Optical Rectenna For Direct Conversion Of Sunlight To Electricity

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ABSTRACT

ITN Energy Systems is developing a next generation, high efficiency direct conversion device (DCD) that converts available electromagnetic radiation (i.e. solar spectrum) directly into electric power. ITN's DCD consists of an optical antenna that efficiently absorbs incoming radiation and couples the energy into a high-speed quantum tunneling diode. In contrast to traditional single junction semiconductor PV that are fundamentally limited (~30%) by the band gap and the match of the band gap to the solar spectrum, conversion efficiencies >85% are theoretically possible with ITN's DCD. ITN has demonstrated conversion efficiencies >50% using lower frequency arrays with wire bonded COTS Schottky diodes. All aspects of the DCD array are scaleable to THz frequencies required for photovoltaic applications. The key challenge to making ITN's DCD commercially viable as a solar energy converter is further development of high frequency MIM diodes. We will present a brief overview of the program concept, goal, and progress-to-date.

1. Concept

ITN's direct conversion device (DCD) consists of two key elements: 1) An optical antenna to efficiently absorb the incident solar radiation, and 2) A high frequency metal-insulator-metal (MIM) tunneling diode that rectifies the AC field across the antenna providing a DC power to an external load. *The combination of a rectifying diode at the feedpoints of a receiving antenna is often referred to as a rectenna*. Rectennas were originally proposed in the 1960s for power transmission by radio waves.[1] Later, concepts were proposed to use rectennas for photovoltaic applications (optical rectenna).[2]

Early optical rectenna concepts were based on simple scaling of microwave antenna theory and the proof-of-concept was never demonstrated. Non-optimized element design, impedance mismatch between components, inefficient rectifying junctions, and lack of state-of-the-art nanopatterning may have all contributed to their unsuccessful attempts. In related research programs, ITN has been working extensively in developing antenna arrays with more realistic scaling relationships and more efficient diodes.

As discussed below, we have made great progress in demonstrating the feasibility of both the antenna arrays and MIM diodes. Current development indicates that MIM diode development is the main limiting factor that is preventing the optical rectenna from becoming a commercially viable next generation photovoltaic device.

1. Antenna array

As a means for capturing the abundant energy from solar radiation, an antenna is the ideal device since it is an efficient transducer between free space and guided waves. In the case of conventional PV cells, solar radiation is only absorbed if the photon energy is greater than the band gap. Because the band gap must also be tuned to minimize the excess energy lost to heat when the photon energy is significantly above the band gap, a significant portion of the incident solar energy, up to 24%, is not absorbed. In contrast, an antenna array can efficiently absorb the entire solar spectrum with nearly 100% efficiency theoretically possible (efficiencies greater than 96% have been predicted for realistic systems with ITN's models). Rather than generating single electron-hole pairs as in the PV, the electric field (E) from an incident electromagnetic radiation source will induce a time changing current (i.e. wave of accelerated electric charge) in a conductor. Efficient collection of incident radiation is then dependent on resonance length scales and impedance matching of the antenna to the diode to prevent losses.

In addition, for solar energy conversion the antenna must be designed to couple with a fairly complex waveform- best described as a broadband, time varying arbitrarily polarized wave. In previous work, ITN, in collaboration with the University of Colorado, has developed and experimentally validated sophisticated models to enable design of antenna structures to meet these strict criteria.

To demonstrate the high absorption efficiencies possible with antenna arrays, we have fabricated dipole rectenna arrays to operate at 10 GHz. The results show that these arrays can operate at very high conversion efficiencies, > 50%, limited only by saturation of the Schottky diodes. Because the results were obtained using inexpensive, COTS Schottky diodes, we expect much higher efficiencies (>85%) could be demonstrated with higher quality diodes. In addition, we have used the lower frequency rectenna arrays to address coupling to complex waveforms (elliptical polarization and broadband solar radiation source). The grid array, shown in Figure 1, meets all the criteria with efficiency demonstrations comparable to the linear dipole arrays. These results show that the design of high absorption efficiency optical antenna arrays is quite feasible.

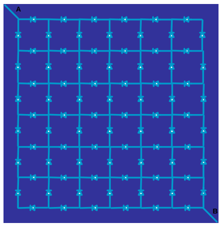

Figure 1. Grid arrays design.

2. Metal-Insulator-Metal (MIM) Diodes

As with the antenna, we must overcome the band gap limitations of the PV conversion device to achieve high conversion efficiencies. With PV, each photon above the band gap, regardless of photon energy, generates a single electron-hole pair, which delivers an energy proportional to the band gap to the load. A photon far above the band gap still delivers the same energy as a photon exactly matched to the band gap, with the excess energy lost as heat. In contrast, a sufficiently ideal non-linear metal-insulator-metal (MIM) diode can circumvent this limitation by operating as an ideal quantum detector in which the voltage at which photogenerated carriers are delivered to the external circuit increases linearly with frequency. The energy delivered to the load can then be as high as the photon energy, for all photon energies.

For high frequency diodes, the limiting factor is typically parasitic capacitance. Historically, Schottky diodes have been limited to $\nu < 5$ THz, while MIM diodes have been used for over 25 years at frequencies down to $\nu \sim 150$ THz (2 μm); currently being extended farther into the IR and optical. State-of-the-art MIM diodes, however, are typically limited by two factors: 1) Integration and stability of the point contact configuration 2) Zero bias response; an external bias is required on most MIMs developed to date to achieve sufficiently ideal diode behavior. The key then is to develop planar MIM diodes that are sufficiently non-linear and asymmetric to have good responsivity with no external bias applied.

To guide this development, ITN, in collaboration with NIST, has established and experimentally validated a tunneling model to predict the dark J-V characteristic of MIM diodes. As shown in Figure 2, the tunneling conductance is a function of the barrier height (ϕ_1), barrier width (d), and difference in metal work functions ($\Delta\phi$). Diodes with very high non-linearity and asymmetry, with a high zero bias responsivity, can be achieved.

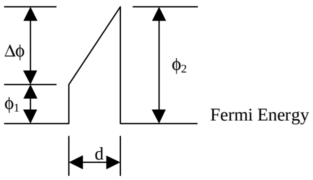

Figure 2. Model Parameters.

Using analogies from superconductor-insulator-superconductor (SIS) tunnel diodes[3], the model was expanded to predict the illuminated response of MIM diodes. An interesting observation is the appearance of "photon-steps"[4] in the illuminated I-V characteristics (see Figure 3). Essentially, the photon-energy acts as an additional bias on the diode resulting in the diode turn-on voltage shifting by an energy $h\nu/e$ from its dark I-V position. These "photon-steps" enable the output voltage of the diode to scale linearly with the incident frequency. A MIM diode with sufficient non-linearity, asymmetry, and zero bias responsivity can therefore lead to an optical rectenna with very high efficiency.

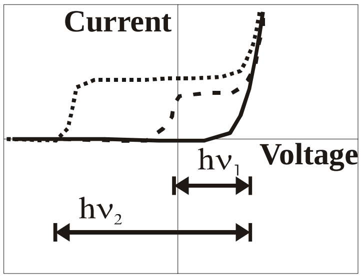

Figure 3. Schematic illustration of "photon-steps."

We have extensively studied the Nb/NbOx/Ag system. Although very small devices (~ 50 nm x 50 nm) are required to minimize parasitic capacitance at THz frequencies, much of the processing and development work can be done at larger scales (micron) where processing is easier. Highly nonlinear, asymmetric devices with a high zero bias responsivity have been demonstrated at these length scales. At the higher frequencies, nanometer scaled MIMs have been fabricated and, in collaboration with NIST, we have demonstrated room temperature optical rectification with an unbiased planar MIM diode. Unfortunately, the processing issues are much more complex for the smaller devices. The dark I-V characteristic of the nano-devices are not nearly as non-linear or asymmetric as the "ideal" micro-MIM devices fabricated. Impedance mismatch between the antenna and diode have also limited the efficiency of these devices.

2. Progress-to-Date

In the "Beyond the Horizons" program, we are proposing to optimize planar MIM diode performance for incorporation into ITN's DCD technology. In our previous research experience, we have learned that sufficient control over several processing parameters, i.e. interface integrity and uniform barrier formation, are key to optimization of the planar MIM structure. We have added an ion beam deposition system and small cluster tool that will allow us better control of film microstructure and controlled tunneling barrier formation. To date, we have focused on optimizing dark I-V characteristics for crossing wire patterns (Fig. 4a) ranging in size from 100 to 500 nm square. Promising diodes will be monolithically integrated at the feedpoints of dipole antenna (Fig. 4b). Our first year goal (Sept. 2002) is to demonstrate the feasibility of high efficiency DCD technology operating at a single wavelength in the solar spectrum.

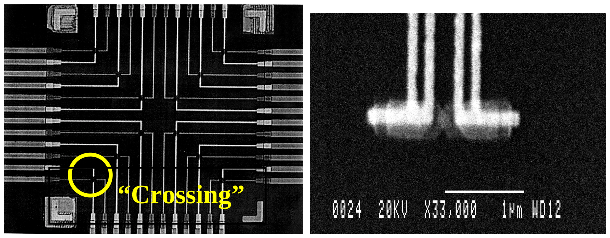

Figure 4. (a) Crossing wire MIM pattern and (b) MIM monolithically integrated into a dipole antenna.

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[1] W.C. Brown, *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-32, p:1230 (1984)

[2] A.M Marks, US Patent No. 4445050 (1984), B.J. Zwan, US Patent No. 4251679 (1981)

[3] J. Tucker, *IEEE Journal of Quantum Electronics*, vol. QE-15, p:1234 (1979)

[4] A.H. Dayem and R.J. Marti, *Physics Review Letters*, vol., 8, p:246 (1962)