Chapter 5

Terahertz Detectors (THzDs): Bridging the Gap for Energy Harvesting

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Additional information is available at the end of the chapter

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Abstract

It is indispensable to integrate electronics with environment for better lives. Huge amount of solar energy, dark energy, and unused microwave energy is untapped till now due to insufficient availability of high frequency THz detectors. The difference between THz wave detection and THz electric field detection must be clear. THz wave detection connects the detection of explosives, drugs, astronomy, metals, and imaging applications, etc. On the other hand, THz electric field detection involves the conversion of electromagnetic (EM) radiations to usable DC power. The optimum choice of detectors for energy harvesting is a highly diverse area. The latter part is concentrated on the non-linear behavior of the incoming radiations and has been highlighted also. In this chapter, metal-insulator-metal (MIM) diode detectors have been explored to become a best choice for high frequency detectors.

Keywords: metal-insulator-metal (MIM) diodes, terahertz detectors (THzD), rectenna, tunneling

1. Introduction

In order to fulfill the world energy demands increasing day by day, it is perquisite to have some alternate for the conventional energy resources and energy harvesting methods. Since last few decades, advancement in the field of the THz rectification reveal another way to develop highly sensitive uncooled THz detector. Undoubtedly, a terahertz measurement requires a highly sensitive detector to obtain distinct spectra. One problem faced by the detection of THz waves is low photon energy of milli-electron volts (meV), making the development of a high-performance terahertz detector a difficult task. By serendipity, accurate modeling and applications of the nanoscale materials and devices have conquered these difficulties.

There is a fine line between the egoistical requirement and legitimate demand of energy around the world. By 2030, the demand for energy is projected to increase by 55%, while requirement of oil is increased from 11.4 to 17.7 billion tons [1]. Between 2005 and 2030, energy consumption is expected to increase by 50%, with the bulk of the demand coming from developing countries. The energy provided by the Sun at the Earth's surface on 1 day is more than enough to fulfill the needs of the whole Earth for more than 25 years, if utilizes efficiently. But due to low conversion efficiency, a prevalent commercial usage of solar energy is hardly seen. A portion of the increasing developments, utilizing the enhancement in nanotechnology may be able to change this situation. During the clear climate conditions, the Earth gets 1000 W/m^2 solar irradiation from the Sun [2]. This enormous energy received from the Sun has opened the ways to look for novel systems to convert unused energy radiated continuously from the Sun into usable electricity. The continuous research results in environmentally friendly and clean energy sources and will replace our conventional sources of energy such as coal, gas, oil, hydro, combustible, petroleum energy, nuclear energy, etc. By-products of these sources lead to greenhouse effects and the solar energy is considered to be the most excellent substitute for it as compared to other energy resources. There is a good scope for renewable/green energy corner as its share is less than 1% as compared to present energy resources.

The requirements of efficient energy utilization could be estimated from the fact that during the 2012 Olympics held in London, organizer had managed new facilities with energy efficient, sustainable, and recyclable designs and they cut down the watts to maintain the games clean, green, and energy efficient. The London games had left a benchmark as the most energy-efficient Olympics to till date. A similar kind of legacy is being followed by Rio Olympics 2016. This scenario has motivated the researchers toward exploring renewable energy and unused energy resources (dark energy, unused heat and radiations).

Rectenna is one of the energy harvesting devices, which is a combination of rectifying high frequency diode and an antenna. Rectenna (Rectifier antenna) is a system that is capable for harvesting the infrared and visible wavelengths. The heart of the rectenna system is a metal-insulator-metal (MIM) device that can convert such an energy collected by nanoantenna into usable electric energy.

2. Why THz region?

A lower electromagnetic (EM) region has been occupied for mobile communication systems, and the higher EM region has been occupied for optical communication. However, the THz region is still untapped and has not been completely in use, and this regime has become of colossal importance in extensive disciplines. This region embraces numerous aspects of space research, medical studies, atmospheric studies, natural science, plasma physics, defense and security, process control, etc. The close correlation of electrons and THz radiation is also reflected in the use of THz spectroscopy, which is a contemporary field for the researcher to attract toward it. THz spectroscopy is publicized to provide insight into the electron mobility in semiconductive and conductive nanostructures (like in MIM nanostructures and tunneling spectroscopy) that are suitable for fast electronics systems, which are used to convert solar power into electrons. MIM diodes are able to work in semiclassical and quantum region (**Figure 1**) further broader this window.

It is also applicable for nonlinear optics and image spectroscopy. THz imaging has become a significant function in this region. The initial development of the premature terahertz time domain spectroscopy was the innovation that a range of materials, which are opaque in the visible and near-IR region together with clothing and packaging materials, are reasonably transparent over a great extent of the THz range [3]. Room temperature operation of the infrared and far infrared frequencies detectors too increased the interest toward this region.

The popularity of the study of this region can be estimated by the fact that about 50% of the luminosity and most of the photons energy emitted since Big Bang of the space are contained by the THz radiations [4]. Every technology has dark side as well as brighter one; research in THz range has been obstructed by the absorption of the Earth's atmosphere amongst various main factors is the water vapors present there.

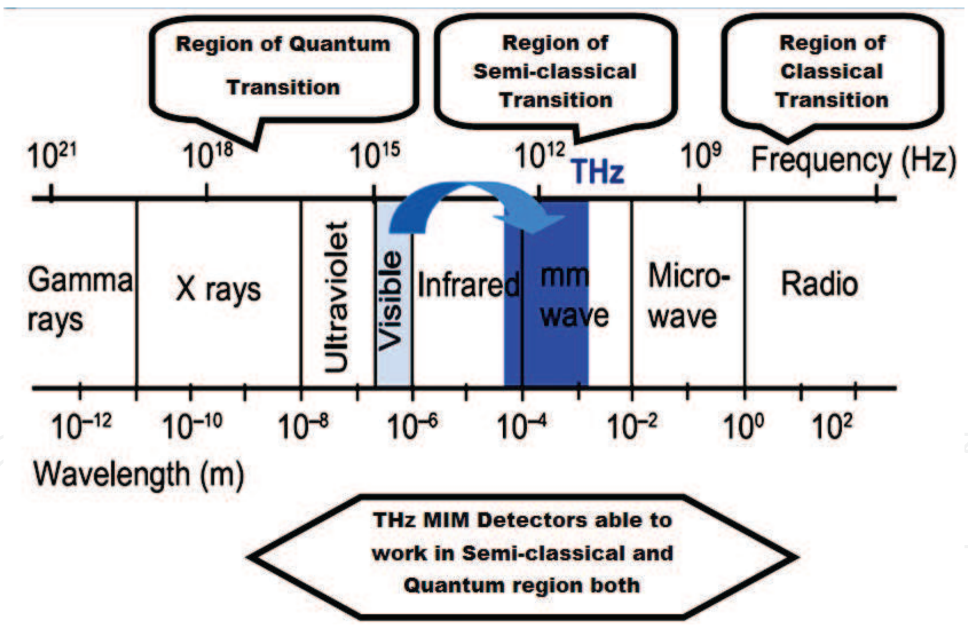

Figure 1. Schematic of the EM spectrum shows the working region for MIM devices.

3. Rectenna made easy

We are more than 7 billion today and multiplying every second around the globe. Specialists believe that further 50% extra energy will be required by 2050 to prolong humanity.

Nevertheless, it does not mean that population is the only stumbling block, but the ever inflating ego and diminishing humanity is also responsible for more energy needs. There is a fine line between the egoistical requirement and legitimate demand of energy around the world. Among various developed countries, Americans build up no more than 4.5% of the world's population and yet consume almost 20% of its energy. Its energy consumption is truly extraordinary [5]. In order to cope up with these problems, appropriate measures intended at reducing the dependence on the present fuels are needed, and the exploration for clean and renewable unconventional energy resources is one of the most urgent confront to the sustainable development of creature evolution.

There are several unconventional sources of energy like thermal energy, nuclear, vibration, wind, water, solar energy, etc. Solar energy is estimated to provide a significant contribution for the solution of energy problem today. Just a small portion of the Sun's energy that hits the Earth is sufficient to meet all our power needs. A little amount of the solar energy reaching the Earth is utilized for producing electricity by using present solar systems. Still the energy demand met by using solar energy is very less. Solar cells based on photovoltaic technology have many applications in solar ponds, vehicles based on solar energy, water pumps, lights, satellites calculators, solar telephones, and many more. But there are several shortcomings of this technology in terms of bulky solar panels, costly installation, low conversion efficiency, and dependencies on the weather conditions. The photovoltaic technology used for energy harvesting has limitation of maximum conversion efficiency by the Shockley-Queisser limit. However, in comparison the rectenna system is able to provide monospectral radio frequency-DC (RF-DC) with a conversion efficiency of 100% [6]. Moreover, photovoltaic technology is expensive and some poisonous by-products are produced during the manufacturing process. Therefore, in this perspective to obtain high efficiency, a green source of renewable energy, rectenna, has emerged as one of the best solutions for meeting the growing energy demand. A system that converts unused EM radiations and radiations from the Sun into usable DC is a rectenna system. It consists of a high frequency antenna to capture the incoming signal and provides the signal to prerectification block. The band-limited signal from prerectification block has been converted to DC which after sufficient filtration applied to output load, as shown in **Figure 2**.

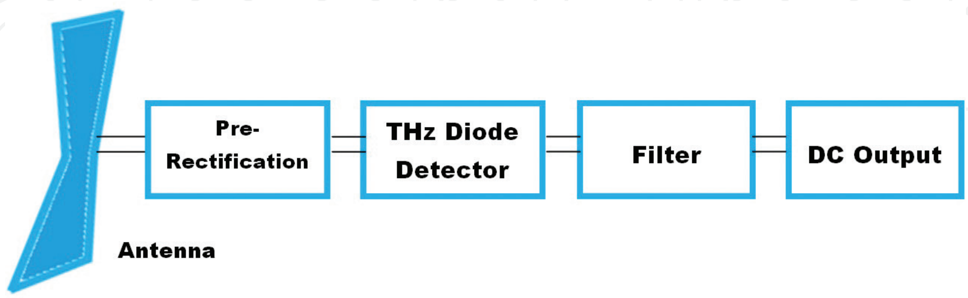

Figure 2. Block diagram of rectenna system.

The term rectenna, i.e., rectifying antenna, was coined by William C. Brown, he used an array of diodes for conversion of incoming microwave power into DC [7]. However, the rectenna

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system in contrast also suffered from limited multispectral efficiency. The progress in the computer-aided design structure has currently cut down the design processes, in which complex electronic circuits such as high-frequency filters, antennas, and rectenna can be designed with a high level of buoyancy and reliability at very low cost and in small period of time.

3.1. Nanoscale antennas

For the collection of the EM field which is a combination of electric and magnetic fields, optimized antenna design and analysis must be taken care. Maxwell's field equations describe the full apparatus of EM fields. Antenna's geometric structure to associated wavelength and its polarization play a very important role. The receiving antenna must be located in the plane of polarization antenna for highest absorption of the electromagnetic fields. Several THz detectors and emitters establish the polarization with associated spectral response, e.g., dipole antennas are mainly based on linear polarization, whereas systems in incoming fields can either respond circularly, elliptically, or linearly polarized light [8].

Several nano-sized antennas, available [9–11] to capture the small wavelength signals, are half-wave dipole, spiral-type, Bow-Tie, Yagi-Uda, etc. The shape and size of the antenna is very important for THz energy collection. The μm-shaped antenna is required to collect the small wavelength signals. Latest nanotechnology for terahertz detection has now demanded for diode-integrated antennas or antenna-coupled diode detectors. The schematic diagram of integrated antenna with diode is shown in **Figure 3**.

Baily gave the concept of capturing the solar power with antennas for the first time employing the wave nature of incoming power [12]. Antenna-coupled detectors with micro-bolometer, metal-insulator-metal diode, and Schottky diodes have been used for detection in the sub-mm-wave and mm-wave regions with various antenna configurations [13, 14]. The surface plasmons are generated on the antenna due to incident EM radiations. Due to the appropriate impedance matching between the antenna geometry and the coupled MIM diode, these plasmons transfer to diode and it generates output DC.

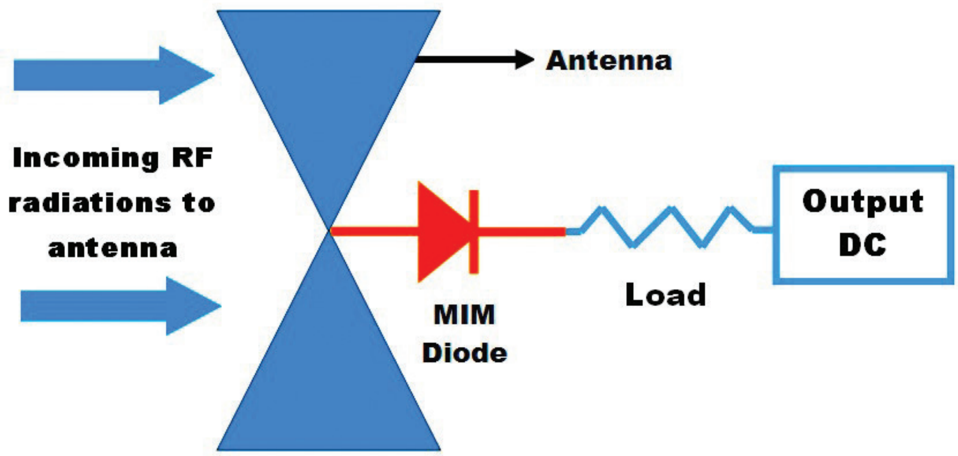

Figure 3. A typical schematic of antenna coupled diode detector.

3.2. Potential detectors available

Commonly available detectors for high-frequency (HF) range are Schottky diode, geometric diode, and MIM/MIIM. High challenges are involved in designing of these detectors due to complex geometries involved, HF challenges and increased fabrication cost. Nevertheless, due to the advancement in technology, highly optimized diode detectors are available nowadays which perform well up to several hundred THz.

3.2.1. Schottky diode detector

For THz detection, a long time battle has been continued between Schottky and MIM diodes [15]. The *n*-doped GaAs semiconductor is the key contender for THz applications, used in the metal-semiconductor structure. Schottky diode's series resistance is high-frequency-dependent parameter and essentially becomes a complex function of device geometry and material conductivity [16]. The diode conversion efficiency η_d [17] is the key to determine the system's performance given by

$$\eta_{\text{diode}} = \frac{\text{DC Output power}}{\text{RF Power incident on diode}} \tag{1}$$

Let

$$\eta_{\text{diode}} = \frac{1}{A+B} \tag{2}$$

The low-frequency term is given by

$$\begin{aligned} A &= 1 + \frac{R_L}{\pi R_S}\left(1 + \frac{V_{bi}}{V_D}\right)^2 \left[\theta_{ON}\left(1 + \frac{1}{2\cos^2\theta_{ON}}\right) - \frac{3}{2}\tan\theta_{ON}\right] \\ &\quad + \frac{R_L}{\pi R_S}\left(1 + \frac{V_{bi}}{V_D}\right)\frac{V_{bi}}{V_D}\left(\tan\theta_{ON} - \theta_{ON}\right) \end{aligned} \tag{3}$$

And high-frequency term is given by

$$B = \frac{R_S R_L c_j^2 \omega^2}{2\pi}\left(1 + \frac{V_{bi}}{V_D}\right)\left(\frac{\pi - \theta_{ON}}{\cos^2\theta_{ON}} + \tan\theta_{ON}\right) \tag{4}$$

where c_j is the diode's junction capacitance given by

$$c_j = c_{j0}\sqrt{\frac{V_{bi}}{V_{bi} + V_D}} \tag{5}$$

Also

$$\tan\theta_{ON} - \theta_{ON} = \frac{\pi R_S}{R_L\left(1 + \frac{V_{bi}}{V_D}\right)} \tag{6}$$

The cut-off frequency of Schottky is given by

$$fc = \frac{1}{2\pi R_s c_j} \tag{7}$$

where R_L is the DC load resistance and R_S is the diode's series resistance, c_j is the junction capacitance, V_{bi} is the diode's built-in voltage in the forward bias region, V_D is the self-bias voltage due to rectification across the terminals of the diode, θ_{ON} is forward-bias turn-on angle depends on diode input power, ω is the angular frequency. For higher frequency operation, the diode series resistance and junction capacitance must be lower. Planar Schottky diodes are able to operate at higher frequency with additional cooling mechanism required. Moreover, Schottky diodes cannot operate at zero bias; hence, MIM diodes are the best choice.

3.2.2. MIM diodes

The MIM diode is a combination of two metal plates separated by a very thin insulating layer of the order of few nanometers. The contact area between upper and lower layer determines the active device area. The area may vary from few μm^2 to several hundred μm^2 depends upon the operating frequency. There are various parameters needed to be optimized for high conversion efficiency like metal work function, insulator electron affinity, and its thickness, which are responsible for the best detector. The dependencies of these parameters can be estimated from the fact that the small deviation (in the range of Å) of an insulating layer and diode area can cause a significant change in the tunneling characteristics, and *I-V* responses [18]. Depending upon the application involved, the type of detector will be used. Comparison of different parameters has been shown in **Table 1**. Also, the fabrication of geometric diodes and other geometric field enhancement diodes is much more complex and expensive in comparison with MIM diodes. Detailed comparative analysis of these diodes has been discussed in our previous publication [19].

3.2.3. Geometric diode

It is the geometry of the device, which allows a preferential motion of charge carriers in a direction defined by its geometry. The asymmetric structure of the device forces to flow the charge carriers in one direction only, and it rectifies an alternating current as a result and hence gives the diode like actions. The diode acts as a funnel for the flow of carriers moving from left to right or right to left (depends on the design of geometry), with restricted flow in one direction and ease flow in other direction as shown in **Figure 4**. These diodes are able to convert from few THz to 1000 THz into usable DC [20].

Parameters	**Detectors**		
	Schottky	**MIM**	**Geometric**
Max frequency of operation	Up to 30 THz [21]	Up to 150 THz [22]	Up to 28 THz [23]
Minimum size of active area	NA	1 μm^2 [24]	1 nm (neck length) [23]
Zero bias resistance	NA	Few 100 kΩ [25]	Few 10 kΩ [26]
Diode capacitance	Few fF [27]	1.8×10^{-15} F [28]	1.8×10^{-17} F [28]
Applications	For few THz detection	For few 100 THz detection	For few 100 THz detection
Fabrication complexity	Small	High	Very high

Table 1. Comparison of High high-fFrequency detectors.

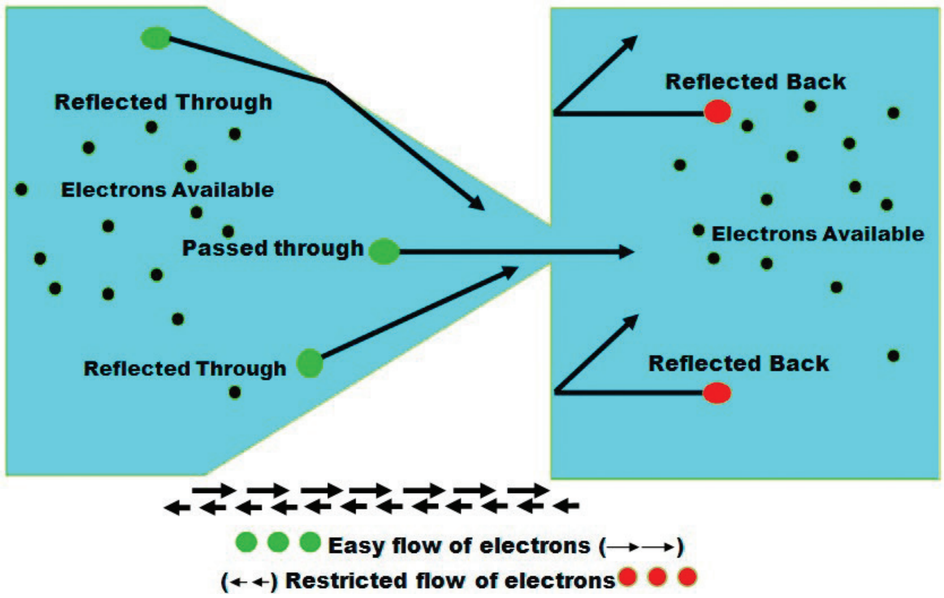

Figure 4. Schematic diagram of geometric diode.

4. Metal-insulator-metal (MIM) diodes

MIM diodes are the successor of Schottky diodes. The Schottky diodes have been routinely used for high-frequency applications like rectification and mixing. MIM diodes are not influenced by parasitic capacitors as compared to Schottky diodes. Extremely broader bandwidth, minute size, room temperature operation, effortlessly integrability with CMOS innovation [28], and zero bias voltage requirements are different encouraging factors for MIM diodes to be investigated with increased interest from last two decades. It is an exceptionally encouraging innovation for terahertz regime. The femtosecond quick exchanging time of these diodes makes them valuable in numerous low power and ultra-fast applications going from rectenna sunlight-based cells as an energy harvesting device [29] to imaging, sensing, and hot electron transistors, also in numerous refined microelectronic products such as switching memories, display devices (LCD backplanes), field emission cathodes [30], etc. MIM diode is a thin-film device in which the electrons tunnel through the insulator layer from the first metal layer to the second metal. **Figure 5** shows the schematic representation of the MIM diode.

Charge transport across the insulator occurs due to quantum-mechanical tunneling of electrons. A similar concept applies to MIM diodes, the process in which a particle penetrates or tunnel via the energy barrier in place of jump over it in contrary to classical mechanics. When the electron reaches the barrier, the insulator in between the metal electrodes absorbs some part of the energy passes through the barrier reaching to the second electrode, but another part reflects back due to some irregularities in thee insulator. How much the energy absorbs and reflected originally depends upon the different characteristics of material used such as work-function difference of metal electrodes, electron affinity of the insulator material, thickness of the barrier, applied potential energy, etc.

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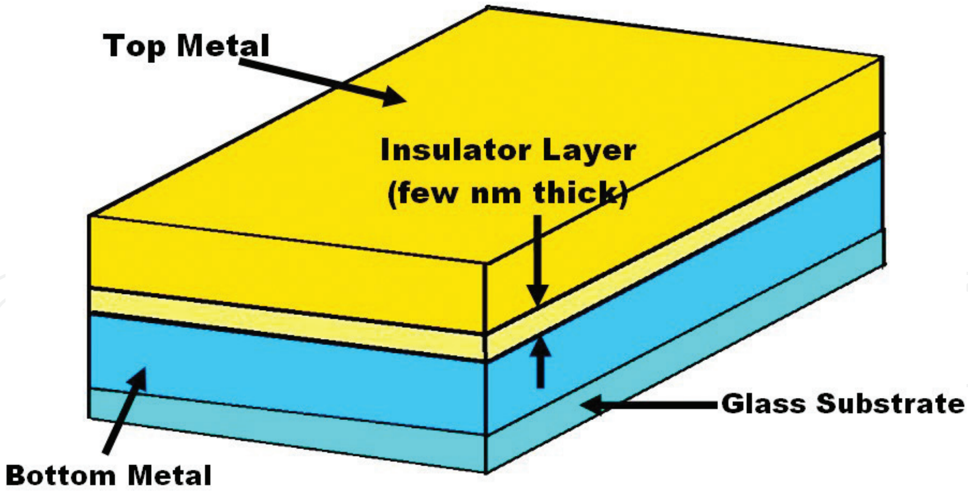

Figure 5. MIM diode schematic diagram.

Due to the tunneling phenomena involved, the energy beam absorbed makes it travel at ultra-high speeds. The speed is much higher than that on a normal conductor or a semiconductor like silicon. Tunneling is a highly nonlinear phenomenon, and hence these diodes are exploited for the rectification, mixing, and detection of alternating currents at very high frequencies even in the THz spectral region. **Figure 6** shows the typical schematic diagram of the MIM band and Fowler-Nordheim tunneling method.

The frequency response of the diode is governed by the resistor-capacitor (RC) time constant. Higher the cutoff frequency, lower the capacitance and resistance. The impedance of the diode must be close enough to the impedance of the antenna for maximum power transfer, and the capacitance must be minimized for operation at THz frequencies. Thickness cannot be decreased to facilitate tunneling, hence only area is left to be altered. Krishnan et al. report

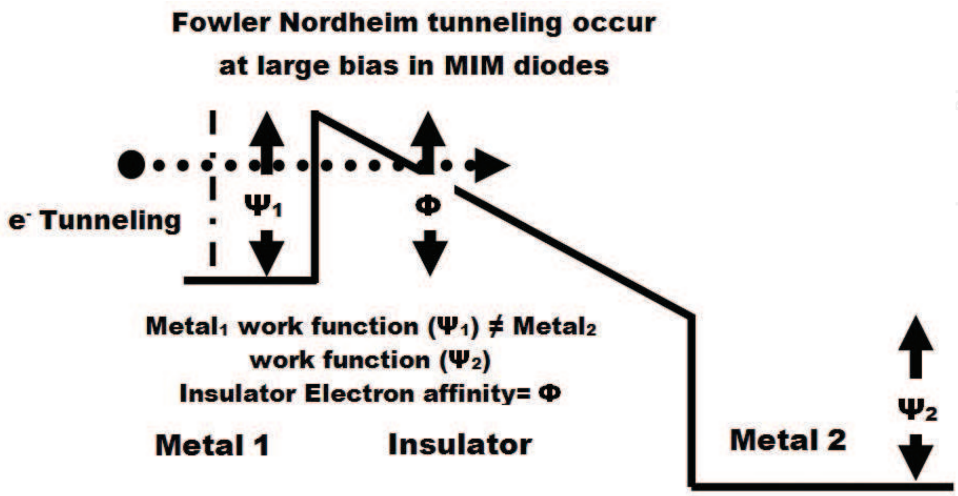

Figure 6. A typical schematic of MIM band diagram with FN tunneling.

the fabrication of terahertz MIM diode, the atto-farad capacitance (10^{-18}) is required, which further needs the device areas less than 100 nm × 100 nm for typical material systems which require e-beam lithography. However, this challenge of fabricating such nanoscale geometry has been overcome to a large extent by using modern lithographic techniques. Miniature-size diodes can be fabricated with the modern ultra-fine deposition techniques, such as e-beam lithography, reactive sputtering, etc., with small size, higher cutoff frequency, and thin insulating layer. **Table 2** lists these features of the MIM devices fabricated using different techniques.**Table 2** lists these features of the MIM devices fabricated using different techniques.

Trade-off between asymmetry and diode junction resistance can be overcome using multi-layer structure [34]. In comparison to the MIM diode, the tunneling current can be easily engineered in such multi-insulator MIM diodes by simply altering the type and number of insulators. This changes the number of barrier heights present at each interface and consequently the *I-V* characteristics. Reasonably good results for asymmetry and nonlinearity have been obtained by means of such diodes [35]. Among multi-insulator MIMs, the double insulator (MIIM) is a common preference [36].

4.1. Tunneling probability

Probability of electrons penetrating the insulator layer is called as tunneling probability. It is also called as transport probability, it is the ratio of the number of electrons incident on the interface with the electrons that reflected back. In order to tunneling take place, the two metals having insulators in between must have different work functions. When a bias voltage is applied between the metal electrodes of MIM diode, the potential barrier is reduced and charge carriers start tunneling between the two electrodes through the thin-film. Tunneling occurs in either direction, but by proper choice of metal electrodes with different work functions, the magnitude of the tunneling current will become larger in one direction than in the other direction. The tunneling current is calculated using Simmon's method [37]. This method assumes low-temperature operation hence neglecting thermal currents and incorporating tunneling as the main electron transport mechanism.

MIM combination	Active area	Insulator thickness	Patterning technique	Cut-off freq.	Ref.
Ni-NiO-Ni	110 × 110 nm^2	3.5 nm	E-beam lithography	30 THz	[31]
Ni-NiO-Cr	1.6 μm^2	3 nm	E-beam lithography	94 GHZ	[32]
Ni-NiO-Ag	3.1×10^{-4} μm^2	6 nm	E-beam lithography	343 THz	[33]
Cu-CuO-Cu	2 × 2 μm^2	2 nm	E-beam/reactive sputtering	–	[34]

Table 2. Comparison of MIM diodes fabricated using latest deposition methods.

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Different algorithms such as TMM (transmission matrix method), WKB (Wentzel, Kramers, and Brillouin) approximation, and NEGF (nonequilibrium green function method) have been developed for calculating the tunneling probability. Simmon provides an approximation of a finite probability of electron penetration in the course of the insulator using WKB method. But this method overvalued the transport current. NEGF formulism is the method used to calculate the tunneling transmission probability. Using NEGF approximation, the total number of electrons emitted from left electrode and right electrode can be taken into consideration by defining two quantities, namely, left electrode and right electrode coupling functions, **Figure 7** shows the application of NEGF formulism to MIM diode [38]. TMM is also a powerful fast method for the analysis of transport properties of nonhomogeneous systems [32]. These algorithms have been compared for the calculation of transport probability in [39].

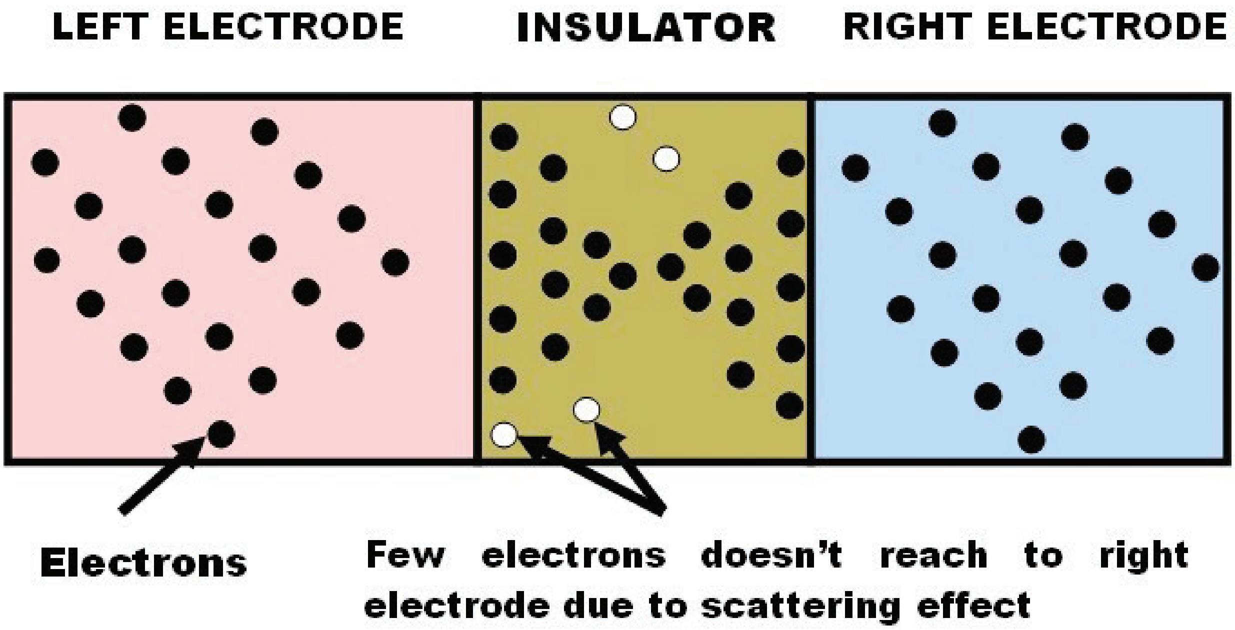

Figure 7. A typical schematic diagram showing the application of NEGF to MIM diode.

5. Modeling, fabrication and characterization of MIM diodes

An efficient modeling of MIM diode enables an investigator to predict the optimum material combination and device geometry for desired current-voltage characteristics. The accuracy of modeling depends on correct estimation of modeling parameters such as applied bias voltage, barrier thickness, dielectric constants of the insulator layers, and effective mass (assumed to be unity).

Various research groups are working to design an accurate model for rectenna system using different software such MATLAB, PSpice, Mathemaica, ADS, etc. [32, 34, 40]. We had not combined MIM diodes with antennas but modeled and fabricated MIM diodes for using two combinations (aluminum and chromium) of materials and assume the incoming energy to diode to be 100%.

5.1. Simulation

The diodes are simulated using model [35] and fabricated diode's *I-V* characteristics have been verified also. This simulator models the current density of MIM diode assuming a perfect insulator for a solely tunneling based analysis of current-voltage characteristics. We simulated the MIM diode for (Al-Al_2o_{3-} Cr) in MATLAB for current density and nonlinearity.

5.2. Fabrication

For the fabrication of MIM diode, the aluminum (work function of 4.28 eV) is used for the preparation of bottom electrode, and aluminum dioxide Al_2o_3 (having electron affinity of 1.25 eV) is used as a barrier layer after plasma oxidation of aluminum. For top electrode, chromium (work function of 4.5 eV) is used having sufficiently higher work function comparative to other materials with similar work function like titanium, niobium, and silver [41]. The basic steps involved in the fabrication of MIM diodes are explained below.

5.2.1. Substrate preparation

The substrate on which the MIM diode is fabricated is a microscopic glass slide, which is optically flat and smooth on both sides. The reason for using a glass substrate is that it is a transparent material, inexpensive, and readily available. Yet another reason is that, if silicon is used, it needs to be oxidized to form SiO_2 before the metals could be deposited to prevent the shorting of metals with the substrate. Since glass as a substrate needs to be cleaned before fabrication. Complete process for cleaning has been followed as explained in Ref. [34].

5.2.2. Metal deposition

The metal deposition for MIM diode is done by thermal evaporation. Two fundamental requirements for the metal to be deposited are the adhesion to the substrate and a smooth uniform surface. The fabricated MIM diode with the base metal made of aluminum and top metal made of chromium. The metal has been deposited using smart coat 3.0 by the thermal evaporation method. This method involves heating a material to the point of evaporation, usually at a pressure of around 10^{-6} mbar. The smart coat is cleaned properly by IPA or acetone. Using an automatic mode, the materials are loaded in the chamber and the deposition has been done. Thickness is accumulated at the program deposition rate. Basically, the potentiometer is controlling the current supply providing to the filament and accordingly controlling the rate of thickness Å/s, more the current more the rate of thickness. The rate of deposition can be monitored on the display panel. Mainly the current value is dependent on the material that are depositing, for example, for Al (aluminum) it will have 10—15 A current value and for Au (gold) it required > 70 A. Vibrations on the crystal holder produced due to external factors or due to internal vacuum pumps inside the smart coat 3.0 may vary the readings on thickness monitor. For the desired thickness (kÅ) continuous monitoring is required. **Figure 8** shows the smart coat 3.0 used for metal deposition.

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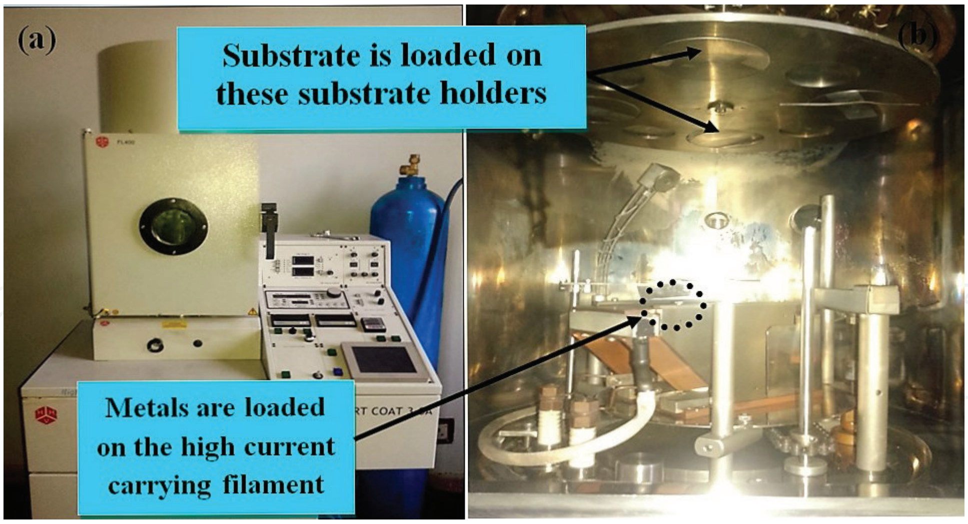

Figure 8. (a) Smart coat machine for thin-film deposition (b) Inside smart coat chamber.

5.2.3. Oxide formation

After loading the material in the smart coat chamber, the insulator layer is formed (using an aluminum mask) by the exposure of the oxygen (or argon) gas applied at a rate of 20–30 psi for a period of 10–12 minutes to form the plasma oxides on the base metal. Comparatively, thin layer with low impedance is formed in comparison with other deposition techniques. Similar procedure is used for the formation of top metal electrode as used for bottom electrode. After following the procedure completely, the final device is formed. **Figure 9** shows the fabricated diode and the mask used.

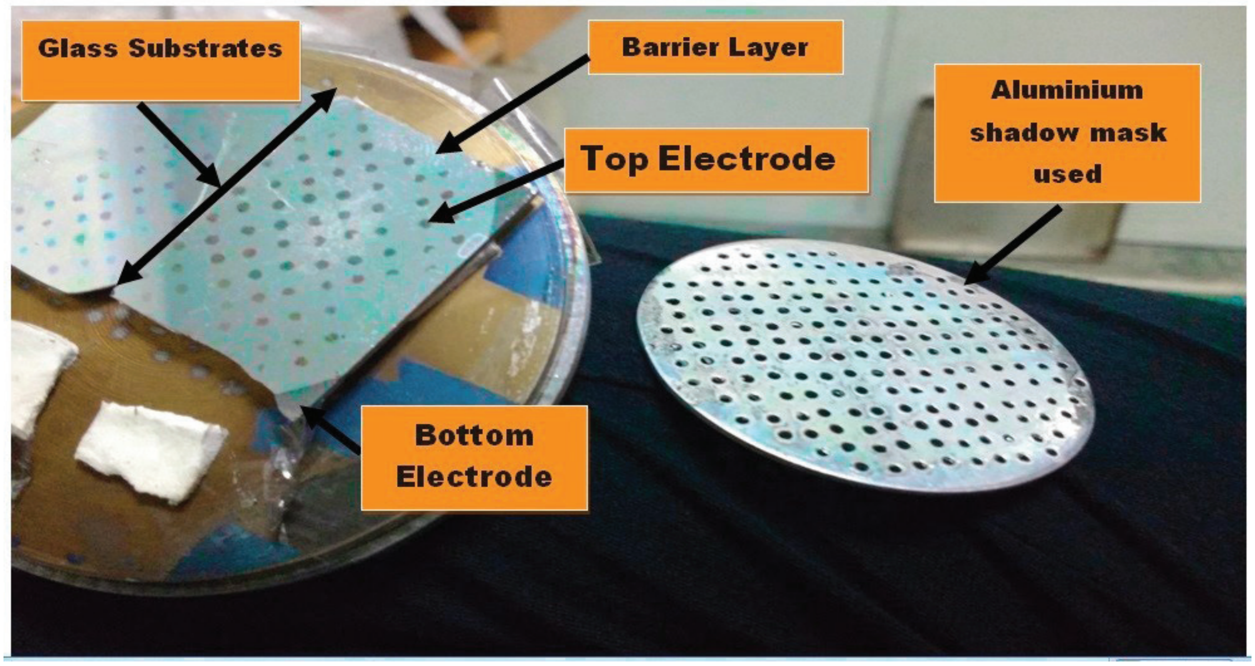

Figure 9. Fabricated MIM diode and mask used.

5.3. Electrical characterization

5.3.1. Experimental setup

The setup to measure the *I*(*V*) characteristics of the fabricated MIM tunnel diode is shown in **Figure 10**. It includes a probe station and a source meter. The source meter used is Model 2450 from Keithley instruments, which can vary the voltage from ±5 μV to ±220 V and can measure current from ±10 pA to ±1 A. The source measurement unit is connected to a probe station, and the measurements were taken so that any interference affecting the device could be avoided. This way a test bed was set up in which the device testing has been conducted. **Figure 10** shows the DC setup used for characterization of diode. The voltage sweep range set to be in low voltage in the values of few millivolts and the maximum sweep was selected from 1 to +1 V in order to get a proper *I-V* characteristics.

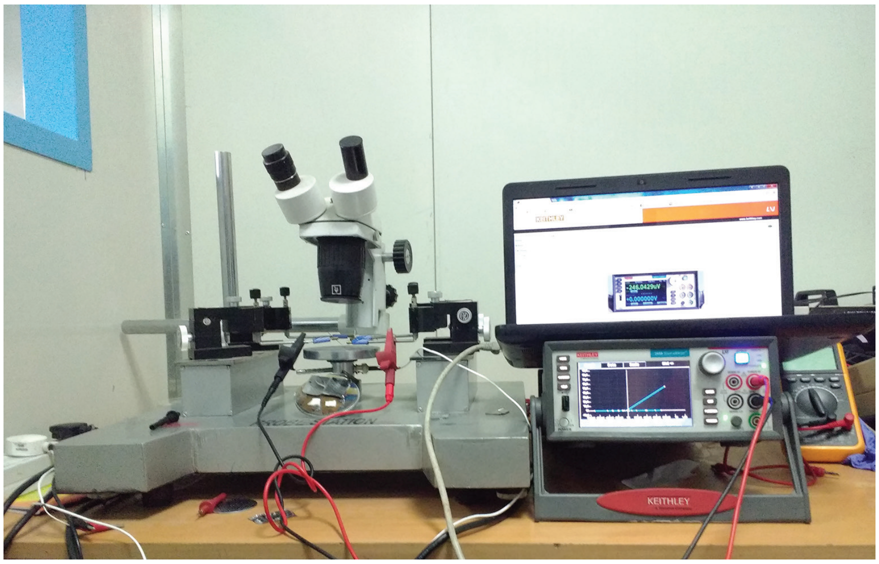

Figure 10. Setup for DC characterization.

Chromium is supplied with a negative bias and aluminum is supplied with a positive bias. The probes are lowered very slowly, so that the probe making contact with the top electrode is just in contact and the second probe on the bottom electrode is scraped a bit to ensure the proper contact with the aluminum.

5.3.2. DC characteristics

The DC characteristics of the fabricated diode MIM (Al-Al$_2$o$_3$-Cr) include the *I*(*V*) characteristics and the nonlinear characteristics. The responses of the diode are obtained with a biased voltage of ±1 V. The *I*(*V*) characteristics of the fabricated MIM diode which are compared with the simulated one and are in good agreement with is shown in **Figure 11**. Maximum current density observed is 2 × 10^{-4} A/cm^2 at 0.8 V which is less in comparison with the theoretical

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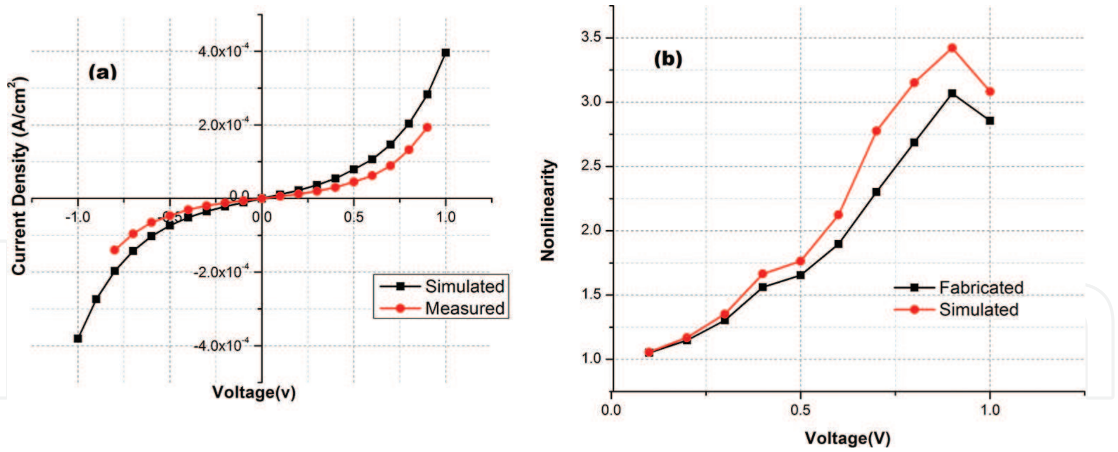

Figure 11. Measured DC characteristics of (Al-Al_2o_3- Cr) MIM diode, (a) current versus voltage relationship (b) nonlinearity versus voltage.

value due to some imperfections in fabrication processes. However, the nonlinearity is approximately 3.1, which is close to the modeled value.

6. Conclusion

Accurate detection and modeling of transport characteristics for any energy harvesting system are the main key for the calculation of *I-V* characteristics of MIM diode for THz energy harvesting applications. Due mainly to some poor characteristics of detector system the most of the harvesting systems suffered a lot. The MIM diode is one of the most suitable candidates for terahertz energy harvesting applications. Most of the innovations are the results of anterior modeling and fabrication of the device that result in better performance of the detectors. Since the future MIM detectors may incorporate thin insulating layers, which may result in structural irregularities; therefore, its meticulous modeling and optimum fabrication methods are essential before the actual implementation of the device. Potential approaches and factors responsible for designing most critical rectifying diodes operating at terahertz frequencies are discussed, and one of the material combinations for MIM diode has been modeled and characterized. It will augment the capability of naive researchers in identifying the latest THzDs to be used, their limitations and solutions to derive new paths for energy harvesting.

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