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Solar power conversion using diodes coupled to antennas

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In the developing technology of rectenna solar cells, light is received as electromagnetic waves in micro-antennas and converted to direct-current power using ultra-high frequency nano-scale diodes.

Semiconductor solar cells have improved over the years but are subject to some fundamental limitations. Long wavelength light is not absorbed, and short wavelength light is only partially used, leading to maximum conversion efficiencies below approximately 30%. Multi-layer cells can improve upon that, but with additional complexity and cost. Semiconductor solar cells also require costly refined materials and transparent conducting layers. These layers are required to make electrical contact with the illuminated side of most solar cells and typically incorporate indium, a limited and expensive resource.

Antenna-coupled diode solar cells, also called rectenna solar cells, work on an entirely different principle, much like a crystal radio receiver but for light. Incoming solar radiation (electromagnetic waves) is received by sub-micron-size antennas, which convert it to ultra-high-frequency alternating current (AC). This current passes through a nanometer-scale, ultra-high-frequency diode, which converts the AC to direct current (DC) and provides usable power (see Figure 1). A solar cell would incorporate a large array of millions of these elements in tandem deposited onto a glass or plastic substrate. Fabrication costs can be low, with devices processed cheaply in a roll-to-roll process.[1]

In principle, the conversion efficiency for rectenna solar cells can be very high, limited to 93% by the entropy of the photon gas,[2] but other constraints limit the efficiency to well below this number. The demands placed on the diode are extreme. First, it must operate efficiently at extremely high frequencies—close to a petahertz (10^{15}Hz) for visible light—orders of magnitude higher than the fastest electronics. Second, it must couple electrical power efficiently from the antenna. To do so, the impedance (a measure of the ratio of the voltage magnitude and phase to that of the current in an electronic element) of the diode must match the low impedance of the antenna. Unfortunately, the two requirements conflict with each other. An additional challenge for rectenna solar cells is power loss in the antenna, because, at petahertz frequencies, metals become very resistive. One possible solution is to use dielectric antennas.[3]

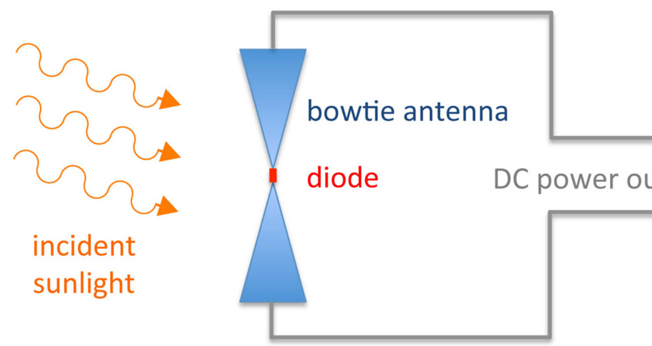

Figure 1. *Rectenna solar cell. The antenna converts incoming solar radiation to a petahertz alternating current through the diode, which rectifies it. The resulting direct-current (DC) power is available at the output leads.*

A particular implementation for rectenna solar cells was patented in 1984.[4] In a project led by ITN Energy Systems,[5] our group developed metal/insulator/metal (MIM) diodes for rectenna solar cells.[6] MIM diodes make use of femtosecond-fast transport of electrons tunneling through a nanometer-thick insulating region. By adding a second insulating layer, we can enhance the device nonlinearity.[6,7] An example of an MIM diode coupled to a bow-tie antenna for terahertz operation is shown in Figure 2. Extending the response to efficient power conversion at visible (petahertz) frequencies is problematic. To be fast, the diode capacitance must be small. For a device such as an MIM diode, which is sandwiched between two electrodes, the device area must be small, well below $1\mu m^2$. However, for a diode to have a low resistance, it must pass a large current at low voltage, which corresponds to a large area. The conflicting area requirements are fundamental and, so far, have precluded the use of MIM diodes for direct solar conversion.[8]

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10.1117/2.1201108.003807 Page 2/3

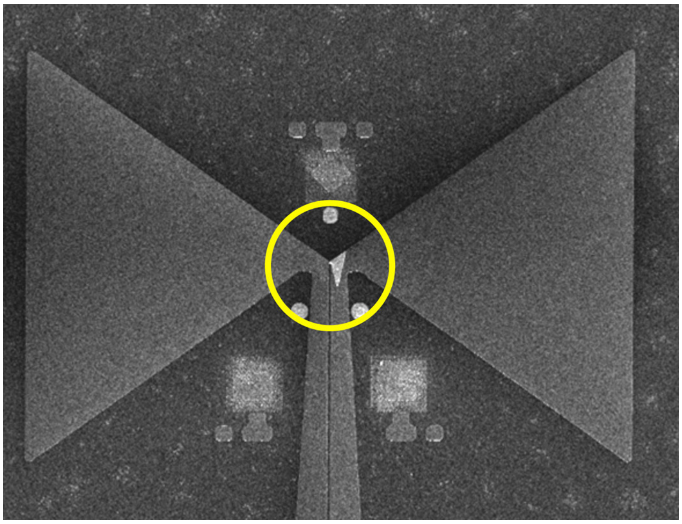

Figure 2. *Metal/insulator/metal diode rectenna. The 300nm×300nm niobium/niobium pentoxide/niobium diode is formed at the tiny overlap region at the center of the yellow circle. The bow-tie antenna was designed to receive terahertz radiation.*

A completely different approach is a device we call a geometric diode. In a conductive material, charge carriers move unimpeded for a mean-free path length (MFPL) until they collide with a defect (a thermal vibration or a surface). A geometric diode consists of a thin film with an asymmetric structure no greater in size than the MFPL—see Figure 3(a)—in which charge carriers move more easily to the left than to the right. This planar structure avoids the capacitance/resistance tradeoff because it is not a sandwich structure. Made out of a conductive material, it can have both low resistance and ultra-low capacitance. The challenging part is that the MFPL tends to be tiny, requiring ultrafine lithography to form the device. For metals, the MFPL is only a few nanometers, but for graphene films it can be hundreds of nanometers or more. For that reason, we make our geometric diodes from graphene: see Figure 3(b).

Developing an efficient rectenna solar-cell technology is a major undertaking. A key challenge, providing a diode that can convert the petahertz frequencies of visible light to DC *and* couple efficiently to antennas, cannot be met by conventional technologies. We presented a new device that may provide the solution, the geometric diode. Specifically, we demonstrated a geometric diode that works in converting IR light (corresponding to 28THz) to DC, but much development remains. The materials and the structure of geometric diodes will have to be improved to form a practical rectenna solar-cell diode technology. Even the basic theory of operation needs more work, because at petahertz frequencies it must be analyzed using

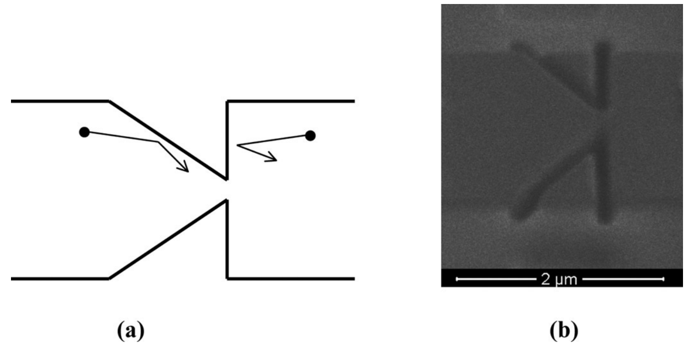

Figure 3. *(a) Charge carrier motion in a geometric diode. Charges moving to the right are funneled through the constriction, while charges moving to the left are more likely to be reflected back. The asymmetric conduction occurs only if the neck is no larger than the charge-carrier mean-free path length. (b) Graphene geometric diode. The graphene is the dark-grey horizontal strip. In this device, the neck size is 200nm.*

quantum mechanics, with very different characteristics from the classical AC-to-DC converters that we are used to. These aspects represent the focus of our future work.

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