Chapter 1
Will Rectenna Solar Cells Be Practical?

Garret Moddel

Abstract Optical rectennas are an attractive technology for high-efficiency, low-cost solar cells if several technological issues can be addressed. These devices combine submicron antennas with ultra-high speed diodes to rectify incident radiation. Visible light frequency operation requires a quantum approach to analyze the rectification process and design the devices. The small coherence area for sunlight limits the power per rectenna, which affects the conversion efficiency. In assessing the broadband ultimate efficiency obtainable from rectenna solar cells it turns out that operating voltage plays the same role that band gap energy plays in conventional solar cells, leading to a single cell limit of 44 %. Parallel plate diodes cannot provide the 0.1 fs *RC* time constant that is required to rectify visible light frequencies, and so other potential solutions such as traveling-wave diodes, sharp-tip diodes, or geometric diodes are required. Waste heat harvesting and thermophotovoltaics using optical rectennas would relax the *RC* constraints because the infrared frequencies are lower than those for visible light, but with substantial coherence impediments. With innovation and careful development rectenna solar cells have the potential to provide an exciting new photovoltaics technology.

1.1 Rectenna Solar Cells: Einstein or Maxwell?

In conventional solar cells each photon generates electron–hole pairs that provide electrical power. Imagine instead a "crystal radio" for light that absorbs electromagnetic radiation in an antenna, converts it to current, and channels it to a diode that rectifies it, providing electrical power. This antenna-coupled diode,

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called an optical rectenna, incorporates a submicron antenna and an ultra-high speed diode. It might appear that while the conventional solar cell is based on Einstein's photon view of electromagnetic radiation, the rectenna relies instead on Maxwell's electromagnetic waves. Is that correct?

Semiconductor solar cells have well-defined efficiency limitations. They are subject to the Trivich–Flinn [1] limit (later incorporated into the Shockley–Queisser [2] picture). Those devices cannot absorb low energy photons and use only a band gap energy's worth of high energy photons, limiting the ultimate conversion efficiency to 44 % and the real efficiency to substantially less. Multijunction solar cells can more efficiently convert the broad solar spectrum, but the materials required to absorb different parts of the spectrum are a challenge to provide. Semiconductor materials are expensive to produce, and commonly used transparent conductors that they require are limited in availability.

Classical rectifiers, on the other hand, can rectify a broad range of frequencies at close to 100 % efficiency. If optical rectennas operate in the same way, then very high efficiencies over a broad spectrum should be obtainable. The materials used in rectennas can be inexpensive and widely available, composed of thin-film metals and insulators on a variety of substrates. Rectenna solar cells would appear to be very attractive.

The issue of whether a classical Maxwellian view of electromagnetic radiation and rectification or an Einsteinian view of quantized photons applies to optical rectennas will be discussed in this chapter. The classical-versus-quantum dichotomy provides a foundation for understanding many of the issues in solar rectenna technology.

1.2 Rectenna Basics

A rectenna consists of an antenna, diode, and load, all in parallel, as shown in Fig. 1.1. The optical frequency signal from the antenna is rectified by the diode and flows through a low-pass DC filter to the load. This circuit acts as a diode clamp, raising the output DC voltage to as high as the peak input AC voltage.

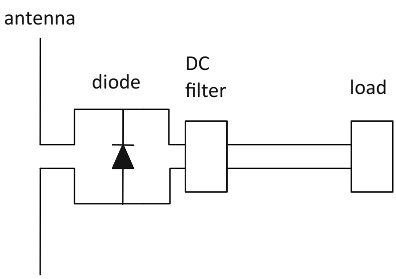

Fig. 1.1 Rectenna circuit

The history of rectenna solar cells, from the initial conceptualization by Bailey in 1972 [3], is well documented in several chapters of this book and will not be given here. For decades there was little interest in the field. In 1998 we started investigating metal-insulator-metal (MIM) diodes for solar rectennas [4, 5] in a project directed by ITN Energy Systems [6], but only in the last few years has there been a substantial upsurge of interest in the field, with dozens of laboratories around the world investigating various parts of the technology.

The devices turn out to be more challenging—and more interesting—than it might initially appear. In this chapter I outline the main issues, which correspond to the chapters of this book. They include:

- The coherence of sunlight, which is of crucial concern for rectenna solar cells
- A quantum theory of rectification (Maxwell does not suffice)
- Diode challenges and potential solutions, including MIM structures and new concepts
- Antenna constraints
- Ultimate and practical power conversion efficiency limits, including for harvesting heat
- Commercialization

I conclude with an assessment of the technology's viability.

1.3 Coherence of Sunlight

In a conventional solar cell each photon is collected independently, and so the coherence of sunlight is not an issue. In contrast, in a rectenna the current collected from the entire antenna converges at the diode, resulting in the cancellation of out-of-phase components. Therefore the incoming radiation must be spatially coherent [4].

Solar radiation on earth is somewhat coherent due to the limited solid angle subtended by the sun. A consequence is that sunlight is spatially coherent only over a limited area. A coherence of 90 % for a broadband solar spectrum can be obtained over a circle having a radius of 19 μm [7], as described in Chap. 4.

This result has broad consequences. The efficiency of rectenna solar cells is a function of collected photon flux for two reasons: (1) a high photocurrent is needed to offset the effects of diode reverse-bias leakage (discussed in more detail in Sect. 1.5.3) and (2) high photocurrent can produce frequency mixing in the diode, which can enhance the broadband efficiency (discussed in more detail in Sect. 1.8.3). With a limited acceptance area because of coherence constraints, the collected photon flux is limited. This constraint cannot be relaxed by concentrating the sunlight with lenses or mirrors that are larger than the coherence area, because that would produce the same sort of cancellation of out-of-phase currents as would result from increasing the antenna area.

1.4 Quantum Rectification

The optical radiation incident on rectennas is quantized in the form of photons, but it is less obvious that the quantum nature of the energy is maintained in the current flowing from the antenna to the diode and in the rectification process itself. In fact, a quantum description is required for each of these processes in optical rectennas. As is generally the case, there must be a correspondence between the quantum processes and a classical description. For rectennas this correspondence appears for low photon energy and high photon flux. A microwave antenna can be accurately described classically, but an optical rectenna requires a quantum description.

1.4.1 Semiclassical Versus Classical Models

The photon energy, $\hbar\omega$, at which the classical description becomes inadequate depends on the diode current–voltage [$I(V)$] characteristics, as described by Grover et al. [8] and in Chap. 2. When $\hbar\omega/e$, where e is the electron charge, becomes sufficiently large as defined below, then a semiclassical description is required. It is semiclassical as opposed to fully quantum because the electronic transitions are described quantum mechanically, but the description of the field can be classical.

The reason that a classical description is no longer accurate at this point has to do with the rectification process. In classical rectification a sinusoidally oscillating voltage across a diode induces a continuously varying current whose magnitude is larger for one polarity than for another. In semiclassical rectification the $I(V)$ curve is instead sampled at discrete points corresponding to $\pm\hbar\omega/e$ about an operating voltage, as shown in Fig. 1.2. In fact, discrete sampling of the $I(V)$ curve occurs for classical rectification too, but it is not apparent because $\hbar\omega$ is so small. Only when $\hbar\omega/e$ is on the order of or greater than the voltage at which significant nonlinearity appears in the $I(V)$ characteristic does the quantum nature become apparent.

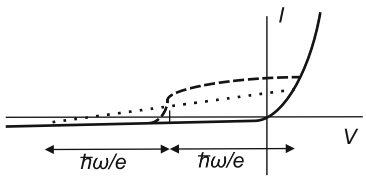

Fig. 1.2 Sketch of a current–voltage [$I(V)$] curve for a rectenna diode. The *solid curve* shows the $I(V)$ for the rectenna in the dark, and the *dashed curve* shows the $I(V)$ under illumination. Power is obtained in the second quadrant. The operating voltage for the maximum power point is indicated by a *small vertical line* on the V axis. The secant resistance (defined in Sect. 1.4.3) is the reciprocal of the slope of the line connecting the dark $I(V)$ curve at $\pm\hbar\omega/e$ about the operating voltage and is shown as a *dotted line*. The secant resistance 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

1.4.2 Photon-Assisted Tunneling

After the photons are absorbed by the antenna, their energy quantization is maintained in form of surface plasmons making up the current flowing to the diode. At the diode these energy packets can induce transitions of the charge carriers, usually electrons, from one side of the diode to the other. For diodes in which charge carriers tunnel from one conductor to another through a thin insulator, such as MIM diodes, the process is known as photon-assisted tunneling (PAT). PAT theory was developed for superconducting junctions by Tien and Gordon [9] and Tucker [10] and applied to MIM diodes by Heiblum [11], and others, and is described in Chap. 2, which is based largely on Grover et al. [8] Also shown in Chap. 2 is that the PAT formalism may be generalized to non-tunneling diodes within certain limits. Therefore the PAT rectification theory applied here and elsewhere to MIM diodes at optical frequencies can also be applied to other types of diodes.

1.4.3 Semiclassical Responsivity and Resistance

For rectennas the responsivity (β) is a measure of current (or sometimes voltage) produced in response to a given incident power and is a function of the derivatives of the current with respect to voltage, specifically $\beta = I''/2I'$. In the semiclassical case required for optical frequencies the differentials are replaced by discrete differences spaced at $\pm\hbar\omega/e$.

The maximum quantum efficiency, i.e., number of collected electrons per incident photon, is unity. This corresponds to the maximum responsivity that can be obtained for a given photon energy.

Matching the diode resistance to that of the antenna is crucial for efficient power transfer. Usually the challenge is to obtain a diode resistance that is sufficiently low. At classical frequencies the resistance is the reciprocal of the $I(V)$ curve slope at the operating point. For highly nonlinear diodes this differential resistance can be substantially smaller than the absolute resistance. In the semiclassical case described by PAT theory, this differential resistance is replaced by a "secant resistance," [8] where the secant spans two points on the $I(V)$ curve that are spaced at $\pm\hbar\omega/e$ about the operating voltage.

1.4.4 Operating Voltage

For those acquainted with $I(V)$ characteristics of conventional solar cells, the $I(V)$ curves for optical rectennas under illumination appear strange. In conventional solar cells the $I(V)$ curves are shifted downward under increasing illumination intensity, so that the operating point is in the fourth quadrant. For optical rectennas illumination produces a hump in the second quadrant, as shown in Fig. 1.2. The height of the hump depends on the illumination intensity and its width is a function of the photon energy. The operating point is in the second quadrant.

Since the maximum optically induced current corresponds to one electron per photon, extracting the maximum power from the light will be at a voltage magnitude at which the full photon energy is extracted, i.e., $\hbar\omega/e$. This sets the optimal operating voltage at $-\hbar\omega/e$, at least for monochromatic, low-intensity illumination. The case of broadband illumination is considered in Sect. 1.8.3. Classical rectennas, e.g., those receiving microwave radiation, typically operate with quantum efficiencies far below unity, but compensate by operating at voltages that are many times $\hbar\omega/e$ (produced by mixing, as described in Sect. 1.8.3).

As with conventional solar cells, the operating voltage is determined by the load resistance and the illumination intensity. This operating voltage is self-biased, i.e., no external voltage needs to be applied to achieve it.

1.5 Diode Challenges

There are several misconceptions about diodes for optical rectennas. Research papers appear regularly describing new diode materials or structures that provide responsivity that is better than more commonly used diodes. High responsivity is desirable, but it usually comes at the expense of compromises in other factors that have a larger impact on rectenna performance. As we will see, the crucial—and most difficult to solve—problems are diode resistance, capacitance, and reverse-bias leakage.

The requirements imposed on diodes for optical frequency rectification are extreme. The most commonly used diode that can operate at the petahertz frequencies required for optical rectennas, which is several orders of magnitude higher than the fastest electronics, is the MIM diode. A band diagram for an MIM diode having two different metals is shown in Fig. 1.3. In MIM diodes charge carriers, usually electrons, tunnel from one metal layer to the other through an

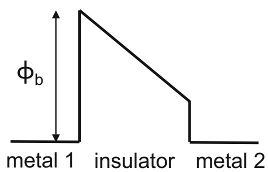

Fig. 1.3 Energy band diagram for a metal-insulator-metal (MIM) diode under zero bias. The Fermi levels of the two metal layers and the conduction band edge of the insulator are shown as a function of position. Metal 1 is shown as having a larger barrier height, φ_b, than metal 2

oxide whose thickness is a few nanometers. The tunneling time is on the order of femtoseconds [12], but the response time is limited by other factors described below.

1.5.1 Resistance

The impedance of the diode must match the impedance of the antenna for efficient power transfer. The antenna impedance is usually dominated by the resistance, which is typically on the order of a few hundred to a thousand ohms at visible light frequencies [13] and lower at terahertz frequencies [14]. A diode having a large responsivity but a resistance of tens of kilohms or more is useless. The relevant diode resistance is the secant resistance at the operating voltage, described in Sect. 1.4.3 above.

For MIM diodes, obtaining a sufficiently low resistance requires low barrier height (typically no more than ~0.5 eV), thin insulators (typically below 3 nm in the case of single-insulator diodes), and as large an area as possible given other constraints.

1.5.2 Capacitance

The frequency of light near the center of the solar spectrum is 6×10^{14} Hz, corresponding to a time constant $\tau = 1/2\pi f \cong 0.3$ fs. To rectify this frequency efficiently the rectenna *RC* time constant must be much less than τ. The diode resistance must be matched to the antenna resistance for efficient power transfer, and the relevant resistance for the *RC* time constant is the parallel combination of these two resistances, as evident from Fig. 1.1.

Ignoring the factor of 2 that arises from the parallel combination of resistances, the diode *RC* time constant must be much less than τ. For a diode resistance $R = 100\ \Omega$, the diode capacitance C must then be less than 3 aF. For MIM diodes $C \sim 10^{-14}$ F/μm^2, so that obtaining a sufficiently low capacitance would require an area of ~10×10 nm^2. Even if that could be obtained, the resistance for such a small diode would be unacceptably high. The lowest conceivable resistance would correspond to a large breakdown current density, say 10^7 A/cm^2, at a low voltage, say 0.1 V. For an area of 10×10 nm^2 this would result in $R \sim 10$ kΩ, which is two orders of magnitude too large for efficient power transfer from the antenna. The full calculation is presented in Sanchez et al. [15], Grover et al. [16], and Chap. 2.

In short, planar MIM diodes cannot provide a sufficiently low *RC* time constant to rectify visible light. Even thermal infrared light, at a factor of 20 lower in frequency, would be an extreme challenge to harvest efficiently using planar MIM diodes.

1.5.3 Reverse-Bias Leakage

In the $I(V)$ curve of Fig. 1.2 there is significant reverse-bias leakage, i.e., significant current for negative voltages. When the rectenna is illuminated a hump rises in the $I(V)$ curve in the second quadrant, with the rise proportional to the illumination intensity. For the rectenna to deliver power to the load this rise must be much larger than magnitude of the current leakage at the operating voltage. Under solar illumination of an antenna that is as large as a coherence of 90 % allows, having a radius of 19 μm, the photon current[1] is ~1 μA at −1 V [17] (in Chap. 3, Fig. 3.10 shows a somewhat smaller current because 97 % coherence is used, which corresponds to a smaller coherence area). To be able to rectify most of the photocurrent, the reverse-bias leakage at −1 V must be much less than 1 μA. For devices with smaller antennas, having a radius of roughly one fourth of a wavelength, the leakage current must be even lower. This is a real challenge to achieve in a diode that also provides the required low forward-bias resistance described in Sect. 1.5.1.

1.6 Potential Diode Solutions

1.6.1 MIM Diodes

The femtosecond carrier transit time in MIM diodes, along with their relative ease of integration with antennas, would appear to make them enticing candidates for solar rectennas. However, as described above, their large *RC* time constant eliminates parallel plate MIM diodes as candidates for visible light frequency rectification. They can work at low terahertz frequencies, but for thermal infrared frequencies of ~30 THz and higher they cannot respond efficiently.

In principle it is possible to compensate the diode capacitance with a parallel inductance, which should allow high-frequency operation. It is difficult to provide adequate inductance (L) directly adjacent to the diode, but even if it could be accomplished it would provide compensation only over a narrow frequency range around the radial frequency (ω) where $\omega C = 1/\omega L$.

There have been reports of MIM diode operation at visible light frequencies [18], but in such cases either the efficiency was low, the response was bolometric (i.e., due to change in resistance with temperature, which cannot provide power), or due to the formation of an unintentional thermocouple (described in Chap. 9).

The metal layers are usually deposited by sputtering or evaporation. The MIM diode characteristics and reliability can be improved by using smooth substrates

[1] Defined as the electric current that would result if each photon produced one electron charge.

and atomic layer deposition (ALD) of the insulators, as described by Alimardani et al. [19] and in Chap. 6. The insulator can be formed by oxidation of the base metal layer or by deposition. Devices for testing and optimization can be formed using a simple point-contact approach, as described in Periasamy et al. [20] and Chap. 15. Unfortunately, these improvements cannot solve the fundamental *RC* problems.

It appears that another type of diode is required for optical frequency operation.

1.6.2 Metal Multi-insulator Metal Diodes

Instead of the usual single-insulator MIM diodes, multiple insulators can be used to form MIIM diodes. The incorporation of multiple insulators provides enhanced $I(V)$ nonlinearity, which brings several advantages [4]:

1. Enhanced responsivity (defined above in Sect. 1.4.3), so that the diode produces more current for a given optical power input.
2. Because the $I(V)$ rises more rapidly than in an MIM diode, the secant resistance (described in Sect. 1.4.3) will be smaller, and hence provide a better match to the antenna for a given capacitance, with results for specific diodes shown in Fig. 5.12 of Chap. 5.
3. Reduced reverse-bias leakage current.

The enhanced nonlinearity of multi-insulator diodes results from one of two mechanisms, as described in Grover et al. [21], Chaps. 5 and 6. One is due to the formation of a resonant well between two insulating layers, which enhances tunneling when the applied voltage places the Fermi level at the resonance energy. A second mechanism is due to the formation of a step in the insulator conduction band edges, such that electrons must tunnel through both insulators for one voltage polarity and just one insulator for the other polarity.

We have found that metal multi-insulator diodes can be deposited successfully by sputtering. More control in layer thickness and uniformity can be achieved using ALD, and multi-insulator diodes with ALD insulator have exhibited highly nonlinear $I(V)$ characteristics [4, 22].

Although multi-insulator diodes are an improvement over single-insulator devices, they still are subject to the fundamental *RC* limitations described above in Sect. 1.5.2.

1.6.3 MIM Traveling-Wave Diodes

For a lumped-element MIM diode, the electron tunneling properties control the *RC* characteristics. On the other hand, for a traveling-wave diode the impedance is determined largely by the geometry, as for a transmission line. The signal from both

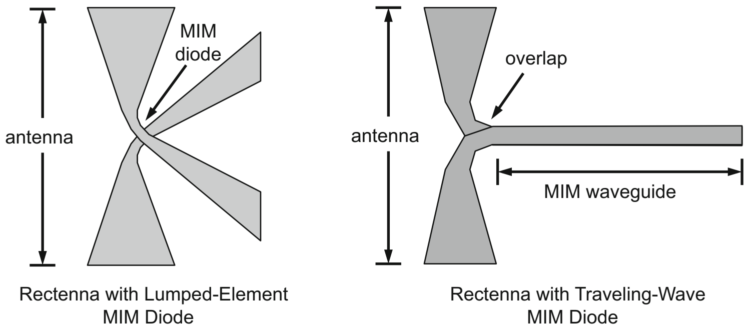

Fig. 1.4 Comparison of lumped-element and traveling-wave MIM diodes in a rectenna (*top view*)

arms of the antenna is introduced to the diode at one edge, as shown in Fig. 1.4, so that the wave travels down the MIM diode in the form of surface (or interface) plasmons and produces a rectified signal until the plasmons are depleted.

As a means to mitigate the *RC* time constant constraint in optical rectennas we proposed the MIM traveling-wave structure in a patent application [23], and to IBM, and tested it for 10 and 1.5 μm wavelengths. IBM successfully implemented a similar structure but with the traveling-wave structure formed over a Si-SiO_2 waveguide [24]. Based on simulations we have found that traveling-wave MIM detectors can perform much better than their lumped-element counterparts, particularly at wavelengths as short as 3 μm [25].

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.

1.6.4 Sharp-Tip Diodes

One potential approach to circumventing the *RC* trade-off described above in Sect. 1.5.2 is the use of sharp-tip MIM, or metal-vacuum-metal diodes, as described by Miskovsky et al. [26] and in Chap. 7. This approach takes advantage of changes in the *RC* trade-off for sharp-tip tunneling devices. In contrast to parallel plate planar MIM devices, for which *RC* is independent of area, for spherical tips the *RC* is shown to vary with the square root of the area. For that reason the response time decreases for decreasing tip radius. Forming the sharp-tip devices with well-controlled nanometer tunneling gaps is a challenge. Miskovsky et al. are attacking the problem by using ALD of the metal layers to control the spacing.

1.6.5 Hot-Electron MIM Diodes

In a rectenna the incoming radiation is channeled through the antenna to produce an oscillating electric field across the diode. The entire Fermi sea of electrons is modulated, and because of an asymmetry in the diode band structure, as shown in Fig. 1.3, this modulation induces tunneling preferentially in one direction. Alternatively, if the illumination is absorbed directly in one of the metal layers of the MIM diode, the photon energy can be channeled to a single electron, which then becomes hot. If the hot electron has sufficient energy to surmount the band offset, it can ballistically traverse the insulator and produce photocurrent.

In early work on rectenna solar cells in my laboratory, Eliasson considered this mechanism for MIM-based solar cells and analyzed the potential efficiency [4]. He found that the efficiency would be very low for several reasons, dominated by the fact that only approximately 2 % of the hot electrons would travel sufficiently normal to the plane of the insulator layer to traverse the barrier. More recently, others [27–29] have shown that this efficiency can be increased substantially using surface plasmons. Even with the enhancement, however, the efficiency under monochromatic illumination is only a few percent. Without further substantial innovation, hot electron diodes do not provide sufficient efficiency to merit consideration for energy harvesting.

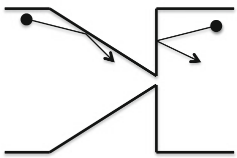

Fig. 1.5 *Top view* of charge carriers reflecting off the edges of a geometric diode

1.6.6 Geometric Diode

In geometric diodes an $I(V)$ asymmetry results from an asymmetry in the physical shape of the device, as opposed to the usual type of diode in which an $I(V)$ asymmetry results from an asymmetry in the electronic band structure. As shown in Fig. 1.5, charge carriers are more likely to move from left to right than the other direction because of the funneling effect of the sloped edges. Such device can have a miniscule capacitance because they are planar, as opposed to having a parallel plate structure. Composed of a conducting thin film, the resistance can be small enough to match the resistance of an antenna. The RC time constant can be significantly lower than that of MIM diodes.

The main challenge in developing geometric diodes is that, for the charge carriers to sense the geometrical asymmetry, their mean-free path length must be on the order of the critical dimensions of the diode. For that reason graphene, which has a relatively large mean-free path length, has been used to form the conducting layer in these diodes, as described by Zhu et al. [30] and in Chap. 10. The $I(V)$ characteristics can be tuned and even reversed by applying a gate field [31]. In rectennas these devices have been demonstrated at 28 THz. Graphene technology is in its infancy, and the standard nanofabrication processes and chemicals that are used successfully to fabricate structures from other materials, degrade the electronic quality of the graphene. For this reason and the difficulty in forming optimal structures, graphene geometric diodes are not yet sufficiently nonlinear to provide efficient high-frequency rectennas.

Another type of geometric diode, developed previously by Song et al. [32], 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 it might be a candidate for operation at higher optical frequencies.

1.7 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. With regard to use in optical rectennas a successful antenna technology must address several key issues:

1. *Impedance*. Antennas usually provide an impedance of ~100 Ω. Providing a higher impedance would make it easier to match the diode impedance for efficient power transfer. However, a higher impedance makes it even more difficult to achieve the $RC \sim 0.1$ fs required to follow optical frequency oscillations. Therefore it is not clear that much can be gained by changing the antenna impedance [16].
2. *Capacitance*. The antenna usually contributes less capacitance to the rectenna system than does the diode. Providing an inductive load would help compensate the diode capacitance over a limited frequency range, as discussed in Sect. 1.6.1.
3. *Polarization*. The antenna must efficiently capture all polarizations. This has been achieved with structures such as the spiral optical antennas described in Chap. 11.
4. *Arrays*. In forming solar rectenna panels, arrays of rectennas will have to work 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 Sect. 1.3, at most a few antennas can feed each diode.
5. *Concentration*. Lenses or other concentrators can be used to increase the intensity received by each antenna. However, the area for each concentrating lens cannot be larger than the coherence area for sunlight.

Chapter 11 provides an overview of optical antenna technology and Chap. 12 describes the efficiency limits for specific antenna materials. Chapter 13 analyzes extending optical antennas into the range of nonlinear operation and examines the effects on impedance.

1.8 Power Conversion Efficiency

The calculation of the power provided by a rectenna solar cell for a given incident intensity is quite different than for a conventional solar cell. There are multiple loss mechanisms for each part of the rectenna process, such that the overall power conversion efficiency is the product of the efficiencies for each step (listed in Chap. 2). These include the antenna efficiency, the coupling efficiency between the antenna and the diode, the rectification efficiency, and coupling efficiency between the diode and the load. The antenna–diode coupling efficiency is a function of the impedances of these elements and is covered in Sect. 1.5.

The rectification efficiency is a function of the diode responsivity $\beta = I''/2I'$, which describes how much current is produced per unit incident optical frequency power. It is quantum limited to one electron per photon, e.g., for 1 eV photons the maximum responsivity is 1 A/W. The other factor in the rectification efficiency is the reverse-bias leakage, covered in Sect. 1.5.3.

The rectification efficiency is quite different for monochromatic as compared to broadband illumination. For monochromatic illumination the ultimate efficiency limit is 100 %. This corresponds to a current of one electron per incident photon and an operating voltage equal to $\hbar\omega/e$ [17]. For broadband illumination there are several different approaches to calculate the ultimate efficiency limit for rectenna solar cells, each of which provides different insights and answers [33]. In the following section I cover some of the most helpful approaches to calculating the ultimate efficiency along with two ways to potentially improve the efficiency by making use of infrared radiation.

1.8.1 Landsberg Efficiency

The radiation from a blackbody source carries entropy due to its spectral distribution. Therefore the ultimate conversion efficiency for this radiation is lower than the Carnot efficiency for a source of the same temperature. It is given by the Landsberg efficiency [34] and is approximately 93 % for the sun modeled as

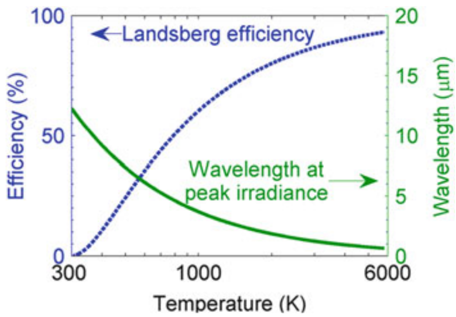

Fig. 1.6 Landsberg efficiency (*dashed line*) and wavelength at peak of irradiance (*solid line*) as a function of blackbody temperature. The peak wavelength is defined for fractional bandwidth normalization [35] (Courtesy of Sachit Grover [36])

a 5,800 K blackbody, as plotted in Fig. 1.6. This provides the ultimate efficiency for any conversion of solar energy, but provides no insights that are specific to rectenna solar cells. Also shown is the wavelength at the peak of the irradiance curve.[2]

1.8.2 Intermediate Absorber (and Thermophotovoltaics)

In this model the sun heats up an absorber which, in turn, radiates a lower temperature blackbody spectrum onto the solar cell. For solar radiation a maximum conversion efficiency of 85 % corresponds to an intermediate absorber temperature of 2,544 K [37]. In a rectenna, as the antenna does not heat up, but rather converts the incident photons into surface plasmons having the same energy, there is no intermediate absorber.

This limit does apply, however, to a thermophotovoltaic (TPV) rectenna solar cell, as discussed in Chap. 17. In TPV, concentrated sunlight heats an absorber to high temperatures so that its emission can be absorbed by narrow bandgap semiconductor solar cells and converted to DC power. There is a symbiosis between TPV and rectenna solar cells that might be exploited. In conventional TPV, because the absorber has a lower temperature than the sun, the peak of its blackbody radiation is at a lower photon energy, as shown in Fig. 1.6. This necessitates a narrow bandgap semiconductor solar cell to convert the infrared radiation, and such materials are difficult and expensive to fabricate. In contrast, rectenna solar cells are easier to fabricate and operate more efficiently for longer wavelengths, because the lower frequency of the light relaxes the *RC* time constant requirements. In addition, because rectennas can harvest low frequency radiation the intermediate absorber can operate at a lower temperature than for conventional TPV. This makes the TPV system design easier because the lower temperature requires less solar concentration, and lower temperature materials are adequate.

[2] In the usual spectral plots, the photon energy of the peak is not unique and depends upon the normalization—irradiance per unit wavelength or irradiance per unit photon energy. Therefore, a universal normalization of irradiance per unit fractional bandwidth [35] is used here instead.

In this way, TPV is made easier to implement by using rectenna infrared harvesters, and the rectenna's job is made easier by the lower frequency TPV radiation. Another advantage of this combination is that rectenna solar cells are expected to be lower cost than conventional infrared solar cells, which reduces the system cost and allows for a larger area within the TPV system to be covered by rectenna solar cells than would be cost-effective to cover by more expensive semiconductor solar cells. Still another advantage has to do with filtering. TPV systems gain efficiency by recycling unused photon, which are reflected to heat the intermediate absorber. With rectennas the filtration process can be provided by the antennas, which are essentially frequency-selective absorbers, allowing the nonabsorbed photons to be reflected back to the absorber. The marriage of rectenna solar cells and a TPV system has much to recommend it, and a host of technical difficulties to surmount to make the technology practical. A major difficulty has to do with the coherence of the radiation, as discussed in Sect. 1.8.4.

1.8.3 Broadband Efficiency Limit

To efficiently harvest the solar spectrum, what is needed is a "photon homogenizer." As presented in Sect. 1.4.4, optimal efficiency can be obtained for an operating voltage equal to $\hbar\omega/e$, with a current of 1 electron per incident photon. This condition can, in principle, be met with monochromatic illumination. With broadband solar illumination each band of frequencies would require its own operating voltage, but the device can operate at only a single voltage. Therefore much of the light cannot be used efficiently.

If this constraint applies to rectenna solar cells then they would be subject to the Trivich–Flinn efficiency limit [1] of 44 %. In conventional solar cells this limit results from the need of solar cells to operate with a single bandgap energy. Here the limit would result from the need to operate at single operating voltage, with identical consequences.

One way to avoid this limit would be to operate at a voltage $\hbar\omega/e$ corresponding to a value of $\hbar\omega$ at the low photon energy end of solar spectrum. Some sort of photon splitter would then be required to take a wide spectrum of photons and cut them down to low energy, where they could all be harvested by a rectenna operating at a low voltage. In practice, such a down-conversion process might be accomplished by an intermediate absorber in a TPV system, described in the previous section. Alternatively, it could be accomplished using a phosphor that emits multiple low energy photons for each high energy photon absorbed. I do not know of any material that would provide that function efficiently.

Another way to avoid this limit would be to operate at a voltage $\hbar\omega/e$ that corresponds to a value of $\hbar\omega$ at the high photon energy end of spectrum. This would require some sort of photon combiner, which would combine photons together. The nonlinear characteristics of a diode do, in fact, perform this mixing function, producing sum and difference frequencies and harmonics. It occurs all the time for microwave rectennas, where the operating voltage is much larger than $\hbar\omega/e$ for microwave frequencies, and power conversion efficiencies in excess of 60 % have been demonstrated [38]. Low photon energy and large photon flux is required to meet the condition for effective mixing. The question is whether this can be accomplished for higher photon energy, lower photon flux solar radiation.

The broadband efficiency limit is calculated in Joshi et al. [17] and Chap. 3. The calculation was accomplished by taking the inverse Fourier transform of the solar spectrum and using PAT theory (described in Sect. 1.4.2) to determine the rectenna output. The result is 44 %, the old Trivich–Flinn efficiency limit, meaning that insignificant photon homogenizing—splitting or combining—takes place. Because of the low solar flux, mixing is negligible.

The 44 % number does not include inevitable losses due to re-radiation from the solar cells. Just as the Shockley–Queisser efficiency limit [2] for semiconductor solar cells is lower than the Trivich–Flinn limit [1], a thermodynamic analysis is needed to supplement the analysis of quantum limits presented in this section, and will result in an efficiency number that is lower than 44 %.

The conversion efficiency of rectenna solar cells can exceed the 44 % limit given above if the spectrum is split and channeled to different rectennas, just as multijunction solar cells can improve the efficiency of conventional bandgap solar cells. To achieve this, the operating voltage for each rectenna should be set to a negative voltage with a magnitude just below $\hbar\omega/e$ for the optical frequency band of interest. The size of the antenna should be adjusted for the wavelengths of interest.

1.8.4 Waste Heat Harvesting

Just as in the case of using infrared rectennas in TPV systems described in Sect. 1.8.2, infrared rectennas can be used to harvest waste heat, subject to the efficiency limit shown in Fig. 1.6.[3] In addition to usual challenges in forming efficient rectennas, the need for coherence creates a severe constraint, as described in Chap. 4. The source of the waste heat is likely to be large and close to the rectenna, so that the solid angle it subtends is large. This results in a coherence area that is smaller than the diffraction limit for the wavelengths of interest. To make waste heat harvesting work with rectennas will require innovations in increasing the coherence of the radiation and/or reducing the antenna size.

There has been some discussion in the literature of using infrared rectennas to harvest heat radiated from the earth's surface. This cannot be accomplished with ambient-temperature solar cells due to the second law of thermodynamics, as can be seen in Fig. 1.6.

Could one instead use infrared rectennas for harvesting the long wavelength end of the solar spectrum, which is inaccessible to conventional photovoltaics? This

[3] It appears that energy recycling in TPV raises the limiting efficiency from the Landsberg efficiency to the Carnot efficiency, as pointed out by Pat Brady.

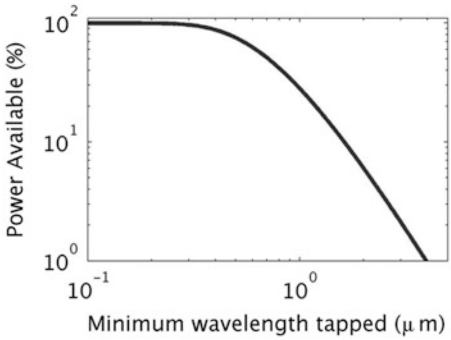

Fig. 1.7 Maximum power available in the solar spectrum as a function of the minimum wavelength that is tapped (Courtesy of Sachit Grover [36])

would somewhat relax the *RC* requirements for rectification. Figure 1.7 helps us answer the question. Reducing the RC requirements by roughly a factor of 10 from that for visible light harvesting, to minimum wavelength of 3 μm, would reduce the available power to just 1 % of the total for the solar spectrum. Even making the low wavelength cutoff 1 μm would reduce the available power to 28 % of the total. There is little to be gained by harvesting only the red end of the solar spectrum. On the other hand, it might make sense to use infrared rectennas to form the long-wavelength-converting cells in a spectrally split multicolor solar system.

1.9 Commercialization

Rectenna solar cells have the potential to be less expensive than conventional solar cells. Only relatively low-cost materials are required. The metal and insulator layers are in the form of very thin films and do not need to be epitaxial. The substrate can be inexpensive plastic or glass, which can instead form a transparent superstrate that provides the dual function of supporting the rectenna structure and protecting it from the elements.

The antenna and diode structures do require submicron lithography to pattern them. For research devices, the fabrication process is slow and expensive, using electron-beam lithography. For large-scale production, however, this can be accomplished by nanotransfer or nanoimprint technology. Demonstration of this process applied to the fabrication of both diodes and antennas is described in Chap. 14. Extending the process to roll-to-roll fabrication is described in Chap. 16.

1.10 Rectenna Solar Cell Prospects

At this time there are no rectenna solar cells. Devices that exhibit detection or power harvesting at tiny conversion efficiencies have been demonstrated at terahertz and infrared frequencies, but nothing that one could in good conscience call a solar cell. So will there be successful rectenna solar cells in the foreseeable future?

The chart that forms Fig. 1.8 shows how the best solar cell efficiencies have risen over the years. Given our experience with other photovoltaics technologies it is not reasonable to expect rectenna solar cells to exceed conventional solar cell efficiencies immediately. Will rectenna solar cells follow the gradually rising trajectory of other photovoltaics technologies? Will it ultimately provide higher efficiency at a lower cost?

Rectenna solar cell technology has several factors in its favor:

1. The ultimate efficiency is at least as high as that of semiconductor solar cells and possibly higher. As discussed in Sect. 1.8, without a "photon homogenizer," i.e., without down-converting or mixing, the ultimate efficiency is 44 %, the same as the ultimate efficiency for bandgap solar cells. Mixing does occur in microwave rectennas, and down-converting does occur in TPV systems, and so it is not out of the question to achieve this in rectenna solar cells. If so, the ultimate efficiency could rise.
2. Multicolor cells can raise the efficiency in rectenna solar cells, just as multijunction solar cells can raise the efficiency of conventional solar cells. In conventional solar cells this requires incorporating semiconductors having different band gaps, which can introduce incompatibilities and be expensive. It is simpler and less expensive to achieve this with rectennas because all that is required to change the wavelength of peak sensitivity is to shift the operating voltage and possibly tweak the size of the antenna.
3. The materials for rectennas are available, and in thin film form, are inexpensive. The processing can be inexpensive, using nanoimprint and roll-to-roll technologies, as described in Sect. 1.8.4.
4. Thermophotovoltaics and infrared rectennas are natural partners, as described in Sect. 1.8.2. If direct conversion of the solar spectrum cannot be achieved using rectenna solar cells, it may be possible to accomplish the conversion with TPV.
5. Another infrared conversion application, waste heat harvesting, is more easily accomplished by rectennas than visible light harvesting, because the lower optical frequency loosens the *RC* time constant requirements. Conventional solar cells cannot convert these long wavelengths, and the competition, which is thermoelectric devices, are expensive and relatively inefficient.

On the other hand, rectenna solar cell technology development faces some substantial hurdles:

1. For visible light frequency rectification the *RC* time constant must be no larger than ~0.1 fs. As discussed in Sect. 1.5.2, for a diode that matches an antenna resistance of roughly 100 Ω, it is very difficult to provide a sufficiently small capacitance. Planar MIM diodes cannot achieve this. There may be other diodes on the horizon, such as the traveling-wave diodes, sharp-tip diodes, and geometric diodes discussed in Sect. 1.6, that can circumvent the *RC* limitations of parallel plate diodes.

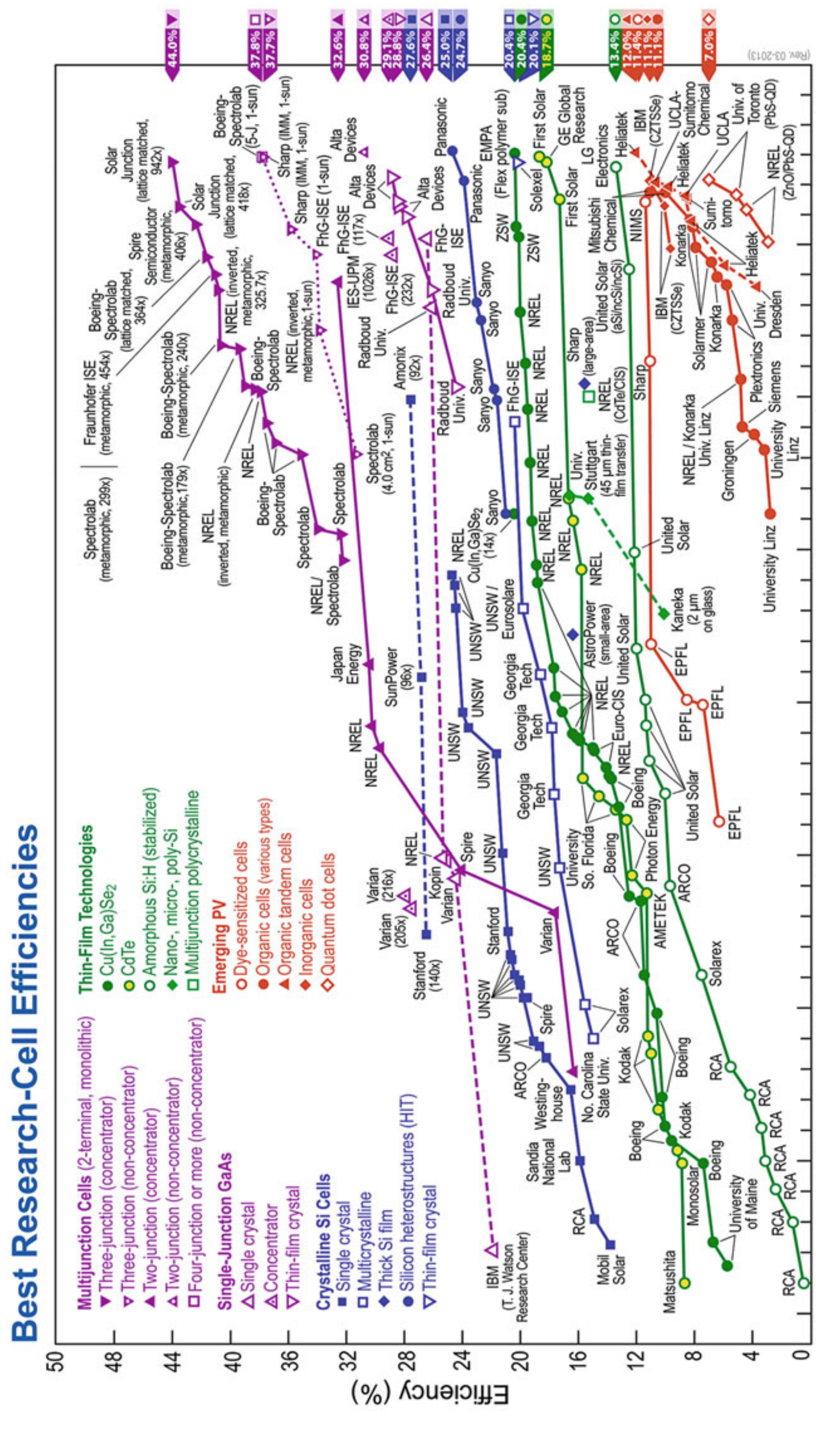

Fig. 1.8 Best efficiencies for research solar cells versus year. Each *curve* represents a different technology. Each successful technology has required at least a decade, and often two, to mature (Courtesy of the National Renewable Energy Laboratory)

2. The diode reverse-bias leakage must be less than 1 μA as discussed in Sect. 1.5.3. This is a challenge to accomplish while simultaneously meeting the *RC* requirements described just above.
3. Compared to the diodes, the challenges for the optical antennas are closer to being met, but still substantial. Meeting the following conditions simultaneously is not easy: Absorbing all incident polarizations efficiently, while maintaining a constant impedance to match that of the diode, while keeping resistance losses low at visible light frequencies where metals become resistive. Including plasmonic enhancements has the potential to improve not only antenna performance but also the diode's as well.

It is clear that rectenna solar cells are in an early stage of development. It will require technical innovations to achieve even moderate conversion efficiencies, and then more sophisticated analysis and development will be required to achieve practical efficiencies. Only recently has an understanding of the quantum rectification process and concomitant efficiency limits come together. Combining this theoretical understanding with advancing nanolithography and thin-film materials will make the development of practical rectenna solar cells an exciting venture and quite possibly a rewarding one.

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