Overview of optical rectennas for solar energy harvesting

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ABSTRACT

Although the concept of using optical rectenna for harvesting solar energy was first introduced four decades ago, only recently has it invited a surge of interest, with dozens of laboratories around the world working on various aspects of the technology. An optical rectenna couples an ultra-high-speed diode to a submicron antenna so that the incoming radiation received by the antenna is rectified by the diode to produce a DC power output. The result is a technology that can be efficient and inexpensive, requiring only low-cost materials. Conventional classical rectification theory does not apply at optical frequencies, necessitating the application of quantum photon-assisted tunneling theory to describe the device operation. At first glance it would appear that the ultimate conversion efficiency is limited only by the Landsberg limit of 93%, but a more sober analysis that includes limitation due to the coherence of solar radiation leads to a result that coincides with the Trivich-Flinn limit of 44%. Innovative antenna designs are required to achieve high efficiency at frequencies where resistive losses in metal are substantial. The diode most often considered for rectennas make use of electron tunneling through ultra-thin insulators in metal-insulator-metal (MIM) diodes. The most severe constraint is that the impedances of the antenna and diodes must match for efficient power transfer. The consequence is an RC time constant that cannot be achieved with parallel-plate MIM diodes, leading to the need for real innovations in diode structures. Technologies under consideration include sharp-tip and traveling-wave MIM diodes, and graphene geometric diodes. We survey the technologies under consideration.

Keywords: rectenna, optical rectenna, solar cells, MIM diode, graphene diode, efficiency, quantum rectification, photon-assisted tunneling

1. INTRODUCTION

An antenna-coupled diode operating at optical frequencies, also called an optical rectenna, incorporates a submicron antenna and an ultra-high speed diode. The optical rectenna absorbs electromagnetic radiation and converts it to current. A diode rectifies the AC current, providing DC electrical power. Compared to conventional solar cells, which absorb photons and generate electron-hole pairs to provide electrical power, rectennas seem to rely on a classical electromagnetic wave view of light.

The efficiency limitations of conventional semiconductor solar cells have been well studied. They are subject to the Trivich-Flinn [1] efficiency limit (later incorporated into the Shockley-Queisser [2] picture), because conventional semiconductor solar cells cannot absorb photons with energy lower than the bandgap and use only a bandgap energy's worth of high energy photons. The ultimate conversion efficiency limit of these solar cells is 44% and the realistic efficiency is substantially lower. To overcome such limits, multi-junction solar cells were invented to convert the broad solar spectrum more efficiently. However, multi-junction solar cells have their own challenges. Finding materials to absorb different parts of the spectrum efficiently and output similar current levels is difficult and these semiconductor materials are normally expensive to produce.

On the other hand, the power efficiency of radio frequency (RF) rectennas using classical rectifiers can be well over 44% and approach 100%. Optical rectennas will be very attractive if they can operate in the same way as RF rectennas at optical frequencies. They would be highly efficient over a broad spectrum and inexpensive to fabricate. The materials used in optical rectennas would be thin-film metals and insulators or graphene. These materials are widely available and the cost is much lower than the semiconductor materials used in conventional solar cells.

In this paper we will discuss whether a classical view of electromagnetic radiation and rectification or a quantum view of photons applies to optical rectennas. With a fundamental understanding of the optical rectenna technology, we will bring up some major issues with optical rectennas and provide potential solutions.

Next Generation (Nano) Photonic and Cell Technologies for Solar Energy Conversion IV,
edited by Oleg V. Sulima, Gavin Conibeer, Proc. of SPIE Vol. 8824, 88240O · © 2013 SPIE
CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2024700

2. RECTENNAS CONCEPTS & CHALLENGES

A rectenna circuit consists of an antenna connected to a diode, as shown in Figure 1. For operation at optical frequencies, an ultrafast diode rectifies the optical frequency signal absorbed by the antenna, producing a DC voltage. The configuration shown is a clamping circuit, which theoretically can provide 100% conversion efficiency as a classical rectifier. The most straightforward way to use the rectified DC energy is to connect a load with a low-pass filter directly across the diode. Performing a classical circuit analysis, we find that the output DC voltage at the load can be as high as the peak input AC voltage across the antenna.

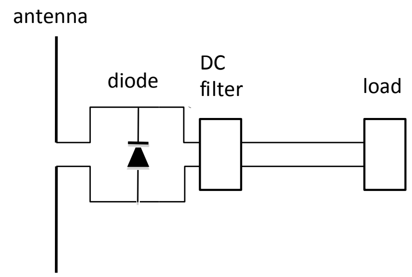

Figure 1. Rectenna circuit.

The concept of rectenna solar cells was first introduced by Bailey in 1972.[3] Due to the lack of efficient optical antennas and ultrafast diodes, optical rectenna research had not been drawing much interest from the solar cell field until recently. Our group started investigating metal-insulator-metal (MIM) diodes for optical rectenna applications [4][5] in 1998, as part of a team led by ITN Energy Systems.[6] Only in the last few years there have been dozens of laboratories around the world investigating various parts of the optical rectenna technology.

With further examination, these devices seem more challenging than what they appeared to be initially. In the rest of the paper, we will specifically discuss the following important issues:

- the coherence of sunlight, which is not an issue for conventional solar cells, but is of crucial concern for rectenna solar cells
- a quantum theory of rectification at optical frequencies
- diode challenges and potential solutions, including MIM structures and new concepts
- antenna constraints
- ultimate and practical power conversion efficiency limits, including heat harvesting

In the end, we will conclude with an assessment of the technology's viability.

3. COHERENCE OF SUNLIGHT

The incoming radiation to the rectenna must be spatially coherent.[4][7] Without spatial coherence, the out-of-phase components of the radiation would lead to a cancellation of the output current. Such an issue does not exist in conventional solar cells, because the photons are absorbed independently.

Fortunately, the solar radiation on earth comes from a limited solid angle from the sun and this makes the radiation spatially coherent over a limited area. However, this area is not large. To achieve 90% coherent solar radiation over a broadband spectrum, the receiving area has to be no larger than a circle with the radius of 19 μm.[7]

This constraint of the rectenna energy absorption area limits the collectable photon flux, which affects the solar cell efficiency. There are two reasons why the collectable photon flux would influence the rectenna efficiency. First, a larger photon flux results in a higher photocurrent. This helps offset the diode reverse-bias leakage and leads to greater efficiency. Additionally, due to a higher photocurrent, the diode is able to produce frequency mixing leading to enhanced conversion efficiency over a broad spectrum.[8] Nevertheless, we cannot break the coherence-area constraint by concentrating sunlight with lenses or mirrors from an area larger than the coherence area, because it would still result in the cancellation of out-of-phase currents.

4. QUANTUM RECTIFICATION

The incident radiation on rectennas is quantized in the form of photons. Such quantization is maintained throughout the energy absorption process by the antenna and subsequent rectification by the diode. This is not obvious in microwave rectennas where a classical description is sufficient to explain rectification. In optical rectennas operating at high frequencies and low photon flux, a semi-classical (or quantum) analysis is used to describe rectification. However, there must be a correspondence between the classical description and the quantum process. For rectennas, this correspondence occurs at low frequencies and high photon flux. In this section we describe the rectification theory used to analyze rectennas.

4.1 Classical vs. semi-classical rectification

Rectification of alternating current to direct current by nonlinear devices is usually described classically. In classical rectification, an alternating voltage applied to the nonlinear diode produces rectified current by a continuous sampling of the diode *I(V)* characteristic. While this description is sufficient to explain rectification at microwave frequencies, it cannot be used at optical wavelengths where the quantized nature of photons becomes important. In tunneling devices, such as MIM diodes, electrons absorb individual photons and tunnel through the insulator. Semi-classical rectification using the theory of photon-assisted tunneling is used to explain this behavior.[9][10]

Photon-assisted tunneling occurs at frequencies where the photon energy becomes comparable to the nonlinearity in the diode *I(V)* characteristics.[11] A high frequency alternating voltage applied across a tunneling device shows up as electronic states separated by the photon energies near the Fermi level. Electrons absorb and emit individual photons and tunnel through the insulator. The diode DC *I(V)* curve is sampled at discrete energies or voltages around the operating voltage. The net illuminated *I(V)* is shown in Figure 2. Such discrete sampling of the *I(V)* in the semi-classical case produces a rectified current different from the continuous sampling in the classical case. The diode AC resistance and responsivity are a function of the photon energy and the diode *I(V)* characteristic.

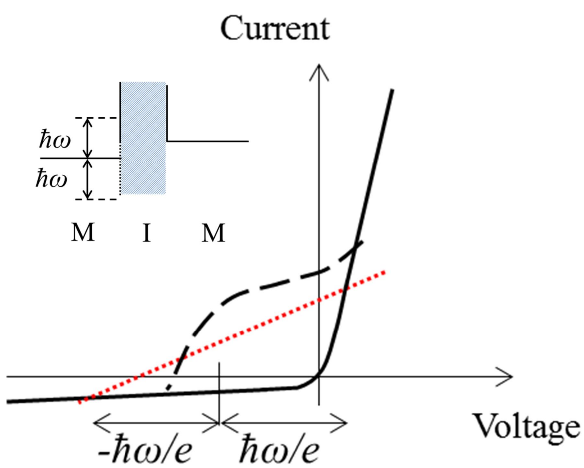

Figure 2. Sketch of a current-voltage [*I(V)*] curve for a rectenna diode. The solid curve shows the *I(V)* for the rectenna in the dark, and the dashed curve shows the *I(V)* under illumination. Photon-assisted tunneling leads to sampling of the *I(V)* curve at $\hbar\omega/e$ above and below the operating voltage. Power is obtained in the 2nd quadrant. The operating voltage for the maximum power point is indicated by a small vertical line on the *voltage* axis. The inset shows a band diagram of a biased metal-insulator-metal diode to illustrate the process. Electron states due to photon-assisted tunneling are shown at energies $\hbar\omega/e$ above and below the Fermi level. The diode AC resistance is the reciprocal of the slope of the secant connecting the points on the *I(V)* curve $\hbar\omega/e$ above and below the operating voltage, and is shown as a dotted line. The secant resistance [9] determines the coupling efficiency between the antenna and diode at optical frequencies, and the conventional resistance of the illuminated *I(V)* curve at the operating point determines the DC coupling between the diode and the load.

4.2 Semi-classical responsivity and resistance

Current responsivity for a rectenna is defined as the rectified current per unit AC input power. Classically, it is given by Equation 1. Diode AC resistance is given by Equation 2.

$$\beta_D = \frac{\partial^2 I}{\partial V^2} \Big/ 2\frac{\partial I}{\partial V} \quad (1)$$

$$R_D = \frac{\partial V}{\partial I} \quad (2)$$

Here β_D is the diode responsivity, R_D is the diode resistance, and the diode current and voltage are denoted by I and V, respectively. In the semi-classical case, given by Equations 3 and 4, the differentials in Equations 1 and 2 are replaced by the currents at discrete voltages $\hbar\omega/e$ above and below the operating voltage.[10]

$$\beta_D^{SC} = \frac{e}{\hbar\omega}\left\{\frac{I(V_O + \hbar\omega/e) - 2I(V_O) + I(V_O - \hbar\omega/e)}{I(V_O + \hbar\omega/e) - I(V_O - \hbar\omega/e)}\right\} \quad (3)$$

$$R_D^{SC} = \frac{2\times(\hbar\omega/e)}{I(V_O + \hbar\omega/e) - I(V_O - \hbar\omega/e)} \quad (4)$$

where β_D^{SC} is the diode semi-classical responsivity, R_D^{SC} is the diode semi-classical resistance, V_O is the diode operating voltage, $\hbar\omega$ is the photon energy, and e is the electronic charge. For an asymmetric diode with negligible reverse leakage current, the semi-classical responsivity under low intensity monochromatic illumination is $e/\hbar\omega$.[11] This means that, for each incoming photon, one electron tunnels through the insulator providing rectification. The diode AC resistance required for impedance matching with the antenna is given by the secant resistance, as shown in Figure 2.[9] In the classical limit, the second and first order difference terms reduce to the differential forms of classical responsivity and resistance. For nonlinear diodes, the semi-classical resistance can be significantly lower than the classical resistance, providing improved impedance match to the low impedance antenna.

4.3 Diode efficiency and operating voltage

A diode under low intensity monochromatic illumination, corresponding to a low diode AC voltage compared to the photon energy divided by *e,* will operate in the semi-classical regime. Unlike solar cells, which operate in the fourth quadrant, rectennas operate in the second quadrant of the *I(V)* characteristics. At each operating voltage, the diode must meet two requirements for efficient transfer of power between the antenna and the diode: a good impedance match between the antenna and the diode, and a low RC time constant, where R is the parallel combination of the diode and antenna resistances. These two requirements will be discussed in detail in section 5. If these conditions are met, an asymmetric diode with negligible reverse bias leakage current would excite one electron for each incoming photon and produce a constant rectified current. For a diode with turn-on voltage at zero, the maximum power extracted out of a photon will be for a diode operating voltage of $-\hbar\omega/e$. Diode efficiency can approach 100% at this voltage. Efficiency at higher (negative) operating voltages is zero. The operating voltage affects the broadband efficiency in the same way as the semiconductor band-gap does for conventional solar cells. We will discuss the efficiency limits of rectennas under broadband illumination in section 8.

5. DIODE REQUIREMENTS

In this section, we will discuss some important diode requirements such as resistance, capacitance, and low reverse-bias leakage. Compared to the high responsivity requirement of the diode, these other requirements have often been ignored. Most of the proposed new diodes in the literature that exhibit high responsivity sacrifice their electrical performance and result in a lower overall rectenna efficiency.

To show the diode requirements, we use MIM diodes as an example. A typical band diagram of an MIM diode is shown in Figure 3. As mentioned in section 4.1, in MIM diodes charge carriers tunnel through a few nanometers thick oxide from one metal layer to the other. Although this tunneling time of the carriers is on the order of femtoseconds, the factors described below limit the diode response time and the overall rectenna efficiency.

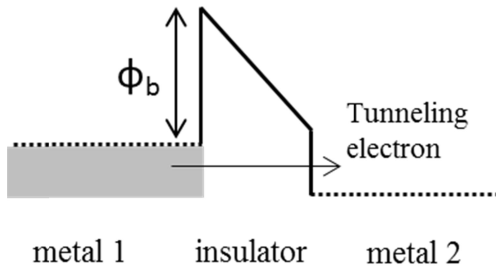

Figure 3. A typical band diagram of a metal-insulator-metal diode under applied bias. The Fermi levels of the two metal layers and the conduction band edge of the insulator are shown as function of position. In this diode, the barrier height at metal 1 is the energy amount of Φ_b and is larger than that at metal 2. Electrons tunnel from metal 1 to metal 2 through the insulator.

5.1 Resistance

Classical circuit theory shows us that the impedance of the diode must match the impedance of the antenna for efficient power transfer. The impedance of the antenna varies from a few tens to hundreds of ohms at terahertz frequencies [12] and can be up to a thousand ohms at visible light frequencies.[13] This limits the diode resistance to be within the same range for high coupling efficiency. The relevant diode resistance required for matching is the secant resistance at the operating voltage, described in section 4.2.

A MIM diode with an antenna matched resistance of ~100 Ω is a low resistance diode, which requires a low barrier height (typically no more than ~ 0.5 eV) and thin insulators (typically thinner than 3 nm). An easy way to reduce the MIM diode resistance is to increase the diode area, but due to the capacitance requirement described in section 5.2 below, this approach does not help.

5.2 Capacitance

The diode capacitance is a crucial efficiency-limiting factor because the rectenna circuit RC time constant must be shorter than the time constant corresponding to visible light frequencies. Near the center of the solar spectrum the frequency of light is 6×10^{14} Hz, corresponding to a time constant $\tau = 1/2\pi f \cong 0.3$ fs. Assuming a matched diode resistance, the rectenna circuit RC time constant must be much less than τ. Such short τ requires the diode capacitance C to be less than 6 aF for a diode resistance of 100 Ω.

For MIM diodes, an extremely small area of $\sim10\times10$ nm^2 is able to provide a sufficiently low diode capacitance on the order of atto-farads. Assuming such small area is achievable, the resistance for such a small diode would be an unacceptably high ~10 kΩ and would reduce the coupling efficiency down to below a few percent.[14][15] Even if we lower the working frequency by a factor of 20 to infrared frequencies, it would still be challenging to use rectennas with planar MIM diodes to harvest thermal energy.

5.3 Reverse-bias leakage

Another important factor that significantly impacts the rectenna efficiency is the reverse bias leakage. In section 4, we showed that the rectenna operates in the second quadrant of the rectenna illuminated *I(V)*. The hump size in this *I(V)* curve, which is proportional to the illumination intensity, determines the amount of energy harvested by the rectenna. The illuminated *I(V)* is a superposition of shifted multiple dark *I(V)*s. Any reverse bias leakage current, i.e. current at negative bias voltages, will reduce the hump magnitude.[9]

The upper limit of the acceptable reverse-bias leakage can be estimated. Assuming that the antenna in a rectenna system has a circular absorption area with the radius of 19 μm for receiving 90% coherent solar illumination, the photon current is ~1 μA at -1 V bias.[8] Thus, for efficient rectification of the photocurrent, the reverse-bias leakage must be much less than 1 μA at -1 V bias. For MIM diodes, reducing the reverse-bias current while fulfilling the low forward-bias resistance requirement is a real challenge.

6. DIODE SOLUTIONS

In this section, we will introduce several diode solutions for the optical rectenna application, such as MIM diodes, metal multi-insulator metal (MIIM) diodes, traveling wave diodes, sharp-tip MIM diodes, and geometric diodes.

6.1 Metal insulator metal (MIM) diodes

MIM diodes have a femtosecond carrier tunneling time and can be easily integrated with antennas. However, as stated in section 5.2, the RC time constant limitations of MIM diodes prevent them to work efficiently at visible light frequencies and thermal infrared frequencies. At low terahertz frequencies, rectennas using MIM diodes can have high coupling efficiency.

In principle, the addition of an inductor in parallel with the diode to compensate for the diode capacitance can increase the efficiency but at a cost of reduced bandwidth. The radial frequency (ω) of the rectenna follows this equation: $\omega C=1/\omega L$. Implementing an adequate inductance (L) adjacent to the diode is difficult and results in a narrow rectenna bandwidth.

Some groups have reported operational rectennas using MIM diodes at visible light frequencies. Either these devices have a very low efficiency or their optical response is due to a bolometric effect (i.e., due to change in resistance with temperature, which cannot provide power). It appears that another type of diode is required for optical frequency operation.

Although MIM diodes have the fundamental RC time constant constraints, they are relatively easy to fabricate. After the diode is patterned using lithography methods, metal layers can be sputtered or evaporated. Usually the insulator layers are formed by oxidation of the base metal layer, or by sputter deposition. More recently, atomic layer deposition (ALD) of insulators and smooth substrates using alloys are being used to improve diode reliability and *I(V)* characteristics.[16]

6.2 Metal multi-insulator metal (MIIM) diodes

Metal multi-insulator metal (MIIM) diodes were proposed to enhance the *I(V)* nonlinearity of the MIM diodes. The enhanced nonlinearity of MIIM diodes results from one of the following two mechanisms.[17] The first mechanism is due to the formation of a resonant well between two insulating layers. Such a resonant well enhances tunneling when the applied voltage places the Fermi level at the resonant energy level. The other mechanism is due to the formation of a step in the insulator conduction band edge in the MIIM band diagram. The charge carriers tunnel through both insulating barriers in one voltage polarity, but tunnel through only one barrier in the opposite polarity.

The MIIM diodes have several advantages:[4]

- The addition of the second insulator greatly improves the diode responsivity resulting in more current for a given optical power input;
- For a given capacitance, larger nonlinearity in the *I(V)* lowers the diode secant resistance so that the diode impedance is better matched to the antenna impedance.
- The diode reverse-bias leakage current is greatly reduced.

We have successfully fabricated working MIIM diodes by sputtering the metal and insulator layers. ALD can provide better thickness control and uniform layers for MIIM diodes. These MIIM diodes have shown highly nonlinear *I(V)* characteristics.[4][16]

Even though multi-insulator diodes are an improvement over single-insulator diodes, they still suffer from the fundamental RC limitations described in section 5.

6.3 Travelling-wave diodes

The MIM and MIIM diodes are normally coupled to antennas as lumped element devices, as shown in Figure 4(a). In such a configuration, the diode electron tunneling and material properties determine the circuit RC characteristics. The traveling-wave diode configuration was invented to take advantage of using a transmission line impedance to replace the diode impedance, as shown in Figure 4(b). In a rectenna consisting of a travelling wave MIM diode and a bowtie antenna, the AC signal from the two arms of the antenna is fed onto an edge of the diode, so that while the wave is transmitted along the transmission line in the form of a plasmon it is rectified. We simulated the travelling-wave MIM rectennas using COMSOL and MATLAB and found that the device performance is much better than their lumped element counterparts, particularly at frequencies higher than 100 THz.[18]

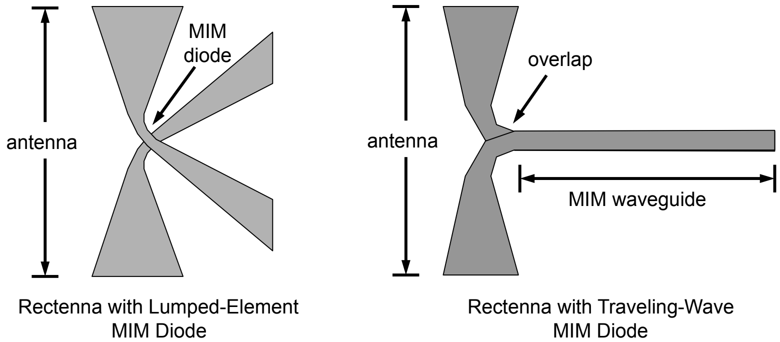

Figure 4. Comparison of lumped-element and traveling-wave MIM diodes in a rectenna (top view).

We proposed the MIM traveling wave structure in a patent application,[19] and to IBM, and tested it for 10 μm and 1.5 μm wavelengths. IBM successfully implemented a similar structure but with the traveling-wave structure formed over a Si-SiO_2 waveguide.[20]

Resistive losses in the metal traveling-wave structure can devour much of the plasmon energy. It remains to be seen whether the high-frequency advantages of MIM traveling-wave detectors can be extended to energy harvesting devices.

6.4 Sharp-tip MIM diodes

Besides the travelling wave MIM approach, another potential approach to circumventing the RC tradeoff is the use of sharp-tip MIM diode.[21] In contrast to planar MIM devices, for which the RC time constant is independent of area, Miskovsky et al. have shown that the RC time constant for spherical tips varies with the square root of the area.[21] This sharp tip effect results in a reduced RC time constant with decreasing tip radius. Fabricating the sharp tip devices with the right tip size and precisely controlled nanometer insulator thickness is a challenge. Miskovsky et al. use the ALD method for growing the metal layers to self-restrict the spacing in between the layers and to form a metal-air-metal diode as the result.

6.5 Geometric diodes

From section 6.1 to section 6.4 we described methods to improve MIM diodes for optical rectennas. In this section, we introduce a new type of ultrafast diode, the geometric diode.

In geometric diodes, the *I(V)* asymmetry results from an asymmetry in the physical shape of the device. Imagine a conductive thin film patterned into an inverse arrowhead shape shown in Figure 5. Charge carriers move from left to right (forward direction) more easily than in the opposite direction because of the funneling effect of the arrowhead shaped edges. As opposed to the MIM diodes having a parallel-plate structure, geometric diodes have a miniscule capacitance because of their planar structure. In addition, being continuous conducting thin films, the resistance of the geometric diodes can be small enough for matching the antenna impedance. Therefore, the overall RC time constant of geometric diodes is significantly lower than that of MIM diodes.

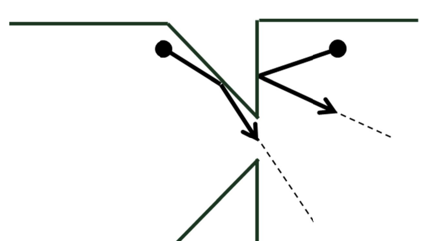

Figure 5. Top view of charge carriers reflecting off the edges of a geometric diode.

The main requirement and challenge in implementing geometric diodes is that, for the carriers to sense the geometrical asymmetry, the critical dimension of the patterned thin film has to be on the order of the mean-free path length (MFPL) of the charge carriers. This requirement involves high resolution nanoscale lithography methods for patterning, and a thin film material having large MFPL. Zhu et al. chose graphene, which has a relatively large MFPL, to form the conducting layer in these diodes.[22] Another advantage of using graphene as the diode material is that the charge carrier type and concentration can be controlled by changing the gate voltage. As a result, *I(V)* characteristics of the graphene geometric diodes can be tuned, and the asymmetry even reversed, by applying a gate field.[23] The rectification effect of these diodes has been demonstrated at 28 THz frequency after coupling them to bowtie antennas.[22] The measured detector noise equivalent power (NEP) of these rectenna devices is an order of magnitude better than the best reported graphene terahertz detector. However for solar energy harvesting, the quantum efficiency of these devices is still low at ~0.01%. This is mainly due to the poor electrical properties of chemically processed and patterned graphene leading to a low diode *I(V)* asymmetry. Current graphene technology is still in its infancy. The best quality graphene is produced by the exfoliation method using scotch tape and graphite flakes.[22] The standard nanofabrication processes and chemicals degrade the electronic quality of the graphene.

Another type of geometric diode, developed previously by Song et al.,[24] makes use of an asymmetric nanochannel formed in a GaAs-based semiconductor structure. Its depletion layer varies with applied voltage, and the device has been demonstrated at 1.5 THz in rectennas. With some modifications or changing the diode materials it might be a candidate for operation at higher optical frequencies.

7. OPTICAL ANTENNAS

In contrast to optical-frequency diodes there are fewer impediments in the formation of high performance optical antennas for rectenna solar cells, although challenges remain. A successful optical antenna technology must address several key issues:

- Impedance -- Antennas usually provide an impedance of ~100 Ω. A higher impedance would make it easier to match the diode impedance for efficient power transfer. However, a higher antenna impedance makes it even more difficult to achieve the required RC time constant ~0.1 fs to follow optical frequency oscillations. Therefore it is not clear if changing the antenna impedance provides any improvement.[15]

- Capacitance -- Compared to the diode capacitance, the antenna capacitance contributes much less to the rectenna system. Providing an inductive load would be helpful to compensate the diode capacitance, but it will greatly reduce the rectenna working bandwidth, as discussed in section 6.1.

- Polarization -- For solar energy harvesting applications, the antenna must efficiently capture all polarizations of the incident radiation. The antenna geometry can be changed to a structure that provides polarization independence. A spiral antenna is one example of such an antenna.

- Arrays -- A successful solar rectenna panel requires arrays of rectennas working in tandem. This will affect the acceptance angle. It is advantageous to have as wide an acceptance angle as possible so that solar tracking is not required. Because of the coherence constraints described in section 3, at most a few antennas can feed each diode.

- Concentration -- Lenses or other concentrators can be used to increase the intensity received by each antenna. However the area of each concentrating lens cannot be larger than the coherence area for sunlight.

8. POWER CONVERSION EFFICIENCY

8.1 Landsberg efficiency

The spectral distribution of a blackbody causes the radiation to carry entropy. Conversion efficiency for radiation from a blackbody is slightly lower than the Carnot efficiency for a source of the same temperature. The Landsberg efficiency limit is strictly a thermodynamic radiation conversion limit and does not provide any insight specific to rectennas.

For the sun, modeled as a 5800 K blackbody, the corresponding Landsberg efficiency limit is 93%. Figure 6 below shows the Landsberg efficiency limit as well as the peak irradiance wavelength versus blackbody temperature. The addition of the peak irradiance curve illustrates the need for rectennas that can operate at short wavelengths so rectennas can be used in applications with a high Landsberg efficiency limit.

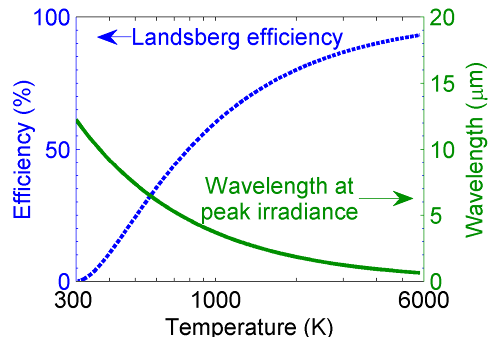

Figure 6. Landsberg efficiency (dashed blue line) and wavelength at peak of irradiance (solid green line) as a function of the blackbody temperature. The peak wavelength is defined for fractional bandwidth normalization.[25] (Courtesy of Sachit Grover[10])

8.2 Intermediate absorber (and thermophotovoltaics)

This model has an intermediate absorber which absorbs solar radiation and heats up. The absorber then reemits as a blackbody but at a lower temperature than the sun. For an intermediate absorber at 2544 K, the corresponding Landsberg efficiency is 85%. As shown in Figure 6, peak radiation wavelength increases with decreasing blackbody temperature. For semiconductor photovoltaics, it is difficult and expensive to fabricate devices with a sufficiently small bandgap for efficient operation at these frequencies. Rectennas however, benefit from the lower frequency as it leads to a relaxed RC time constant requirement.

8.3 Waste heat harvesting

Another potential application for rectennas is waste heat harvesting. In addition to the previous challenges, waste heat harvesting has the additional challenge that the source will likely be large and close to the rectenna. This results in a small coherence area.

Despite some discussion of using rectennas to harvest waste heat from the earth's surface in the literature, this energy cannot be harvested with ambient temperature solar cells.

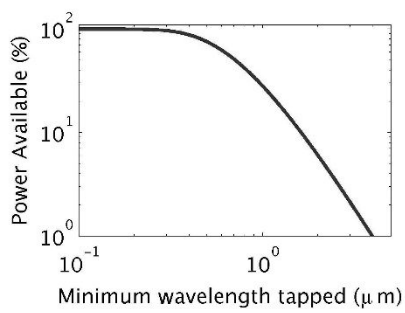

Figure 7. Maximum power available in the solar spectrum as a function of the minimum wavelength that is tapped. (Courtesy of Sachit Grover[10])

8.4 Broadband efficiency limit

For a rectenna to operate efficiently, the operating voltage should be equal to $\hbar\omega/e$, giving 100% quantum efficiency (one electron excited per incident photon). For a monochromatic source this condition can be met. For broadband illumination at solar intensities, since the device can only work at a single operating voltage, only photons at the operating voltage can be used most efficiently. Lower energy photons are wasted and the potential of higher energy photons is only partially used. This prevents efficient collection of the entire spectrum. As a result, the maximum efficiency that can be obtained from an ideal diode under broadband illumination is 44%.[8]This is the same as the Trivich-Flinn efficiency limit of solar energy conversion by quantum processes.[1] In conventional single junction solar cells, the same limit applies due to the constraint on the solar cell to operate with a single bandgap energy.[2] Thus, for rectennas, the operating voltage limits the efficiency in the same way as that the bandgap limits the efficiency in conventional solar cells.

For input intensities significantly higher than the photon energy, multiple photons can excite a single electron and rectification at operating voltages greater than $-\hbar\omega/e$ is possible. Photons with energies below the operating voltage can be used to enhance rectification efficiency. This is useful for broadband illumination where a high efficiency limit can be achieved due to mixing of photons of same or different energies. However, for solar intensities mixing is negligible because of the low solar photon flux.

9. CONCLUSIONS

In conclusion, rectenna solar cells are indeed attractive for their high efficiency and low cost, but the required research work is at a nascent stage. In this paper, we introduced the semi-classical model for the operation of optical rectenna solar cells. Optical rectennas operate in the second quadrant of their illuminated *I(V)* characteristics for energy harvesting. For a diode with negligible reverse leakage current and matched impedance to the antenna, rectenna efficiency under monochromatic illumination approaches 100%. For this monochromatic case, the diode operates at a voltage equal to the photon energy divided by *e*. The operating voltage limits efficiency in the same way as the bandgap does in conventional semiconductor solar cells. This results in a broadband rectenna efficiency limit of 44% for the solar spectrum. Despite having the same 44% efficiency limit as the Trivich-Flinn limit for conventional solar cells, optical rectennas have a few advantages over their semiconductor counterparts. First, rectennas utilize inexpensive materials compared to many of the exotic single crystal semiconductor materials used in high efficiency conventional solar cells. Additionally, integration of a variety of antenna sizes could easily allow energy harvesting from a wide range of the solar spectrum at high efficiencies.

In order to develop practical and high efficiency rectennas, we considered the following diode requirements: matched diode resistance with the antenna impedance for high coupling efficiency, low diode capacitance for an overall short RC time constant, and low reverse leakage current for energy harvesting. We studied MIM and MIIM diodes because of their femtosecond fast tunneling mechanism. Careful analysis shows that rectennas with MIM diodes suffer from an RC time constant limitation at optical frequencies. We introduced some other diode designs having shorter RC time constants which can be integrated into optical rectennas. These designs include travelling-wave diodes, sharp-tip MIM diodes, and geometric diodes. Although these diodes require further investigation, they have the potential to lead to practical rectenna solar cells. Just like other solar cell technologies in their emerging stages, rectenna solar cells currently face quite a few challenges. In the near term, rectennas have many advantages over semiconductor based devices for waste heat harvesting at lower frequencies, with relaxed time constant requirements.

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