Using Plasmonic Photonic Crystals to Produce Highly Efficient Thermophotovoltaic Solar Cells

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One of the greatest challenges facing humanity is accessing to safe, clean, and sustainable energy supplies. Sustainable energy supplies include all renewable sources, and new technologies that improve energy efficiency. Thermophotovoltaics (TPVs) covert heat differentials into electricity using a photovoltaic cell\(^1\). A basic TPV system consists of a thermal absorber, emitter and a photovoltaic solar cell. It has the advantages of fuel versatility (solar, nuclear, etc.), very quiet operation, low maintenance, and high power density. However, their energy efficiency is still very poor compared with other electricity-generating technologies. Currently, the biggest challenge for TPVs is to increase the system efficiency while lowering the cost. One solution to improving the efficiency could be tailoring the spectrum of the emitter to match the peak response of the photovoltaic cell such as using photonic crystals\(^2\).

Here we proposed using plasmonic photonic crystals as thermal emitter to produce highly efficient TPV solar cells. Plasmonic photonic crystals, such as metal-insulator-metal (MDM) structure\(^3\), manipulate the surface plasmon polariton (SPP) fields and resonant at certain wavelengths through a defect in the crystal. The plasmonic crystals can be designed to tailor both the emission spectra by changing the structural parameters, such as periodicity, hole sizes, and dielectric thickness. An emitter structure can be optimized to emit most of its power right above the bandgap of the photovoltaic solar cell to maximize the efficiency. To increase the heat absorption, we used nano-cones/pyramid structures as thermal absorber to enhance the optical absorption. Figure 1 shows the basic structure of our proposed TPV. It includes the thermal absorber which can absorb effectively most of the thermal radiation, and the plasmonic photonic crystal structure as the emitter to selectively emit the light.

\(\text{Figure 1 Our proposed thermophotovoltaic structure}\)
Gallium Antimonide (GaSb) photovoltaic has an energy bandgap of 0.72eV at room temperature\(^4\), which is corresponding to the wavelength of about 1.72 \(\mu\)m. Figure 2 is the blackbody radiation spectra at different temperatures. To maximize the emissivity of the emitter, the peak wavelength of the radiation should be around the bandgap of GaSb photovoltaic. So, the temperature of the emitter should be around 1700 K. The reason that we selected GaSb instead of other semiconductor materials is that GaSb has a relatively small bandgap, which is in the infrared region. So the temperature of the emitter doesn’t need to go too high.

3D finite-difference time-domain (FDTD) methods were used to model the emissivity of the thermal absorber and plasmonic emitter structure. High performance computing system (Quest)\(^5\) at Northwestern University has been used to satisfy the huge memory and time requirements of the 3D FDTD simulations. Figure 3 shows one of the simulation results of the proposed Tungsten absorber structure. It shows a very high emissivity over a broad wavelength spectrum, and therefore, it can effectively absorb most of the visible and infrared light. Figure 4 is the simulated emissivity spectrum of the proposed emitter structure. By changing the period, the peak of the emitted spectrum could be changed. With the periodicity of 1.5 \(\mu\)m the peak emissivity wavelength is matching the bandgap of GaSb cell.
To fabricate the emitter, our low-cost, parallel nanofabrication technique, Superlens Lithography, was used to pattern a large area of uniform nanoholes perforated in Tungsten and AlN layers. Tungsten was used because it has a high enough melting point, while AlN and W have a very small thermal coefficient difference. Figure 5 shows the microspheres array used as superlens to focus UV light and generate the nano-holes array. The empty spot missing one microsphere can be used to generate a cavity spot. In parallel, focal ion beam (FIB) milling were also used to drill the nanoholes in a small area to compare the results. Figure 6 shows the emitter structure fabricated by FIB milling.

Future research direction will be assembling the structures into TPVs system with GaSb solar cell, and measuring the efficiency of the new TPV system.

References:

5. See Quest website: http://www.it.northwestern.edu/research/adv-research/hpc/quest/