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Nanoantenna with Geometric Diode for Energy Harvesting

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Abstract A graphene based geometrical diodes coupled with nanoantennas for infrared (IR) energy harvesting has been introduced. The geometrical diode is an electronic device in which the current flow through it is controlled by its geometry. The I–V characteristics of the graphene based geometrical diodes are calculated by the Monte Carlo simulation. Different shapes of graphene geometrical diodes, arrowhead, modified staircase, and quarter-elliptical geometries have been examined. The equivalent impedance, capacitance, and responsivity of each geometric diode have been calculated. The radiation characteristics of nanoantenna designed at 20.5 THz have been investigated. The IR harvesting using nanoantenna coupled with the graphene geometric diode has been calculated and interpreted. Full-wave simulation for the nanoantenna coupled to the geometric diode has been introduced. The DC voltage collected by the nanoantenna and rectified using the geometrical diode has been calculated.

Keywords Graphene · Rectenna · Geometric diodes · Nanoantenna

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1 Introduction

Clean and cheap energy can be a promising contribution to sustainable energy is controlled by the increasing size of the population and industrial development. Semiconductor-based solar cells are utilized to harvest energy only from the visible range of the spectrum with overall efficiency less than 30%. The other major energy component in the infrared range remains completely untapped [1]. The current research concentrates on improving the existing technology and finding new energy harvesting methods. A rectenna is a special type of antenna connected to a diode that is used to convert microwave energy into direct current (DC) electricity. The arrangement of the basic rectenna circuit is shown in Fig. 1. With an efficient collection by the antenna, perfect matching between the antenna and the diode and efficient rectification, rectennas achieve 100% conversion efficiency. The concept of rectennas for conversion of solar power to DC has been around for almost 40 years [2]. An infrared rectenna is a combination of a receiving nanoantenna and a teraherz (THz) rectifying diode [3]. Different types of antennas have been used at THz frequencies for the rectenna system [4–7]. Rectennas require efficient diodes having a higher frequency of operation along with sufficiently large power handling capacity. Schottky diodes and metal/insulator/metal (MIM) diodes are mostly investigated diodes for many applications [8]. MIM diodes have shown their reliable frequency response up to 100 THz. Whereas Schottky diodes have been limited to few THz. The RC time constant is the limitation of MIM diodes because the impedance of the diode must be equivalent to antenna impedance. The RC time constant must be smaller than the reciprocal of the operating frequency. For higher efficiency up to infrared and far infrared the geometric diode for use in rectenna-based applications in the visible and infrared range has been reported [9]. The geometric diode recently presented in [10, 11]. The geometric diode consists of a conducting thin-film, such as graphene, patterned in a geometry that leads to diode behavior. The geometric diode has recently attracted considerable attention. This diode is able to meet the dual requirements of a low resistance and a low capacitance required to operate at infrared frequencies. The planar configuration of the diode gives it an extremely low capacitance, making it more suitable for high frequency operation than a MIM diode [12].

In this paper, separate antenna and geometric diode that used in infrared rectenna can be created. This has the advantage that both the antenna and diode designs can be optimized separately. The effect of changing the shape of the geometric diode on its current–voltage characteristics is explained. Section II describes the different shapes of graphene geometric diodes and the Monte Carlo simulation to calculate their characteristics. In Section III, the construction of the nanoantenna at 20.5 THz is explained. Section IV demonstrates the results for the received voltage from the infrared radiation. Finally, Section V summarizes the conclusions of this study.

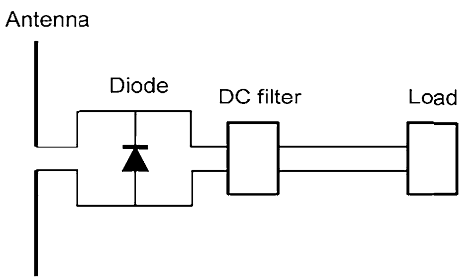


Fig. 1 The basic rectenna circuit arrangement

2 A Geometrical Diode for Infrared Rectenna, Structure and Method of Solution

A geometric diode is the geometry of the device which allows a motion of charge carriers in a direction defined by its geometry. The geometric diode made from graphene layer on a silicon oxide substrate, SiO_2 above a substrate Si layer. Graphene is a specific structural form of carbon. It is a 2-D material, composed of carbon atoms in a hexagonal lattice structure. The graphene material is used for its long charge mean-free-path-length (MFPL) and capability of handling extremely high current density $\sim 10^8$ A/cm^2 [13]. MFPL is distance that an electron travels until its initial momentum is destroyed. If graphene is placed on a SiO_2, the electron mobility in graphene can be as high as 200,000 cm^2 V^{-1} s^{-1} for temperatures below 200 K [13]. As long as the graphene is defect-free, at temperatures above 200 K, the electron mobility will be limited to 40,000 cm^2 V^{-1} s^{-1}. SiO_2 also functions as isolation between the diode and substrate Si. The current–voltage, I(V), characteristics of the diode can be calculated using Monte Carlo simulations of Drude charge carriers as well as quantum simulations based on the non-equilibrium Green's function method [12]. A flowchart of the Monte Carlo simulation steps is shown in Fig. 2. In the Monte Carlo simulation, the electrons are assumed to move in a straight line with a constant velocity, over a distance equal to the MFPL, until they collide. After each collision, the electrons are assumed to have an instantaneous randomly directed Fermi velocity v_F. An external electric field can be applied, which adds a constant velocity term v_{ext}, e.g. a drift velocity. The drift velocity is determined from $v_D = \mu E$. The magnitude of the electric field is determined as $E = V_{bias}/w_{diode}$ where w_{diode} is the width of the over which the bias is applied. This velocity is directed either in the forward or backward direction of the diode, and is added to the Fermi velocity to yield the electron's total velocity. More details about the Monte Carlo simulation can be found in [14]. The DC current flow through the rectenna is calculated by

$$I(V_{Dc} + v) = \sum_{n=0}^{\infty} \frac{1}{n!} \frac{d^n I_{DC}}{dV_{DC}^n} [v]^n \tag{1}$$

$$I(V_{Dc} + v) = I_{(DC)} + v \frac{dI_{DC}}{dV_{DC}} + \frac{1}{2} v^2 \frac{d^2 I_{DC}}{dV_{DC}^2} + \cdots \tag{2}$$

The geometrical diode can, in its simplest form, be modeled as a parallel resistance and capacitance. The resistance of the diode is effectively the sheet resistance of the thin-film material. For graphene, the resistance depends on the doping level, which is n-type, in this case due to the influence of SiO_2 substrate. The resistance of graphene depends on the majority charge carrier concentration, which can be adjusted by varying the doping chemically or by changing a gate voltage and is calculated from:

$$R_D = \frac{dV_{DC}}{dI_{DC}} \tag{3}$$

The capacitance of the geometric diode can be calculated as the parallel combination of two capacitance elements: the capacitance (C_D) between the arrow-shaped conductor on one side of the neck and the square area on the other side and the quantum capacitance of the neck region [15]:

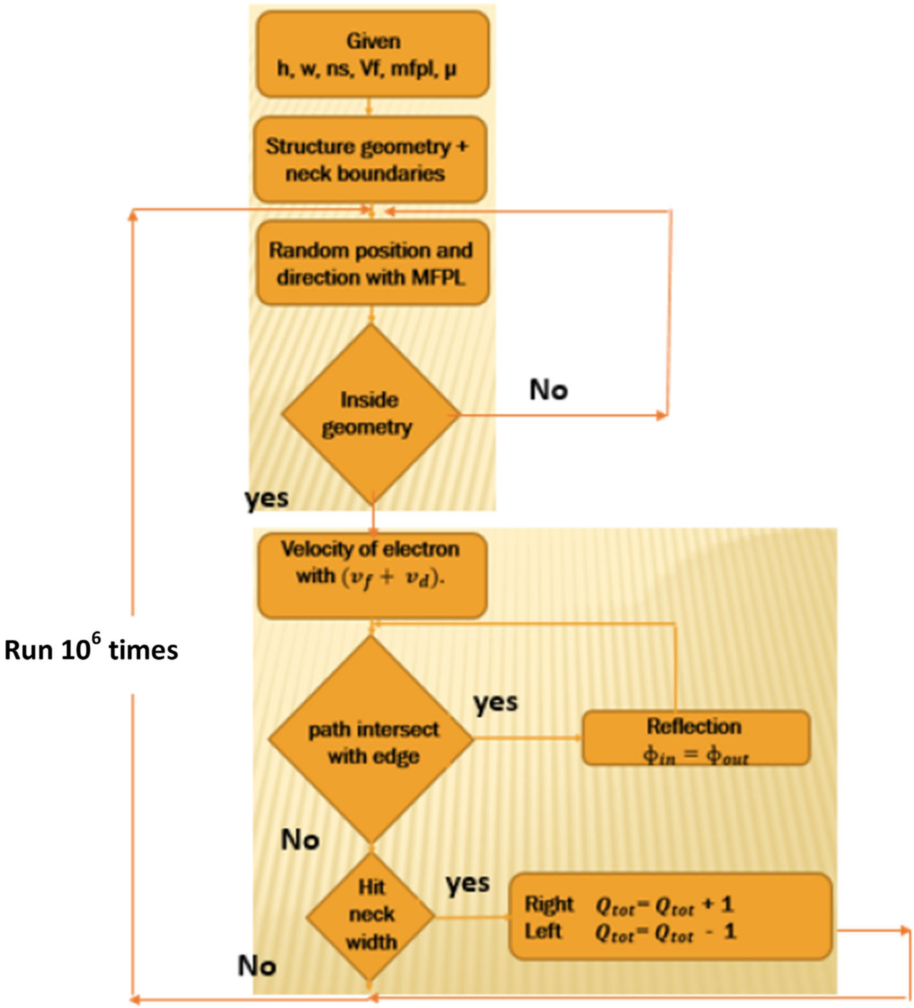


Fig. 2 The flow chart of the Monte Carlo simulation

$$C_D = 2 \int_0^{\frac{d_{shoulder} - d_{neck}}{2}} \frac{\varepsilon_0(\varepsilon_2 - \varepsilon_1)}{\frac{\left(\frac{d_{shoulder} - d_{neck}}{2} - w\right)S}{h\left(\frac{d_{shoulder} - d_{neck}}{2}\right)} + \frac{4}{\pi}\ln 2} dw \tag{4}$$

where ε_1 = dielectric constant of graphene, ε_2 = dielectric constant of SiO_2, and h = thickness of the SiO_2 substrate. Increasing the oxide thickness decreases the capacitance which in turn increases the cut-off frequency as the nonlinearity of the $I(V)$ curve. The time constant of the geometric diode is given by:

$$\tau = R_D C_D \tag{5}$$

The operating frequency of the geometric diode is calculated by:

$$f_c = \frac{1}{2\pi R_D C_D} \quad (6)$$

The geometric diode responsivity is calculated by:

$$S = \frac{1}{2}\frac{d^2 I_{DC}/dV_{DC}^2}{dI_{DC}/dV_{DC}} \quad (7)$$

3 Geometric Diode, Numerical Results

The schematic diagram of a graphene diode for rectenna applications in THz range is shown in Fig. 3a. The diode consists of pure graphene layer of thickness 10 nm printed on 90 nm thick silicon oxide substrate. The Si layer is 300 nm thick. The Si/SiO_2 substrates are 9.5 µm by 5 µm. The shape and dimensions of the graphene layer control the behavior of the diode and current flow through it. The dimensions of the most effective parts in the geometric diode performance are the shoulder length 1 µm, shoulder width 500 nm and neck width 50 nm as shown in Fig. 3b. A geometric diode D1 with an arrowhead (triangular) graphene layer for rectenna applications at 28.3 THz shown in Fig. 4a has been reported in [16]. The structure is modelled and simulated using the Mont Carlo simulation. The current–voltage characteristic of the arrowhead geometric diode is calculated and compared with its measured counterpart published in [17] as shown in Fig. 4b. Good agreement between results is obtained and the accuracy of the Mont Carlo simulation is acceptable. The arrowhead diode introduces peak forward current of 4 mA at 1 V. The current has an asymmetry ratio (maximum forward current to minimum reverse current, i.e. I^f_{max}/I^r_{min}) of 9.2. A seventh order polynomial fit has been used to simulate data.

A parametric study on the effect of varying the shape of the arrowhead graphene layer using staircase structure has been investigated. Geometric diodes with graphene film having one, two, four, and five staircase steps are shown in Fig. 5. These diodes are named D2, D3, D4, and D5, respectively. The current–voltage responses for geometric diodes D2 up to D5 are calculated using the Mont Carlo simulation and compared with the results of D1 as shown in Fig. 6a. By increasing the number of staircase steps, the forward current is increased while the reverse current remains constant. The current asymmetry ratio is increased by increasing the number of staircases. The forward current of diodes from D2 to D5 is less than that of D1. The equivalent resistances for staircase diodes versus the biasing

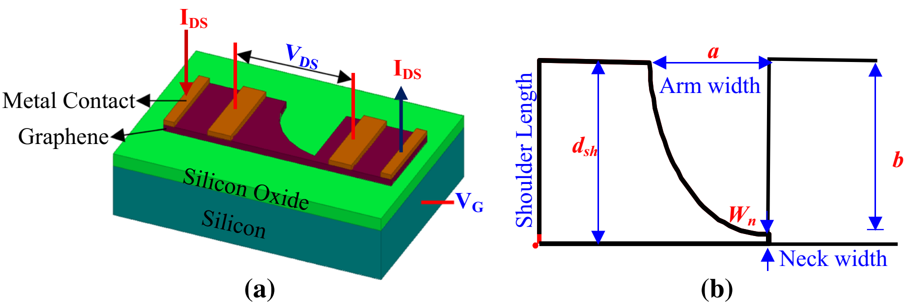


Fig. 3 The 3-D structure of graphene geometric diode with four-point probe configuration for I–V calculations. **a** 3-D view, **b** layout of graphene diode

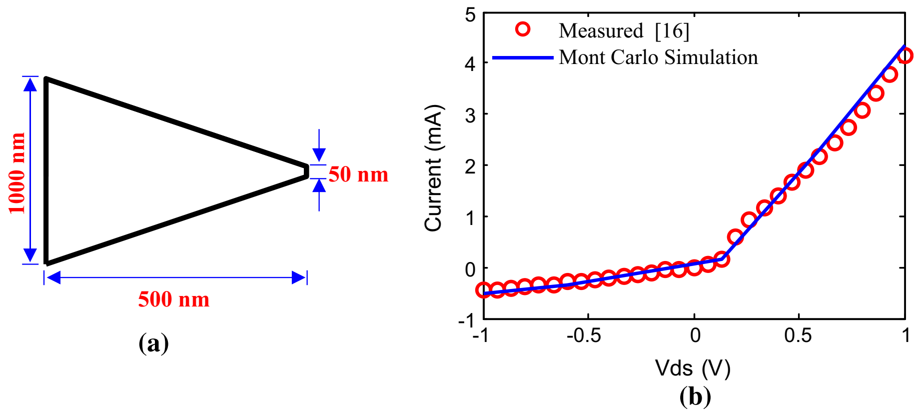


Fig. 4 The triangular geometric diode D_1 and its I–V response. **a** Geometrical diode (D_1), **b** I–V response

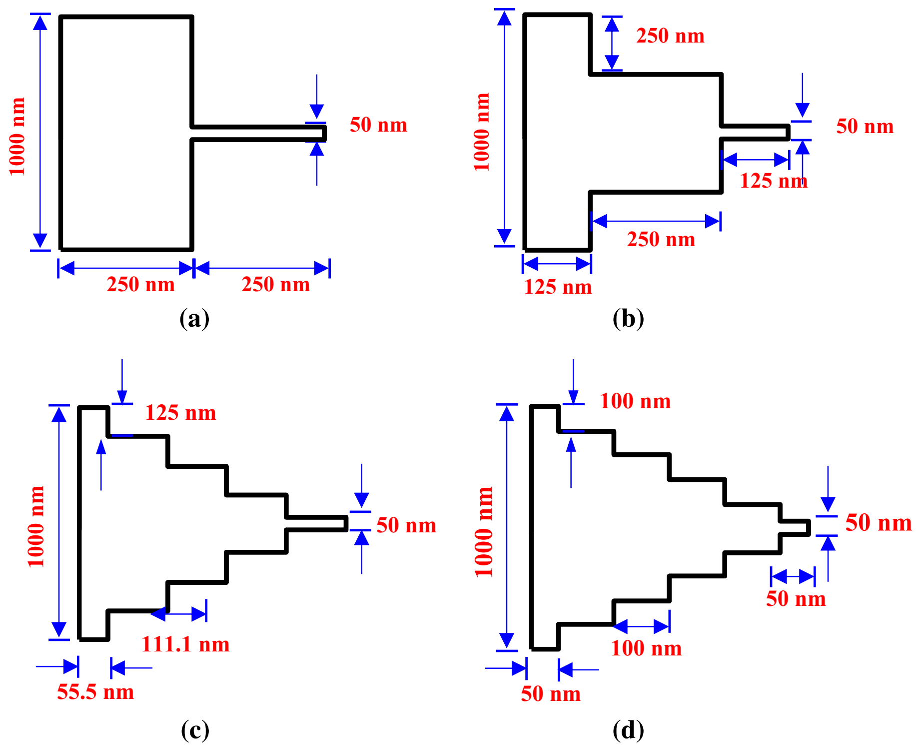


Fig. 5 The detailed dimensions of modified triangular geometric diodes. **a** Diode 2 (D_2), **b** Diode 3 (D_3), **c** Diode 4 (D4), **d** Diode 5 (D5)

voltages are shown in Fig. 6b. The resistance of the diode is increased by increasing the number of staircase steps in the reverse biased region until $V_{DS} = V_T$ but for $V_{DS} > V_T$ the resistance is decreased with increasing the staircase steps. Higher values of the input resistance give a flexibility in impedance matching between the diode and the connected

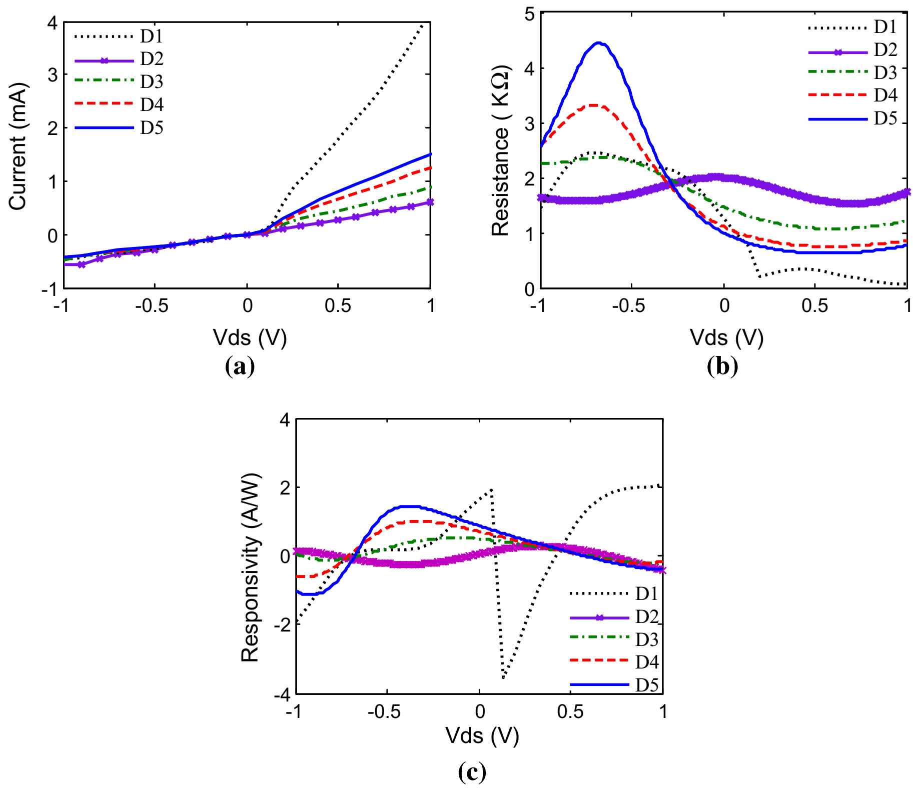


Fig. 6 The electrical characteristics of the triangular geometric diodes. **a** I–V responses, **b** equivalent resistance response, **c** responsivity response

antenna. The diode responsitivities verses the biasing voltage for different geometries are shown in Fig. 6c. Nearly the same behavior of responsitivity is achieved for all diodes configurations in the forward-biased region (except D1).

A novel geometric diode configuration using graphene layer is designed and investigated as shown in Fig. 7. The geometric diode consists of graphene layer with rectangular section with constant shoulder length, 1 μm, neck width of 50 nm, and width of 500 nm. The upper-right part of the graphene layer is a quarter ellipse with minor radius, *a*, and

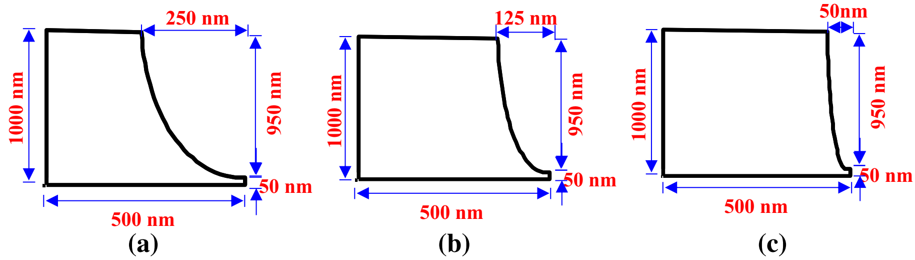


Fig. 7 The detailed dimensions of quarter elliptical shape geometric diodes. **a** Diode 6 (D6), **b** Diode 7 (D7), **c** Diode 8 (D8)

major radius, b, optimized for high forward current. The detailed dimensions of geometric diodes D6, D7, and D8 are presented in Fig. 8a. As the minor radius of the ellipse, *a*, is decreased the forward current is increased while the reverse current remains constant as shown in Fig. 8a. The resistance and responsivity are shown in Fig. 8b, c. Table 1 shows the values of the resistance, capacitance, time constant, responsivity, and cutoff frequency of each diode.

4 The Infrared Nano-dipole Antenna Coupled to Geometric Diode

The infrared nanoantenna of rhombic shaped side conductors made of gold and formed a printed dipole with rhombus side length $L_s = 1.79$ µm, gap .6 µm, and tip angle $\Psi = 20$ degrees is shown in Fig. 9a. The dipole is printed on a SiO_2 dielectric substrate with $\varepsilon_r = 3.9$ and dimensions of $9.5 \times 5 \times .09$ µm^3, and it is designed to receive IR radiation at a frequency 20.5 THz. When the antenna is excited into a resonance mode, it induces a cyclic plasma movement of free electrons on the nanoantenna conductor's surface. The electrons flow along the antenna, generating alternating current at the same frequency of the resonance. This design was originally proposed in [18]. By attaching the geometrical

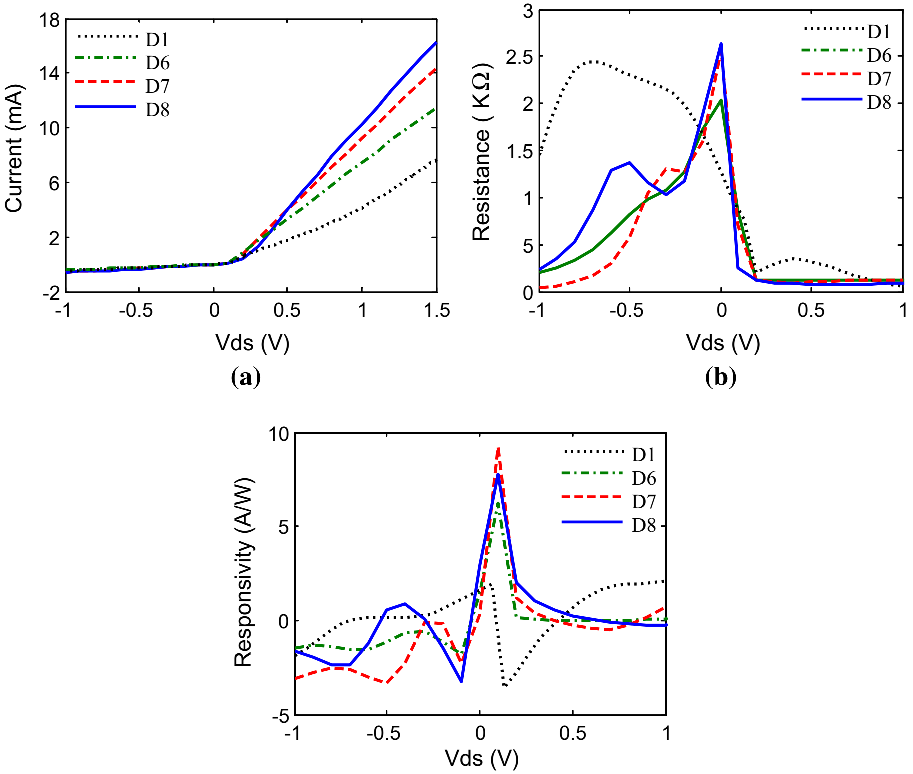


Fig. 8 The electrical characteristics of the quarter elliptical shape geometric diodes. **a** I–V responses, **b** equivalent resistance response, **c** responsivity response

Table 1 The values of the resistance, capacitance, time constant, responsivity, and cutoff frequency of different diodes

	Resistance (KΩ)	Capacitance (F)	Time constant f (s)	Cutoff frequency (THz)	Responsivity (A/W)
D1	1.266	4.2071×10^{-18}	5.326	29.8	1.646
D2	2	3.212×10^{-18}	6.424	24.77	.048
D3	1.471	3.6782×10^{-18}	5.41	29.4	.4853
D4	1.111	3.2991×10^{-18}	3.665	43.4	.7111
D5	1	3.3785×10^{-18}	3.378	47.1	.87
D6	2	4.0879×10^{-18}	8.1758	19.4	1.429
D7	2.564	6.1592×10^{-18}	15.792	10.07	.2821
D8	2.632	9×10^{-18}	23.688	6.7	2.895

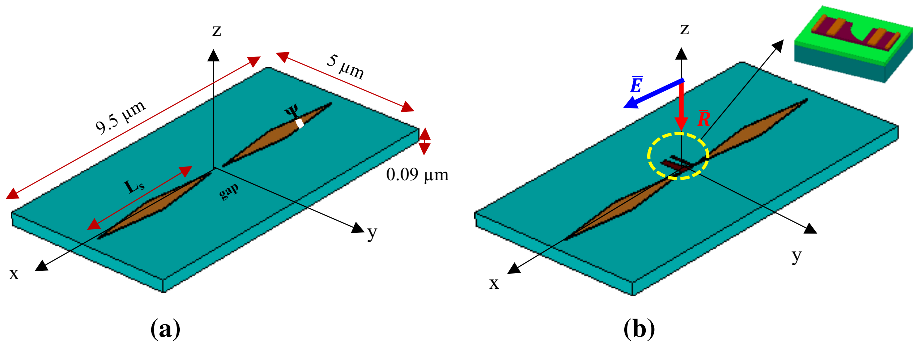
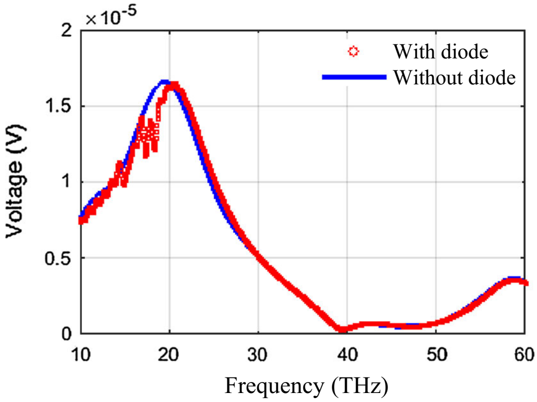


Fig. 9 The configuration of the IR nanoantenna coupled to geometric diode across the gap. **a** IR nanoantenna geometry, **b** IR nanoantenna with diode

diode into the gap between the dipole arms, a rectified DC voltage is obtained. The geometry of the IR nanoantenna coupled to the graphene geometrical diode is shown in Fig. 9b. The dimensions of the geometric diode are optimized to match the antenna input impedance for maximum received power. Consider a x-polarized plane wave incident on the structure and propagates along the negative z-direction. The voltage variation versus frequency for rhombic dipole IR nanoantenna on the dielectric substrate without and with the geometrical diode is shown in Fig. 10. In order to enhance the received voltage from the structure, the side conductors' tip angle is optimized to maximize the electric field across the gap. The geometric diode has negligible effect on the received voltage with maximum of 16.5 µV at 20.5 THz compared to 7 µV using the arrowhead geometric diode presented in [16]. The received voltage depends on the matching between the antenna and the diode, where maximum received voltage is corresponding to good matching condition. The received voltage can be improved by using either an antenna array or by employing lens to focus electromagnetic energy on the geometric diode.

Fig. 10 The received voltage versus frequency for the IR nanoantenna without and with coupling to geometric diode across the gap



5 Conclusion

This paper discusses a detailed study on the design of graphene based geometric diodes for IR energy harvesting. The geometrical diode controls the direction of electron flow through its geometry. The Mont Carlo simulation is used for I–V characteristic calculations. The equivalent capacitance and resistance of the graphene geometrical diode, depends on the influence of SiO_2 substrate. Increasing the oxide thickness decreases the capacitance which in turn increases the cut-off frequency as the nonlinearity of the I(V) curve. A parametric study on the effect of varying the shape of the arrowhead graphene layer using staircase structure has been investigated. By increasing the number of staircase steps, the forward current is increased while the reverse current remains constant. Higher values of the input resistance give a flexibility in impedance matching between the diode and the connected antenna. A novel geometric diode configuration using graphene layer is designed and investigated. As the minor radius of the ellipse, is decreased the forward current is increased while the reverse current remains constant. A comparison between the capacitance, time constant, responsitivity, and cutoff frequency of each diode has been introduced. The infrared nanoantenna of rhombic shaped side conductors coupled to graphene geometric diode is designed to receive IR radiation at a frequency 20.5 THz. For an x-polarized incident plane wave the geometric diode has negligible effect on the received voltage with maximum of 16.5 μV at 20.5 THz.

References

1. Moddel, G., & Grover, S. (2013). *Rectenna solar cells*. Berlin: Springer.
2. Strassner, B. H., & Chang, K. (2005). Rectifying antennas (rectennas). In *Encyclopedia of RF and microwave engineering*.
3. Zainud-Deen, S. H., Eltresy, N. A., Malhat, H. A., & Awadalla, K. H. (2016). Single/dual-polarized infrared rectenna for solar energy harvesting. *Advanced Electromagnetics, 5*(2), 1–9.
4. Galloa, M., Mescia, L., Losito, O., Bozzetti, M., & Prudenzano, F. (2012). Design of optical antenna for solar energy collection. *Energy, 39*(1), 27–32.
5. Moddel, G., Zhu, Z., Grover, S., & Joshi, S. (2012). Ultrahigh speed graphene diode with reversible polarity. *Solid State Communications, 152*(19), 1842–1845.

6. Wang, K., Haifeng, H., Shan, L., Guo, L., Zhang, T., Han, Y., et al. (2016). Design and analysis of a square spiral nano-rectenna for infrared energy harvest and conversion. *Optical Materials Express, 6,* 3977.
7. Kotter, D. K., Novack, S. D., Slafer, W. D., & Pinhero, P. J. (2010). Theory and manufacturing processes of solar nanoantenna electromagnetic collectors. *Journal of Solar Energy Engineering, 132*(1), 1–8.
8. Hashem, I. E. (2013). Infrared solar energy harvesting using nano-rectennes. M.Sc. Faculty of Engineering, Cairo University, Giza, Egypt.
9. Grover, S. (2011). Diodes for optical rectennas. Ph.D. diss., University of Colorado, USA.
10. Zhu, Z., Joshi, S., Grover, S., & Moddel, G. (2013). Graphene geometric diodes for terahertz rectennas. *Journal of Physics. D. Applied Physics, 46*(18), 1–6.
11. Zhu, Z., Joshi, S., Grover, S., & Moddel, G. (2014). High performance room temperature rectenna IR detectors using graphene geometric diodes. *IEEE Journal of Selected Topics in Quantum Electronics, 20*(6), 70–78.
12. Stellingwerff, S. A. (2015). Solar energy harvesting using graphene rectennas: A proof-of-concept study, MS thesis. University of Twente, Netherlands, 2015.
13. Zhu, Z. J. (2014). Graphene geometric diodes for optical rectennas. Ph.D. diss., University of Colorado, USA.
14. Rubinstein, R. Y., & Kroese, D. P. (2011). *Simulation and the Monte Carlo method* (2nd ed.). New York: Wiley.
15. Vendik, O. G., Zubko, S. P., & Nikol'skii, M. A. (1999). Modeling and calculation of the capacitance of a planar capacitor containing a ferroelectric thin film. *Technical Physics, 44*(4), 349–355.
16. Zhu, Z., Grover, S., Krueger, K., & Moddel, G. (2012). Optical rectenna solar cells using graphene geometric diodes. In *IEEE photovoltaic specialists conference (PVSC)* (pp. 002120–002122).
17. Joshi, S., Zhu, Z., Grover, S., Moddel, G. (2012). Infrared optical response of geometric diode rectenna solar cells. In *IEEE photovoltaic specialists conference (PVSC)* (pp. 002976–002978).
18. Eltresy, N. A., Zainud-Deen, S.H., Hend, A. M., & Awadalla, K. H. (2016). Nanoantennas Design and Applications. LAP LAMBRET Academic Publishing, AV Akademikerverlag GmbH & Co. KG, Deutschland/Germany, 2016.

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