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Comparative analysis of efficient diode design for terahertz wireless power transmission system

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The wireless power transmission (WPT) technology is an extension of wireless communication. The physics of WPT and wireless communication are related, but WPT is distinct from wireless transmission for transferring information (such as radio and mobile phones etc.), where the percentage of the power that is received is only important if it becomes too low to successfully recover the signal. With WPT, the efficiency is a more critical parameter and this creates important differences in these technologies. This paper presents the wireless power transmission (WPT), from past work to most recent accomplishments including recent developments, potential approaches and factors responsible for designing most critical rectifying diodes operating at terahertz/petahertz frequencies.

Keywords: Wireless power transmission, Rectenna, Metal-insulator-metal diode, Geometric diode, Geometric asymmetry layout, Terahertz/Petahertz

1 Introduction

Wireless power transmission (WPT) is a phenomenon that takes place in a system whereby *dc* power is transmitted from a supply (or radiator) to an electrical load without using the wires. The WPT technology is an extension of wireless communication. Figure 1 shows the basic block diagram of WPT system. At the transmitting point, the *dc* electrical power is transformed into the microwave and transmitted through the antenna system to some distant end and the power is collected and converted back into *dc* power at the receiving end. In WPT, the efficiency is a more critical parameter and this creates important differences in this technology. As compared to wired transmission, the wireless transmission has low loss and unlimited power handling capability, except the *RF* to *dc* and *dc* to *RF* conversion efficiency limitations. The choice of the remote powering frequency is based on the constraints of the application such as power consumption, device size, read range or proximity, transmission medium and data rate. We are well aware of the convenience that wireless communication brings to us and wireless power will add to that convenience tremendously.

The importance of efficiency in power handling capability of a device in space is explained by Brown[1]. With the advent of wireless and integrated electronics, the demand for handy electronics and wireless sensors has established a rapid growth like structural sensors in buildings, medical implants, global positioning system (GPS), modern mobile phone, multimedia device, or home-entertainment system, wireless base stations, mobile communication (often military) devices, and IPTV set-top etc. By using wireless remote powering, the lifetime of the sensor system is no longer dependent on a battery. Contingent upon the power consumption requirement of the sensor system, wireless remote powering can be performed with either near-field inductive coupling or far-field electromagnetic coupling.

Modern computerized machinery with their very high processing capabilities is making it comparatively easy to design high quality, high frequency electronics, and even more so, to custom-make antennas and other associated devices that can solve specific design problems. In the past, such design problems were delegated in academic and industrial institutions. The development of computer aided design systems and latest multifunction software’s (HFSS, ADS, COMSOL, IE3D etc.) has now simplified the design processes, in which complex electronic circuits such as filters, antennas, rectifications element and complete energy harvesting system like rectenna (rectifier + antenna) can be designed with a high level of confidence and reliability. Computer aided simulation provides an excellent solution to real problems at very low cost in

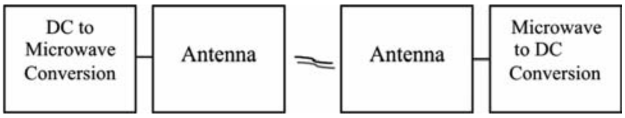


Fig. 1 — Block diagram of wireless power transmission

a small period of time. The conventional photovoltaic (PV) technology[2,3] harvests energy only from the visible range of the spectrum using solar cells whereas the other major energy component in the IR range remains completely untapped limiting overall efficiency of solar photovoltaic system less than 30%. Whereas, efficient collection by the antenna, perfect matching between the diode and the antenna and efficient rectification nominate rectenna to have a theoretical conversion efficiency[4,5] of 100%. Rectenna has already been used in the microwave regime with conversion efficiency up to 90%. Therefore, detailed understanding of alternative energy harvesting techniques such as WPT using rectenna need serious consideration amongst the new generation of researchers to address pressing energy needs of the society. The secrets of success of developing a WPT system at terahertz frequency are in the development and advances in the rectifying diodes which can operate at these frequencies.

1.1 Brief History of WPT

Heinrich Hertz[4] and Nikola Tesla[6] provided the basis for wireless power transmission. Tesla's work was based on much longer wavelengths and provides concept regarding energy conversion dates back. During the last part of world war-II with the development of high-power microwave tube, researchers focused on the Tesla's idea of transmitting electric power via radio waves. William Brown[7] demonstrated the application of microwave power transmission and also demonstrated a new device called the rectenna[8,9] for conversion of microwave to *dc* power with limited efficiency of his experiment. The laser wireless power transmission provides directional illumination. However, the line of sight requirement between the source and receiver is less attractive, economical aspects limited to its performance and provides less efficiency[10].

Using a series of rectenna, the first solely microwave-powered helicopter flight was made on July 1, 1964 in Raytheon's Spencer laboratory. In 1968, the idea of Solar Power Satellites[4] (SPS) has been suggested. Under the SPS concept[11] shown in Fig. 2, a large rectenna consisting of dipole antennas

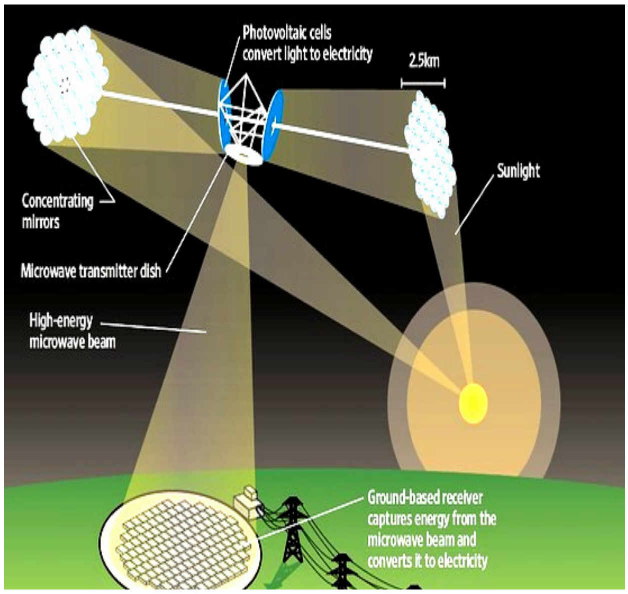


Fig. 2 — Complete diagram of the SPS concept[11]

was built on earth to collect the solar energy relayed by satellites in space. The SPS satellites are put in high earth orbit at geosynchronous location. The SPS program required was discontinued due to the large expenses involved. Involvement of semiconductor devices was at their peak during 1980s to replace the microwave tubes for WPT applications.

At smaller scale the rectenna has been demonstrated for a conversion efficiency[12] of 52%. Rectenna has been explored with difficulty of skin effect resistance problem and physical size requirements at light frequencies by Sarehraz *et al*[13]. Their main focus was to collect solar energy and design the rectenna system which works as a core part for WPT applications. Using dielectric antennas the first issue can be resolved[14] and the second shortcoming can be overcome by using concentrators, there is a more basic problem at hand. Recently, Collado *et al*[15]. verified a low cost, hybrid energy harvesting circuit combining a solar cell and a rectenna competent to harvest and transfer abundant ambient electromagnetic energy and solar energy having an antenna ranges from 800 MHz to 6 GHz (covers the wideband topology) for WPT system.

2 Role of Rectenna in WPT System

A rectenna is a special type of antenna connected to a diode that is used to convert microwave energy into direct current electricity[8,9].

The different parts of rectenna sub-systems shown in Fig. 3, are receiving antenna to collect microwave power, a proper matching network which is needed to ensure a good impedance matching between the antenna and the rectifying circuit for maximum power transfer and rectifications element for microwave to *dc* conversion followed by filter element to extract the *dc* component and reflect back other frequencies. The rectenna is one of the key elements in WPT system. At the receiving end, rectenna works as a core part of a wireless power transmission system and efficiently convert the incoming electromagnetic energy into *dc* energy. The origin of incoming energy can be WLAN (2.4, 5.8 GHz), WiMax, RFID (microwave band: 2.45, 5.8, 24.12 GHz) with various frequency ranges.

The schematic of first rectenna conceived by the Raytheon Company is shown in Fig. 4. The rectenna consisted of filter system designed using 4,480 diodes had a maximum power output[1] of 270 W. Because of the enhance utilization in mobile application rectenna circuits are the subject of further interest. The essence of a rectenna is the rectification performed by the diode. Therefore, the success of the implementation of future wireless power transmission system will depend upon the selection/ availability of suitable diodes for filter application. Here, it is important to know the purpose and performance of the diode, in order to achieve maximum operational efficiency of the rectenna. The future wireless power transmission system requires efficient diodes having a higher frequency of operation along with sufficiently large power handling capacity. In this series, Schottky diodes, MIM diodes and junction less diodes are mostly investigated diodes for WPT applications.

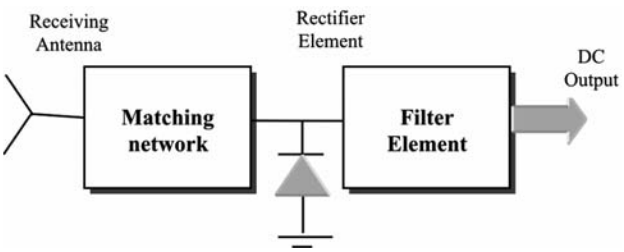


Fig. 3 — Schematic diagram of basic rectenna system

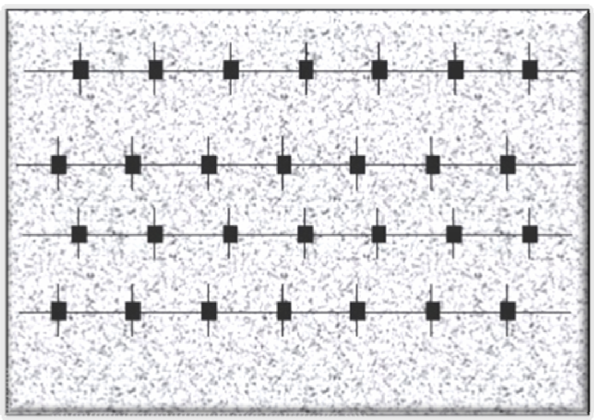


Fig. 4 — Schematic of the first rectenna had a power output of 7 W and 40 per cent efficiency Brown[1]

3 Efficient Diode Designing

3.1 Schottky Diode

Schottky diodes are semiconductor diodes based on a metal-semiconductor interface system. These are mainly utilized for microwave applications such as radio-frequency detection. The *n*-doped GaAs semiconductor is the main contender for THz applications used in the metal-semiconductor system. But due to heat generated at the diode junction during normal diode operation, uplifting in the local junction temperature has occurred strongly which affects the behaviour of the Schottky barrier itself and raises the additional requirement of cooling mechanism. An increase in operating frequency and/or power degrades the diode performance. Schottky diode's series resistance and current saturation effect are high frequency dependent phenomenon and essential series resistance becomes a complex function of device geometry, material conductivity, scattering frequency etc[16,17]. The effect of diode series resistance on optimum diode design has been reported[18].

The diode conversion efficiency (n_d) is key in determining the system's performance[18,19] and given by:

$$n_{\mathrm{d}} = \frac{\text{DC Output power}}{\text{RF Power incident on diode}} \qquad \text{… (1)}$$

$$\text{Let } n_d = \frac{1}{x+y} \qquad \text{… (2)}$$

where the low frequency term is given by:

$$X = 1 + \frac{R_L}{\pi R_S}\left(1+\frac{V_{bi}}{V_D}\right)^2 \left[\theta_{ON}\left(1+\frac{1}{2\cos^2\theta_{ON}}\right) - \frac{3}{2}\tan\theta_{ON}\right] + \frac{R_L}{\pi R_S}\left(1+\frac{V_{bi}}{V_D}\right)\frac{V_{bi}}{V_D}\left(\tan\theta_{ON} - \theta_{ON}\right) \qquad \text{… (3)}$$

and high frequency term is given by:

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

where C_j is the diode junction capacitance given by:

$$c_j = c_{j0}[V_{bi}/(V_{bi}+V_D)]^{1/2} \quad \text{... (5)}$$

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

where R_L is the *dc* load resistance and R_S is the diode's series resistance, V_{bi} is the diode's built-in voltage in the forward bias region, VD is the self-bias voltage due to rectification across the terminals of the diode, θ_{ON} is forward-bias turn-on angle[20], ω is the is the angular frequency. The equivalent circuit of Schottky diode is shown in Fig. 5. For higher frequency operation, the efficient diode can be based on its diode parameters R_S, V_{bi} and c_j.

The diode equivalent circuit consists of a series resistance (R_S), junction resistance (R_S) and junction capacitance (C_j). A load resistor (R_L) is connected in parallel, C_p is the capacitance associated with the device contact pads or package, L_p is the inductance associated with the device wiring and/or package.

In general, the junction capacitance of a diode is given as:

$$C_j = (Area \times \kappa\varepsilon_0)/W_{Depl} \quad \text{... (7)}$$

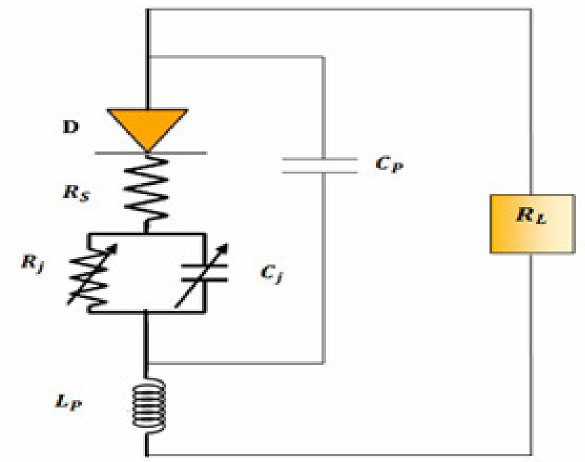


Fig. 5 — Schottky diode equivalent circuit

where Area is the junction area, ε_0 is the permittivity of empty space (8.85×10^{-14} F /cm^2), κ the dielectric constant, W_{Depl} is the depletion width.

The familiar method to calculate the diode impedance (Z_d) can be found as follows:

$$1/R_d + j\omega C_j;\ Zd1 = 1/Yd1 \quad \text{...(8)}$$

where $\omega = 2\pi f$, $f =$ frequency

$$Zd2 = Zd1 + Rs;\ Yd2 = 1/Zd2 \quad \text{... (9)}$$

$$Yd3 = Yd2 + j\omega Cp;\ Zd3 = 1/Yd3 \quad \text{... (10)}$$

So the diode impedance is given as:

$$Z_{diode} = Zd3 + j\omega Lp \quad \text{... (11)}$$

where R_d and Y_d are diode's resistance and admittance,respectively. Considering the reactive part is zero,the diode resistance (R_d) and impedance (Z_{diode}) is given[19] by :

$$R_D = \pi R_S \Big/ \left[\cos\theta_{ON}\left(\frac{\theta_{ON}}{\cos\theta_{ON}} - \sin\theta_{ON}\right)\right] \quad \text{...(12)}$$

$$Z_{Diode} = \pi R_S \Big/ \left[\cos\theta_{ON}\left(\frac{\theta_{ON}}{\cos\theta_{ON}} - \sin\theta_{ON}\right) + j\omega R_S c_j\left(\frac{\pi-\theta_{ON}}{\cos\theta_{ON}} + \sin\theta_{ON}\right)\right] \quad \text{... (13)}$$

For higher frequency operation, the efficiency of the system (rectenna) can be maximized by using an efficient diode and with proper matching of the diode input impedance to antenna's input impedance.

The impedance matching[21] and efficiency optimization not only depends upon the efficient parameters for the device but also on the device computer modeling software used. Fast and accurate computational electromagnetic are now becoming possible today due to many of the software's used like 3-D full-wave EM simulations[16], 3D-electromagnetic field solver[17], distributed-transmission[18], IE3D simulation[19], LIBRA developed by EEsof Inc[20]., microwave studio simulation [21]. Different types of antenna have been used at THz frequencies for rectenna system according to their load and direction has been utilized in order to analyze the *RF-dc* conversion efficiency[22].

Diode parasitics are varied due to the effect of variation in diode geometry which has a significant impact on the diode performance due to the electromagnetic coupling. Parasitic capacitance and inductance of a diode are geometry dependent parameters which not only limit the high frequency mode of operation but also limit the power coupled to the diode. Hence diode geometry plays a significant role. Rectenna's operating up to 35 GHz have been reported at number of places[19,23]. Some work at terahertz and far-infrared frequencies using Schottky diodes for rectenna as well as for other applications have also been reported[2,24,26]. The Schottky diode is used mainly because of its low turn on voltage and low junction capacitance characteristics, which enables it to work at required high frequencies [19].

3.2 Metal Insulator Metal Diode

The choice of a suitable diode for rectification especially in a rectenna system is based on its operating frequency. The transit time of the charges in semiconductor *p-n* junction diodes limits their frequency of operation in the gigahertz range. It is the *RC* time constant which limits the response of the diode. Substantial capacitance due to the parallel plate or sandwich geometry of conventional diodes results in capacitance which further results in substantial *RC* time constant. Reducing the physical size of diode beneficially reduces the capacitance, however, the resistance of the device increases responsiveness to decreasing the size.

Different types of high frequency diodes including metal-insulator-metal (MIM) have also been used in the past for the design of an efficient filter system[27,31]. MIM diode has an advantage of the exceptionally fast response and broad bandwidth over conventional semiconductor diode. MIM diodes operate due to the tunnelling effect that occurs between the metals through the thin layer of the insulator region. For simulation of electron tunneling MIMSIM is a simulation program developed[31] in C/C++ along with MATHEMATICA and MATLAB for simulation of various parameters of MIM.

For thinner barrier regions of the order of few nanometers,the effect of quantum tunnelling takes place for smaller barrier distance and height and the probability of electron tunnelling is better. MIM tunnel diodes are the most readily available at infrared and optical radiation. For asymmetric I-V characteristics, there must be comparatively large difference between the work function of the metals being used in the MIM diode. Based on the number of relative studies[29-31],excellent asymmetry and nonlinearity are achieved if the metal work function and the insulator electron affinity of the metals and insulator used to fabricate the MIM or MIIM (metal-insulator-insulator-metal) diode are close to each other. For example if the material $N_bN/N_{b2}O_5/N_b$ used to construct MIM diode has a metal work function and electron affinity given by 4.33/4.23/4.7 which are closed enough to have a symmetry and nonlinearity in *I*(V) characteristics. Figure 6 shows the energy band profile of MIM diode.

For a micron scale MIM (Cr/CrOx/Au) tunnel diode a typical characteristic I-V curve with significantly high nonlinearity and slight asymmetry is shown in Fig. 7.

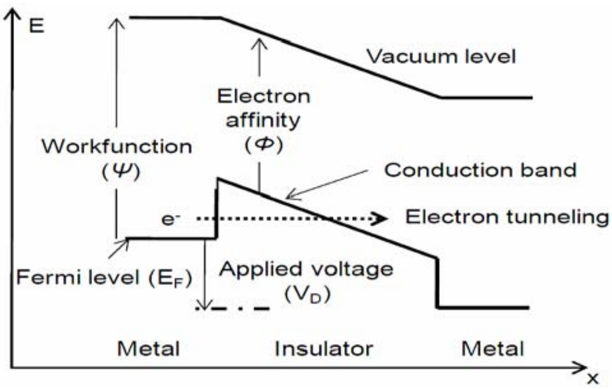


Fig. 6 — Energy-band profile of an MIM diode[28]

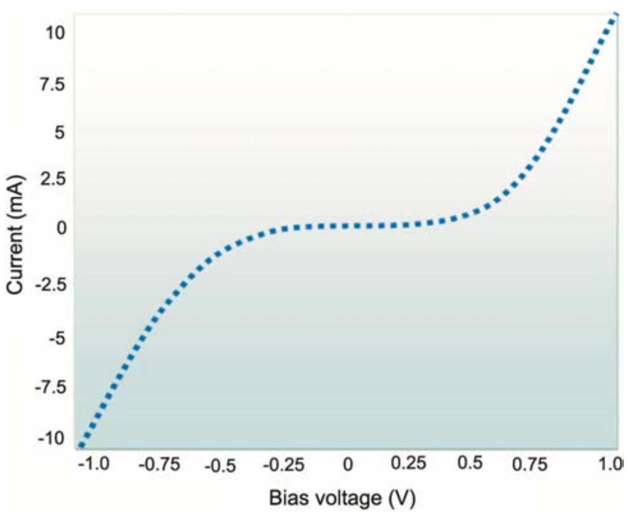
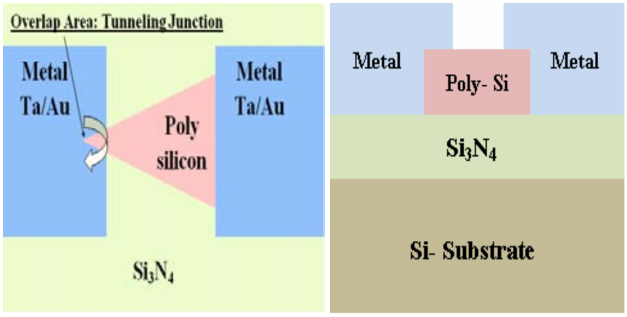


Fig. 7 — I-V characteristic of a micron scale MIM diode[2] (Cr/CrOx/Au)

The geometry of the Schottky diode plays an important role in order to enhance the diode's performance. Geometric asymmetry layout[32] (GAL) technique in improving diode performance has been discussed by Kwangsik *et al*. Figure 8 shows the insulator in between two metals having sharp tip. The effect of high electric fields has been produced with a sharpen triangle shape electrode. The phenomenon is the well known lightning rod effect and the structure is called an asymmetric tunnel diode (ATD) and the corresponding I (V) relationship and extracted sensitivity are shown in Fig. 9. This is true despite the relatively rounded shape of the needle-side points. Further tip sharpening should significantly improve the diode performance.

As compared to cross-bar diode the triangular shape sharpened electrode (the geometric field enhancement associated with the sharp tip) has strongly asymmetric tunneling behaviour. Based on geometry as well as material variation consequent improvements in sensitivity and curvature for diode come out.



Top View (a) Side View (b)

Fig. 8 — Asymmetric diode structure Brown[32]

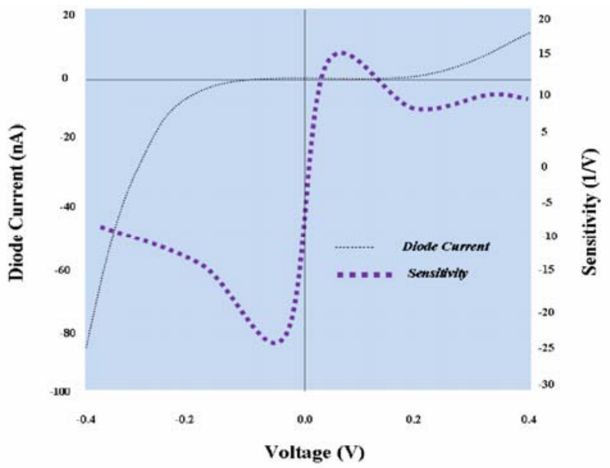
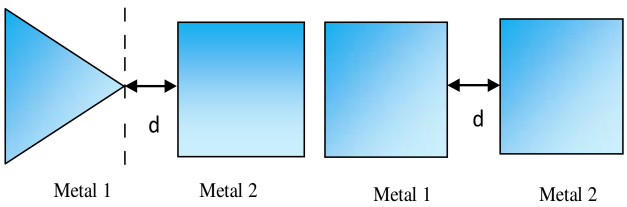


Fig. 9 — Measured *dc* *I*(V) relationship and extracted sensitivity for a polysilicon ATD. The reverse tunneling current level was much higher than the forward level due to the geometric field enhancement from the sharp tip. The filled square line is the calculated sensitivity Brown[32]

An improved geometric field enhancement (GFE) technique[23] of GAL has already been discussed. Figure 10 shows the layout of GFE M-I-M diode and conventional M-I-M diode. Geometrical variation leads to a high electric field and is created near the pointed electrode called the lightning rod effect.

Historically, MIM diode is used as a rectifying device instead of a Schottky diode for frequencies in the far infrared to visible range. The MIM diode is used in these applications because of its fast switching properties. The *RC* time constant is the limitation of MIM diodes because the resistance of the diode must be equivalent to antenna impedance as well as in order to achieve the IR and optical response. The capacitance of the diode must be of the order of ato-farad (10^{-18}) and consequently the diode area[28,31] of the order of few nm^2. MIM diodes fabricate with different metals result in better efficiency energy conversion than with similar metals. M-I-M diodes have shown their reliable frequency response up to 100 THz, extended beyond the far infrared range, whereas Schottky diodes have been limited to few THz.

For higher efficiency up to infrared and far infrared, a new type of diode, the geometric diode for use in rectenna-based applications in the visible and infrared range has been reported[31]. The geometric diode consists of a patterned thin-film that allows a preferential motion of charge carriers in a direction defined by its geometry (Moddel, 2009). The planar configuration of the diode gives it an extremely low capacitance, making it more suitable for high frequency operation than a metal-insulator-metal (MIM) diodes.



(a) (b)

Fig. 10 — (a) Geometrically enhanced layout M-I-M tunnel diode structure, (b) Conventional M-I-M tunnel diode structure Brown[23]

4 Geometric Diode

It is challenging with conventional diodes in order to convert the petahertz range or above frequencies of visible light to *dc* voltage and couple efficiently to antennas. A new device that may provide the solution is 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 gave the diode like behaviour. The diode acts as a funnel for flow of carriers moving from left to right, with restricted flow in the opposite direction as shown in Fig. 11. The rectification property of the geometric diode is based on the Drude model[33,34] which gives a prediction of general electronic conductivity of a metallic system and that can be applied to any material having bulk conductivity. Drude also predicts that electrons in metals are also good conductors of heat as they are good conductors of electricity for them.

The size of the device is approximated by the carrier mean free path length (MFPL). For higher frequency rectification, the diode must have faster response time at the cost of having a shorter mean free path. The mean free path can be reduced by reducing the size of the device, taken into account the collision time scales inversely proportional to mean free path. Material used for geometric diode must have competent MFPL. For graphene used as a material for geometric diode, the MFPL of charge carriers can be an order of magnitude larger than those in metals at room temperature[33]. For silver and gold, the mean free path is approximately 10 to 60 nm at room temperature. For diode any material with high bulk conductivity like metals, plasmas, conductive polymer materials and conductive semiconductors can be used. Geometric diode is capable to operate at higher frequencies[33] up to 1000 THz. The value of capacitance for the geometric diode[35] has very low of the order of 1 aF because of its structure and the material used. This capacitance is the parallel combination of capacitance between the arrow-shaped material on one side of the narrow part and the rectangle on the other side and the quantum capacitance of the narrow part. This gives the device a low *RC* time constant of ~1.6 femto-seconds, allowing infrared detection in the wavelength range 8-14 µm.

Figure12 shows the schematic diagram of geometric diode[36]. The arrow shaped conductor labeled as the neck is equivalent to or smaller than the electron mean-free-path. The geometry channels charge towards the right and block their flow towards the left. In order to produce a shift in the graphene charge concentration, a gate voltage (V_G) is applied on the back side of the silicon substrate to tune the I(V) characteristics.

Figure 13 shows the I(V) characteristics and responsivity of the diode. Using a high-impedance voltmeter, the drain-source voltage (V_{DS}) is measured between the inner electrodes and the current is measured through the outer electrodes for a range of applied voltages. The responsivity is a measure of the output *dc* current as a function of the input *ac* power. As a consequence of the ratio of the absolute value of current at a positive (+V) and a negative (-V) voltage, $A=|I(+V)/I(-V)|$ the asymmetry in the I(V) characteristics which is extremely significant for

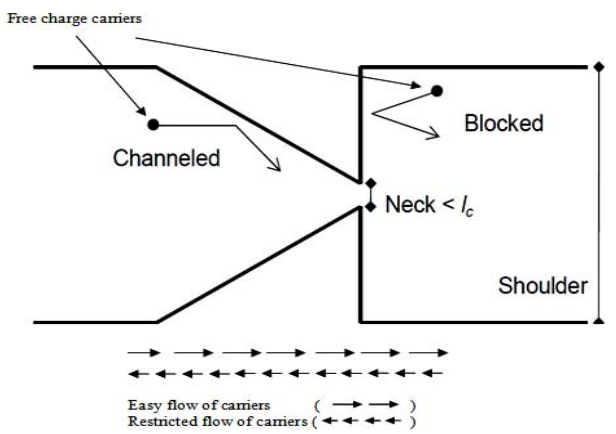


Fig. 11 — Top view of a geometric diode. The device is a thin film patterned such that the asymmetric constriction at the neck region is of the order of or smaller than the mean frees-path length (MFPL) of the charge carriers[35]

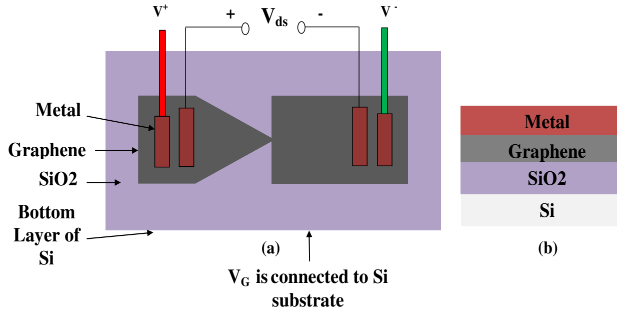


Fig. 12 — Schematic diagram of a geometric diode for measuring the diode I (V) characteristics[36]: (a) Top View (b) Side View[36]

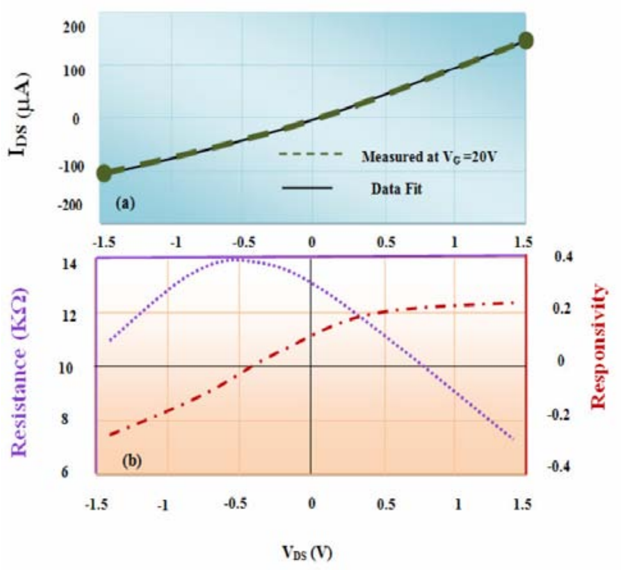


Fig. 13 — Geometric diode characteristics[35] (a) Measured current; (b) resistance and responsivity as a function of drain-source bias for gate voltage V_G = 20 V

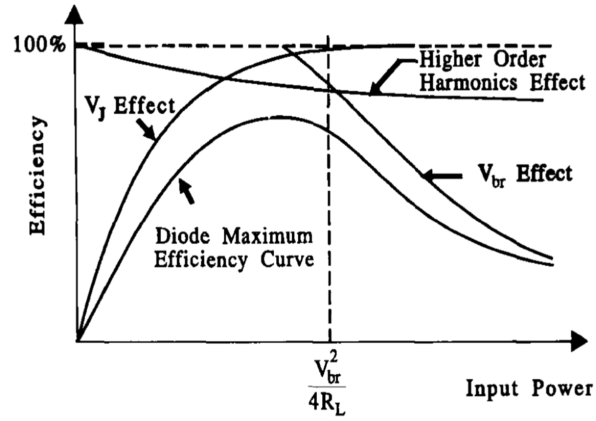


Fig. 14 — Relationship between microwave to *dc* power conversion efficiency and input power[20]

geometric diode has been reported[37]. The unevenness in the *I*(V) characteristics for the device is the measure of deviation of *A* from the unit. In order to simulate the geometric diode different computational simulation methods has been employed (Grover,2011) like a quantum simulation based on the non-equilibrium Green's function technique to model the geometric diode based rectifiers made from graphene[28] and MATLAB for various other parameter simulations.

The different diodes used for microwave to *dc* power conversion has been considered. The theoretical efficiency limit of such devices is too good. The plot which is very important for optimization of various parameters of these devices between microwave to *dc* power conversion efficiency and input power is shown in Fig. 14. The effect of diode forward junction voltage drop V_J, the breakdown voltage V_{br}, and filter higher order harmonics on efficiency with variation in input power is reproduced[19,20]. Due to the limitations of the forward voltage drop of the diode, the efficiency is small in the low power region and comparatively it increases afterwards and limits off with the generation of strong higher order harmonics. The breakdown voltage of the diode also acts as a limiting factor in efficiency.

The proper design parameter considerations like antenna array impedance matching, selection of appropriate high frequency diode operating in microwave/*RF* frequencies with low resistance and capacitance are required for a triumphant rectenna in WPT system. The optimum impedance matching requires the *RC* time constant of the rectenna to be smaller than the reciprocal of the operating frequency, ensuring sufficient large bandwidth and coupling between the antenna and the diode. The available MIM diodes limit the rectenna application up to microwave/ *RF* ranges. These diodes fail to meet requirements for harvesting solar radiation. The design and implementation of low *RC* MIM diodes are essentially required for high power conversion efficiency of solar cells.

Asymmetrically patterned thin films have been investigated with an aim to result low capacitance and low resistance diodes for applications in optical rectenna. The design and implementation of high frequency diodes, low breakdown voltage and of the double insulator tunnel diodes may also be investigated for optical rectenna application. The optimization of the MIM diode parameters like the selection of proper metal and its work function, tailoring of dielectric constant of insulating tunneling region its thickness and barrier heights may result quality diode with highly nonlinear I (V) response and lowest possible forward resistance. The nano-structured geometric diodes with low dielectric constant insulators/ tunneling structure with high conducting grapheme metal electrodes may be potential choice to achieve low barrier and low *RC* constant for future terahertz/petahertz wireless power transmission systems.

5 Conclusions

In the present paper, efforts have been carried out to explore the various important parameters used for wireless power transmissions with a brief discussion of various simulation software used for the device/structure analysis are also highlighted. The paper will be helpful in building a bridge between the fields of EM to *dc* power conversion. It will further enhance the capability of naïve researchers in identifying the tools to be used and their limitation to derive new paths. In our scientific society, there has been intense interest in WPT recently for a number of applications. Future suitable and largest application of the WPT via microwave is a Space Solar Power (SPS). The SPS is expected to realize around 2030. Before the realization of the SPS, we can consider the other application of the WPT which will probably be applied to microwave air vehicle (MAV). Brief advancements in wireless power transmission system from its early effect of recent accomplishments and the role of rectifier (diode) in the same, have been presented. The advancement of the WPT was, however, hampered by the short life span and unreliability of the rectifier element (diode) used in the rectification process. Among the various requirements of the rectifier circuit for conversion of solar power or microwave radiations of higher frequencies into *dc* voltage, the low value of capacitance and resistance is required. This ensures adequate bandwidth and efficient coupling between the antenna and the diode. Therefore, the foremost challenge for high efficiency solar or microwave rectifiers lies in selecting a diode with optimal parameters for efficient power transmission for choosing a class of operation. The planar geometric diodes are best in the class but much research and development is required to realize efficient terahertz/petahertz wireless power transmission systems.

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