Infrared Optical Response of Geometric Diode Rectenna Solar Cells

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***Abstract* — Optical rectennas, consisting of micron-size antennas coupled to high speed diodes, operate by collecting electromagnetic radiation and converting the high frequency AC field to DC power. We report the demonstration of optical rectennas operating at a wavelength of 10.6 µm. The diode is a graphene device that relies on geometric asymmetry to provide rectification. It is coupled to a metal bowtie antenna 5.1 µm in length. The planar configuration of the diode gives it an extremely low capacitance, making it more suitable for high frequency operation than metal-insulator-metal (MIM) diodes. The theoretical efficiency limit of such devices exceeds the Shockley-Queisser limit, making them suitable for broadband optical operation, and in specific, for thermophotovoltaics.**

***Index Terms* — ballistic transport, diodes, optical polarization, rectennas, rectifiers, solar energy.**

I. Introduction

The Shockley-Queisser conversion efficiency limit of single-bandgap semiconductor solar cells is approximately 34%. The theoretical efficiency of harvesting radiant energy from the Sun is 93% [1]. By treating light as an electromagnetic wave and using rectennas consisting of micro-antennas connected to diode rectifiers (Fig. 1a), this limit may be approached.

The concept of rectennas for conversion of solar power to DC has been around for almost 40 years [2]. In the microwave regime power conversion efficiencies of over 70% have been demonstrated [3]. Long wavelength infrared (IR) signals have been detected using thin film MIM diodes with integrated antennas [4]. MIM diodes, in their current configuration, are limited in operating frequency due to large RC response time [5] and poor impedance match to the receiving antenna [6], and cannot be used for power conversion in the visible.

In this paper, we describe the demonstration of the optical response of geometric diodes [7] coupled to metal bowtie antennas at a wavelength of 10.6 µm, paving way to graphene-based rectenna solar cells.

II. Geometric Diode Operation

The diode-like behavior of the geometric device arises from its asymmetric structure, which allows for the preferential flow of charge carriers in one direction. As shown in Fig. 1b, the diode acts as a funnel for flow of carriers moving from left to right, with restricted flow in the opposite direction. 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-free-path length (MFPL) of the charge carriers. This size constraint is required to achieve current rectification so that the charge carriers 'see' the spatial geometric asymmetry. Such a stringent constraint is realized in graphene [8], where the MFPL of charge carriers can be an order of magnitude larger than those in metals at room temperature.

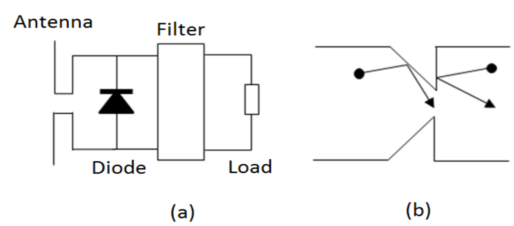

Fig. 1. Schematic of (a) rectenna solar cell and (b) geometric diode.

The geometric diode, as discussed in [9], is an inverse arrowhead-shaped graphene device, enjoying the advantage of having a very low capacitance of the order of 1 aF, due to its planar structure. This gives the device a low RC time constant of ~1.6 fs [9], allowing operation at high frequencies.

The current-voltage [I(V)] characteristics of the diode were found to be asymmetric using Monte Carlo simulations of Drude charge carriers [9] as well as quantum simulations based on the non-equilibrium Green's function method [10]. The interaction of high frequency radiation with such an asymmetric device involves photon-assisted tunneling and rectification [11].

III. Experimental

Geometric diodes were fabricated using e-beam lithography and low power oxygen plasma etching of single layer graphene exfoliated onto a 90 nm oxidized silicon wafer. Thermal evaporation and lift-off of Cr/Au metal contacts formed a four-point probe configuration [9]. Devices with a neck width of 70 nm and shoulder width of 400 nm were obtained. The I(V) characteristics were measured, as shown in Fig. 2a. Fig. 2b shows the asymmetric resistance and responsivity of the device. The MFPL was estimated to be ~50 nm using field-effect measurements on a graphene structure defined adjacent to the geometric diode [12]. Although this value is at the margin of the required neck width, the responsivity of these un-optimized devices is substantial.

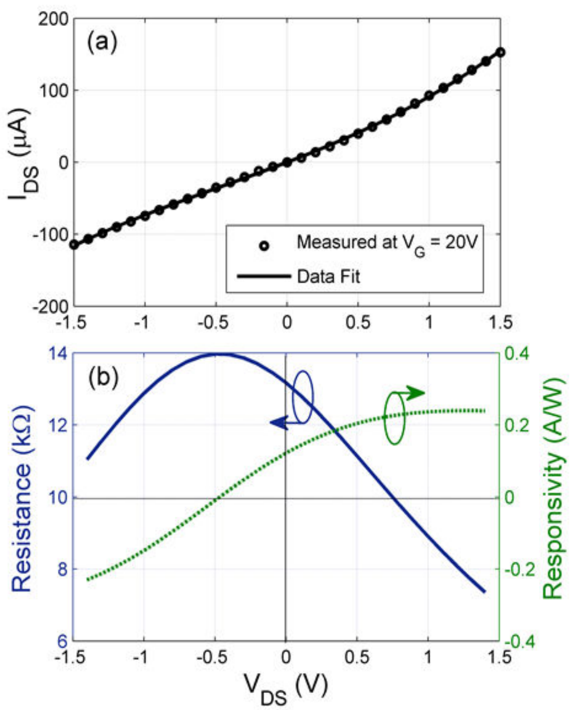

Fig. 2. (a) Measured current; (b) resistance and responsivity as a function of drain-source bias for gate voltage V_G = 20 V. The responsivity is a measure of the output DC current as a function of the input AC power.

For the optical measurements, the rectenna was composed of a 5.1 µm long bowtie antenna made up of two opposing 2.3 µm triangular sections, as shown in Fig. 3, and a 500 nm long geometric diode at the center. Rectification of the rectennas at infrared was measured using a 10.6 µm wavelength laser source. The measurement setup is shown in Fig. 4. A CO_2 laser (Synrad Model 48-1 SWJ) with intensity controlled by a pulse generator was used to illuminate the bowtie antenna of the rectenna. The laser beam was chopped at a frequency of 280 Hz and this value was fed to the lock-in amplifier (Stanford Research Systems SR830). A half-waveplate was used to rotate the polarization of the laser beam with respect to the antenna polarization to investigate the angular dependence of the response.

Positioning of the IR laser beam on the device was achieved using a He-Ne laser beam aligned with the CO_2 laser beam. The electrical measurement setup employed a mercury switch that allowed the probes to stay at ground potential when not in use, thereby preventing any damage to the geometric diode due to accumulated stray charge. Two-point measurements were performed on the antenna devices, with zero bias voltage, to measure the voltage and the current under illumination using the lock-in amplifier.

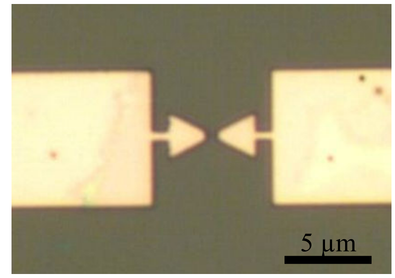

Fig. 3. Optical microscope image of the bowtie antenna coupled to a geometric diode. The scale bar shown is 5 µm. The diode (not shown) is placed at the center of the antenna gap.

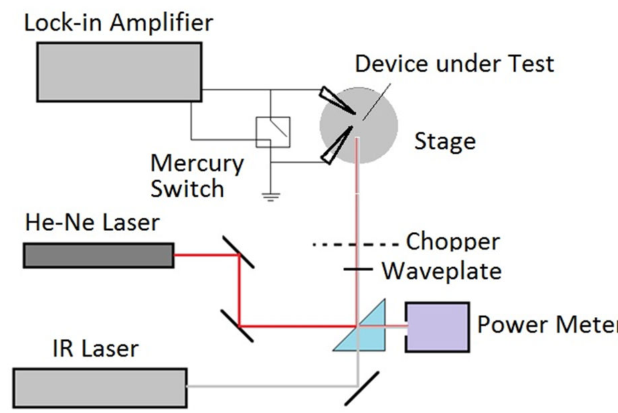

Fig. 4. Setup used to perform optical measurements.

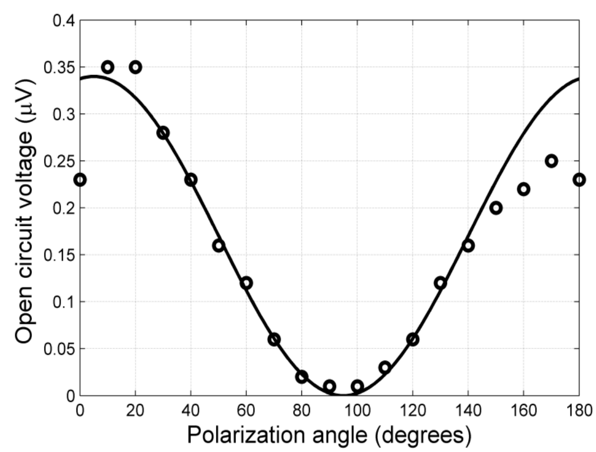

Fig. 5. (a) Polarization dependent voltage response for P_{inc}~5.6 mW/mm^2.

For the voltage response shown in Fig. 5a, the laser intensity at the device was estimated to be 5.6 mW/mm^2. The voltage response is a cosine-squared function of the polarization angle [13], which shows that it is due to absorption by the antenna. This demonstrates the rectifying behavior of the geometric diode at 28 THz. Fig. 5b shows an approximately linear increase in the open circuit voltage with input power when the antenna axis and the incident wave are aligned, for a different device.

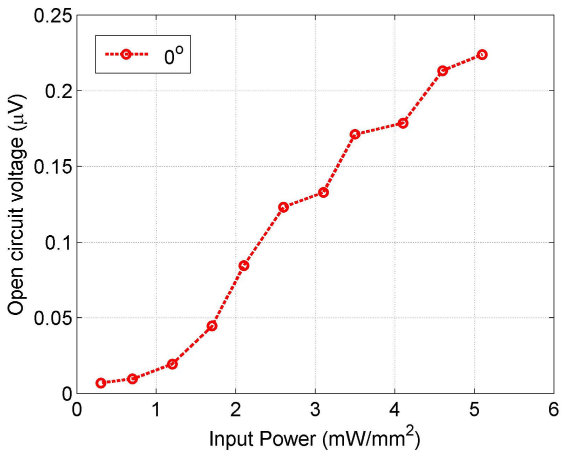

Fig. 5 (b). Open circuit voltage vs. input power for the metal antenna-coupled geometric diode

Geometric diode rectenna solar cells potentially have application in thermophotovoltaics (TPV). Conventional TPV, which incorporates semiconductor junction solar cells, is limited to near-visible operation. Since rectenna solar cells operate in the IR – with design constraints that are more easily met than for the visible because of the lower frequency of IR light – they are better suited for TPV. There is a lot of room for improving the efficiency of the geometric diode rectenna by using higher asymmetry diodes, and better antenna design for efficient capture of broadband IR.

IV. Summary

We have developed and demonstrated the operation of an antenna-coupled geometric diode with infrared light (10.6 μm). The diodes have a planar structure that improves RC response over parallel-plate devices, allowing for operation at IR wavelengths. Geometric diodes with asymmetric I(V) characteristics and having substantial zero bias responsivity, were coupled to bowtie antennas designed for operation at 10.6 μm wavelength. The rectenna device response is polarization-dependent and validates operation of the device at IR frequencies. Further improvement in device and antenna design is expected to provide an efficient device. The device has potential to be used as in flat-panel solar cells and for thermophotovoltaic energy conversion.

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