OPTICAL RECTENNA SOLAR CELLS USING GRAPHENE GEOMETRIC DIODES

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ABSTRACT

A solar cell using micro-antennas to convert radiation to alternating current and ultrahigh-speed diodes to rectify the AC can in principle provide extremely high conversion efficiencies. Currently investigated rectennas using metal/insulator/metal (MIM) diodes are limited in their RC response time and have poor impedance matching to the antenna. We have investigated a new rectifier, referred to as a geometric diode, which can overcome these limitations. The geometric diode consists of a conducting thin-film, such as graphene, patterned in a geometry that leads to diode behavior. We have experimentally demonstrated geometric diodes made from graphene and simulated their characteristics using the Drude model for charge transport. Here we compare the characteristics of rectennas using MIM diodes with those based on geometric diodes and show the improved performance of the latter.

INTRODUCTION

A photovoltaic (PV) rectifier consists of a broadband micro-antenna connected to an ultra-high-frequency diode, as shown in Fig. 1. Such devices, also known as rectennas, have been used for detection and energy harvesting of microwave radiation. Rectennas operating at optical frequencies form a solar cell that does not have the same fundamental limitations as a traditional semiconductor junction solar cell. Rectification of solar electromagnetic-radiation was first proposed in 1972 [1]. Although this concept has the potential to achieve a maximum power conversion efficiency of 93% [2], solar rectification has not been demonstrated as of yet.

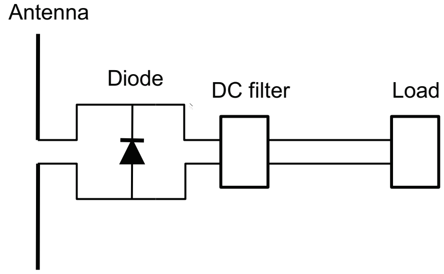

Figure 1 Schematic for a rectenna solar cell.

Optical rectennas impose two critical requirements on the diode. First, the intrinsic response of the diode has to be fast enough to operate at terahertz or petahertz frequencies. MIM diodes that are currently being investigated for use in optical rectennas have response times of femtoseconds [3]. Second, the RC time constant of the rectenna must be smaller than the reciprocal of the operating frequency. Due to their parallel-plate structure MIM diodes' resistance and capacitance cannot be varied independently. Decreasing the diode area to reduce the capacitance increases the resistance of the diode, worsening its impedance match to the antenna. This problem is fundamentally limiting and MIM rectennas can operate efficiently only at mid-infrared or larger wavelengths [4]. As we will show, a geometric diode can overcome these constraints because its planar structure provides a much lower resistance while keeping the capacitance low.

GEOMETRIC DIODE THEORY

The geometric diode allows motion of charge carriers preferentially in a direction that is defined by its geometry [5]. The device consists of a patterned thin-film having an asymmetric constriction that is on the length scale of the charge carrier (electron or hole) mean-free-path length (l_c) in the material. We use graphene as the thin film material because it has a longer l_c than metals, allowing devices to be made larger. The critical region of the device is the arrowhead-shaped constriction (neck) shown in Fig. 2. The width of the neck must be on the order of l_c to obtain current rectification.

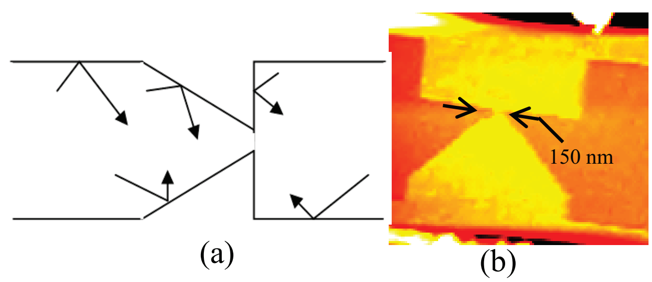

Figure 2 (a) Top-view schematic and (b) atomic force microscope (AFM) image of a fabricated graphene diode.

The operation of the geometric diode can be understood using the Drude model for the motion of free carriers in a conductor. Fig. 2(a) illustrates the motion of the charge carriers assuming specular reflections at the boundaries. When no voltage is applied, an equal number of carriers are scattered to the left and right, resulting in no net current. Under an applied voltage the carriers gain a small extra constant velocity in addition to the random thermal velocity. For large geometries (>> l_c), the shape of the device does not affect the preferred direction of carrier movement. In a geometric diode, where the scale of the asymmetry is comparable to l_c, the motion of the carriers is influenced by the shape. In the region to the right of the neck charges moving leftwards are deflected in the opposite direction due to the vertical edge, while charges in the left region moving rightwards collide with the slanting edge, and funnel through to the right of the neck. Thus, the magnitude of current for an electric field driving charges to the right is higher than for the opposite direction, giving rise to the diode behavior. We are currently investigating the fundamental response time limitations of geometric diodes.

EXPERIMENTAL DEVICES

We have fabricated geometric diodes using graphene obtained by exfoliation [6], which adheres to an oxidized silicon wafer with 90-nm thick SiO_2. Four Cr/Au metal contacts were patterned onto the graphene using lift-off and thermal evaporation. Then a resist was patterned on the graphene using electron-beam lithography in the geometric shape. The exposed graphene was etched away using low-energy oxygen plasma. Finally, the resist was stripped off, leaving the structure shown in Fig. 3.

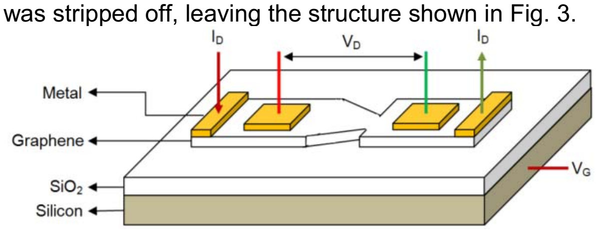

Figure 3 Structure of fabricated geometric diode with Cr/Au contact pads.

Current-voltage [I(V)] measurements were carried out using the four-point probe technique, to circumvent any contact resistance. For a given set of devices, after four-point probe measurements showed that the contact resistance was negligible, measurements using two-point probes closer to the arrowhead constriction were sometimes used to reduce series resistance. Fig. 4 (a) shows a measured I(V) curve. The direction of asymmetry in the I(V) is consistent with the expected direction for majority hole-carriers in the graphene. At zero bias, the geometric diode has a responsivity of 0.3 A/W. This is a factor of six better than the zero-bias responsivity of 0.05 A/W for a low resistance Ni-NiO-Ni MIM diode, estimated using published data for the zero-bias resistance and second derivative of current [7].

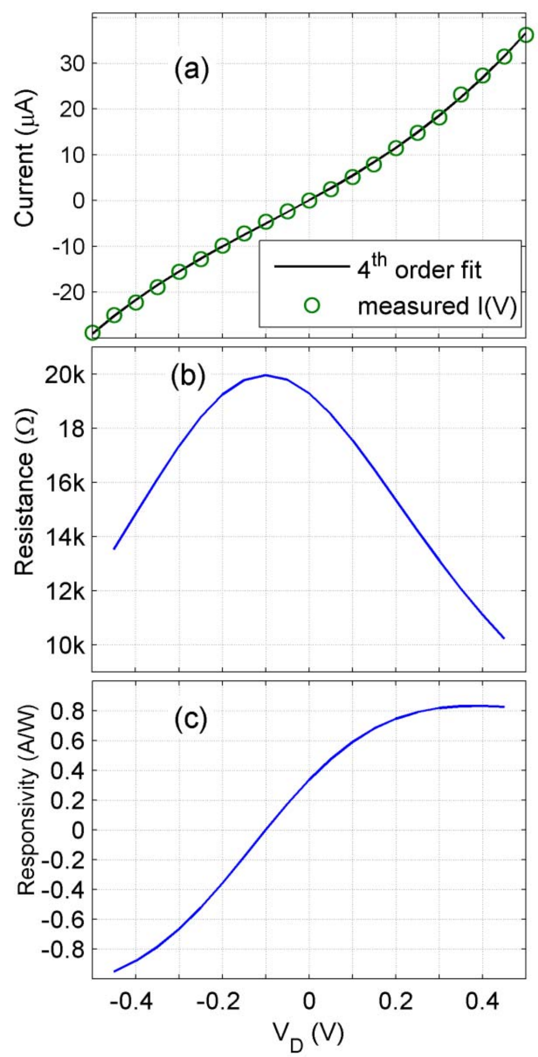

Figure 4 (a) Measured I(V); (b) Differential resistance; (c) responsivity for a graphene geometric diode.

SIMULATION

Using a Drude model for carrier motion in the geometric diode, we numerically simulated the movement of charge carriers in the device to estimate the I(V) characteristics. In this Monte Carlos simulation, carriers move in a random direction at the Fermi velocity after each collision and reflect specularly at the edges. When a DC voltage is applied, a constant field velocity is added to the Fermi velocity. The current at a particular voltage is obtained by counting the net charge flow at a cross section of the device. For example when a carrier traverses that section in the positive current direction, the net charge is decremented by one electron charge unit. After running the simulation for at least 10^6 collision times, a stable I(V) relationship is obtained. In Fig. 5 we show the simulated I(V) curves as a function of neck size, keeping all other parameters fixed.

To analyze the asymmetry of the I(V) characteristics we take the ratio of the absolute value of current at a positive (+V) and a negative (-V) voltage, $A = |I(+V)/I(-V)|$. Deviation of A from unity represents the amount of asymmetry in the I(V) characteristics. This is shown in Fig. 6, for the I(V) curves of Fig. 5. A smaller neck size gives a greater asymmetry, corresponding to better rectifying characteristics. The results of the Drude model simulations are consistent with initial quantum mechanical simulations we are in the process of developing.

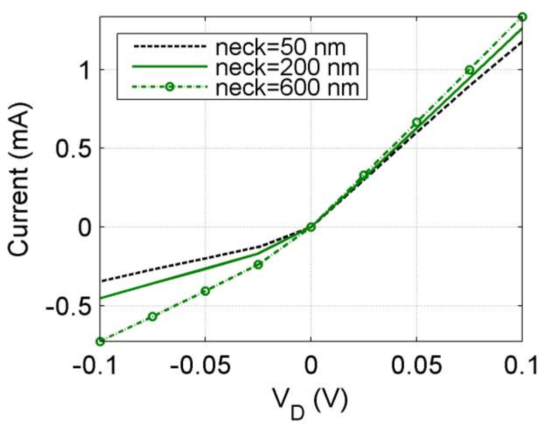

Figure 5 Simulated I(V) curve for the device structure in Fig. 1 with varying neck size. l_c is 200 nm.

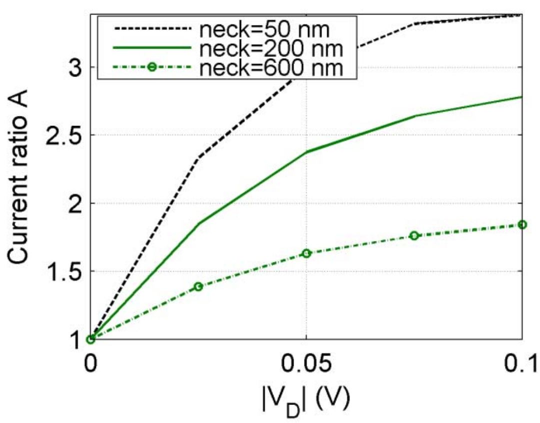

Figure 6 Diode asymmetry $A = |I_D(+V)/I_D(-V)|$ for the I(V) in Fig. 5.

RC TIME CONSTANT ANALYSIS

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 p-type for our case due to the influence of the 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. The capacitance of the geometric diode can be calculated as the parallel combination of two capacitance elements: the capacitance (C_1) 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 [8]. The total capacitance is calculated to be 0.06 fF. Since the resistance of graphene can be adjusted by doping, the impedance of the diode can be tailored to match the antenna impedance, which is about 200 ohms. For these values the overall RC time constant for the geometric diode rectenna is 7 femtoseconds. The calculations are based on our fabricated device and not for an optimized structure. By reducing the area of non-critical region on the sides of neck, we can further reduce the RC time constant. The RC time constant for the geometric diode is much smaller than that of a 100 Ω Ni-NiO-Ni MIM diode with an area of 0.03 μm^2 [7], for which the RC is 127.5 femtoseconds.

CONCLUSIONS

We have developed a geometric diode that can improve the efficiency of rectenna solar cells. Graphene geometric diodes have been fabricated and tested, yielding measured I(V) characteristics that are consistent with Drude-model simulations. This diode is able to meet the dual requirements of a low resistance and a low capacitance required to operate at optical frequencies, which along with a high responsivity lead to an efficient rectenna. Finer lithography is expected to further improve the device responsivity and reduce its capacitance.

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