excellent sensitivity at room temperature and flat optical response over a wide wavelength range.

During the recent years, Golay-cell detectors are used for detecting terahertz radiation. According to the principle of thermal expansion, a Golay-Cell detector can work at room temperature.Its sensitivity is higher than the pyroelectric detector, with the disadvantage of being more sensitive to vibration. Golay-Cell is also sensitive to the infrared flux in ambient, which adds noise to the measurement. In the long process of signal detection, the energy accumulation in the detector can cause a dc drift of the detected signal and reduce the accuracy of detector. To avoid the occurrence of the above circumstances, a chopper is used to make the continuous waves from the THz source to be cut into alternating signal. Thus the bandwidth is decreased to reduce the noise and eliminate the 1/f noise(the DC drift of detector). The signal power can be obtained by measuring the peak to peak value of the alternating signal sent to the detector.

These days, Golay detectors are manufactured in-house and calibrated individually. Delivery includes a detector head and a power supply unit. Also, there is a mount for the filters. The material used for the entrance window of a Golay detector are High-Density Polyethylene (HDPE) window, Polymethylpentene (TPX) window, diamond window.

Golay Detector with HDPE Window: It is used in monitoring and control of MIR and THz radiation. It is served for detecting, processing, and analyzing optoacoustical detector signals. The complex consists of a specialized software and an electronic unit connecting Golay detector with personal computer through USB interface.

Golay Detector with TPX Window: Due to polyethylene window, detectors have wider wavelength range of operation, spreading down to visible/UV. They can be considered as good substitute to diamond window model as TPX has higher transmittance in THz than diamond. Also cheaper than the latter one. It is used in monitoring and control UV-NIR and THz radiation.

Golay Detector with Diamond Window: Due to polyethylene window exchange to Diamond , these detectors have wider operation wavelength range spreading down to visible. They are usually used when someone needs not THz and VIS ranges only but MIR also. It is a bit more expensive than other detectors. It is used in monitoring and control VIS-THz radiation.

The Golay-cell detector is a very effective device for detecting terahertz radiation. It can be used to detect both continuous-wave (CW) and pulsed THz radiation. However, due to a 25 ms to typically 30ms response time, only average power can be measured for short pulse/high repetition rate THz sources. Spectral response is lowered by transmission charactersistics of the input window.

Terahertz detectors for time-domain systems were intensively studied in the 1990s, and now GaAs grown at low temperature is often used as a photoconductive antenna. Electro-optic sampling techniques are available for ultrawideband time-domain detection.One can measure over 100THz using a 10-fs-laser and a thin non-linear crystal such as GaSe. Femtosecond lasers are used mainly for THz time-domain spectroscopy(TDS) whereas other lasers are used for frequency-domain spectroscopy(FDS). Deuterated triglycine sulphate(DTGS) crystals, bolometers,SBDs and SIS(superconductor-insulator-superconductor) junctions are widely used as conventional THz detectors and their performance has improved steadily.Further, a THz single-photon detector has been developed using a single-electron transistor.

Cryogenic detectors means that they operate at temperatures of 4 K (-269 °C) and below, either using liquid helium or a mechanical cooler. Mechanicaly cooled systems cool to operating temperature with no user intervention For applications that do not require as high sensitivity, the pyroelectric detectors that operates at room temperature are excellent. When the lower sensitivity of pyroelectric detectors is acceptable, they provide a less expensive alternative to cryogenic detector systems. Pyroelectric effect is the change of spontaneous polarization as a function of temperature. This change of polarization causes surface charge at electrodes. Commercially available uncooled pyroelectric detectors with broadband capability in the 1–1000 μm wavelength range are fabricated using such materials as LiTaO3,LiNbO3, and DLARGS (deuterated L−alanine doped tri−glycene sulphate). Cooled detectors are superconducting bolometer, Indium Antimonide hot electron bolometer, magnetically enhanced indium antimonide hot electron bolometer, doped germanium photoconductor.

VI.BOLOMETERS

Conventional bolometers are based on direct thermal absorption and change of resistivity. Cooled bolometers take several forms, the most common commercial systems being helium-cooled silicon, germanium, or InSb composite bolometers, with response times on the microsecond scale. NEP is typically 10^{-13}W/ $Hz^{1/2}$ for 4-K operation and improves greatly at millikelvin temperatures. A transition edge sensor (TES) is also a type of bolometer TES which uses a superconducting film. Most THz detectors that employ a TES use the TES as a thermometer, and read out the TES with a superconducting quantum interference device (SQUID) current amplifier. A variety of TES's have been and are being developed for different applications, including ultrasensitive detectors for satellites to measure the polarization anisotropy of the cosmic microwave background.

Superconducting Hot Electron Bolometers (HEBs) are good candidates for detecting weak signals in the submillimeter or terahertz range.A superconducting Hot Electron Bolometer (HEB) is a device that consists of two thick metal pads that are connected (bridged) by a small superconducting microbridge. While a conventional bolometer will usually have its absorber, thermometer, heat sink, and thermal link as separate elements, in a HEB these various elements are combined. In the diffusion-cooled HEB, normal metal pads serve as the heat sink. The superconducting microbridge serves as the absorber and thermometer with a resistance of ~50 ohm. The HEB is a type of TES, so that its resistance versus temperature profile is used as the thermometer. Hot electron bolometers are both diffusion cooled and phonon cooled.

The superconducting bolometer is sensitive to a wide range of wavelengths from 100 GHz to 20 THz. These detectors offer a linear dynamic range over 50 dB and operate with optimised sensitivity as they are not unnecessarily degraded by exposure to background power at unwanted frequencies. Indium Antimonide(InSb) hot electron bolometers(HEBs) and doped germanium photoconductors offer a much greater speed of response than composite bolometers with no reduction in sensitivity. InSb detectors are useful at frequencies up to 500 GHz or 2.5 THz depending on type, while photoconductors are useful at frequencies above approximately 1.5 THz. To gain the most sensitivity from a superconducting bolometer, indium antimonide hot electron bolometer or Ge:Ga photoconductor, it is necessary to cool the detector to cryogenic temperatures to reduce the noise present in the device and detector circuit, and hence maximize the signal that can be seen at that particular temperature. To do this the detector can be mounted in a suitable cryogenic vessel which is evacuated and then cooled to around 4 K i.e. liquid helium temperature. Cryogenic techniques are often viewed as technically daunting, time-consuming and expensive. In these cases while the fabrication of the bolometer structures is routine since feature sizes are large, the very low operating temperatures (<20 K, in some cases) is a major drawback. In addition, these bolometer work in the range < 5 THz, generally. NbN and NbTiN Phonon-Cooled HEBs : High quality, very thin niobium nitride (NbN) films have very high critical temperatures and very short electron-phonon interaction times. The short electron-phonon time is often believed to dominate the thermal relaxation time of the detectors. These HEBs have low LO power requirements (10s of nW) and can be very fast (up to 6 GHz). To date, their performance has been encouraging, but has not surpassed NbN devices.These phonon-cooled HEB mixers have shown themselves to be very promising detectors, and are actively being pursued by a number of research groups internationally. A phonon cooled HEB mixer has all of the same basic attributes as a diffusion- cooled one. In the NbN phonon-cooled device, the speed is obtained by using a very specialized, extremely difficult to produce material. In the diffusion-cooled HEB, geometry and a relatively simpler material can be used to produce similar results.

There are some disadvantages of bolometric type of detectors, such as they are extremely sensitive to background radiation, temperature fluctuation, mechanical vibration and electrical interference, and the performance deteriorates with increasing frequencies in the THz range. Further, bolometers are insensitive to phase which does not allow the reconstruction of the pulse shape in the time domain.The background radiation is the limiting condition of sensitivity of detector. The sensitivity of the bolometer is mainly determined by the system noise temperature. System noise includes noise from the input source and noise generated in the receiver.

Bolometers are macroscopic detectors. Their large size allows them to easily be made to work with room temperature sources without saturating, but it also makes it impossible to get polarization information from them due to their multimode coupling. As they are detectors of power, they do not preserve electric field information.

Superconductor-insulator-superconductor (SIS) tunnel junctions are extremely sensitive heterodyne mixers and have been widely used for frequencies below 1 THz. The upper frequency limit of these devices is determined by the gap frequency of the superconductor. The main advantage of SIS mixers is the wide Intermediate Frequency (IF) bandwidth provided by this type of mixer. HEB mixers do not have an upper frequency limit and provide a very high sensitivity (Trec < 2000 K) and require very low LO power (< 1μW). Although the IF bandwidth of HEB mixers is rather limited compared to Schottky and SIS mixers, HEB mixers are the most competitive devices for heterodyne detection in the THz range. When compared by characteristics like response time and dynamic range, SIS detectors are found to be much superior to their TES counterparts.

THz detectors are characterized by Noise Equivalent Power (NEP) and detectivity.

The noise equivalent power (NEP) is one of the figures of merit for detectors and characterizes their sensitivity. It is defined as the value of rms incident power on the detector generating a signal output equal to the rms noise output (signal−to−noise ratio; SNR = 1).The lower NEP means the more sensitive detector.

NEP is measured in W/ $Hz^{1/2}$. By averaging one can always improve minimal detected power.

Detectivity defined as

$D^* = \sqrt{S}B/NEP$

where B is the bandwidth and S is the detector area.

VII.SCHOTTKY BARRIER DETECTORS

The Schottky diode detector works well above one THz. The noise is not very low. They do not require cooling to cryogenic temperatures and cover a wide frequency range up to several THz. The main disadvantages are the poor sensitivity and the high local oscillator (LO) power requirement of 3-5mW. However, there are several challenges in design, fabrication and operation of these device structures that remain unresolved.

VIII.FIELD-EFFECT TRANSISTOR DETECTORS

A channel of a Field Effect Transistor (FET) can act as a resonator for plasma waves. Recently, non-resonant plasma properties were successfully used for the room temperature broadband THz detection and imaging by silicon FETs. Both THz emission and detection, resonant and nonresonant, were observed experimentally at cryogenic, as well as at room temperatures, clearly demonstrating effects related to the excitation of plasma waves. The possibility of the detection is due to nonlinear properties of the transistor, which lead to the rectification of an ac current induced by the incoming radiation. As a result, a photoresponse appears in the form of dc voltage between source and drain which is proportional to the radiation power (photovoltaic effect). There are three distinct regions of operation of the FETs depending on gate lengths. It has been demonstrated that for gate lengths of the order of 0.1 μm the plasma oscillations will be in the low THZ region. Otherwise the FET can operate as a broad-band THz detector. nitride based FETs are also used for THz detection. Semiconductor nanowires can also be used as building blocks for the realization of high-sensitivity room-temperature terahertz detectors based on a 1D field-effect transistor configuration.

IX.HIGH ELECTRON MOBILITY TRANSISTOR DETECTORS

Semiconductors heterostructure devices such as high electron mobility transistor (HEMT) and heterojunction bipolar transistors can be regarded as a new type of terahertz detector. A self-consistent spatiotemporal variation of quantum confined electron gas with sufficiently high electron mobility in the channel of HEMT has been proved to be an efficient mechanism for the detection and emission of terahertz radiations. The main advantage of the HEMT over the non-laser based sources is working temperature, high tunability and low fabrication cost.. However, the high losses caused by free carrier absorption and small confinement factor of heterostructure are the factors which restricts the use of HEMT at longer THz wavelengths. Further increase in operating frequency (THz range) is expected in ultrathin gate structured HEMT.

X.CONCLUSION

The recent development of easy-to-use sources and detectors of terahertz radiation has enabled growth in applications of terahertz imaging and sensing. This vastly adaptable technology offers great potential across a wide range of areas. The THz region of the electromagnetic spectrum has proven to be one of the most elusive. Terahertz (THz) technology is one of emerging technologies that will change our life. The past 20 years have seen a revolution in THz systems, as advanced materials research provided new and higher power sources, and the potential of THz for advanced research and commercial applications was demonstrated. Another important aim is to make THz detectors cheaper and more convenient to use. The ultrafast high-sensitive THz detectors are meant for exploring fast-changing and transient THz signals and impulses. Terahertz detectors are also an ultimate tool for characterization, calibration and tuning of impulse THz sources. Although much progress is being made in the area of terahertz detectors, it seems that, the so−called THz gap will remain an important challenge to scientists and engineers for foreseeable future.

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