Ultra High Efficiency Thermo-Photovoltaic Solar Cells Using Metallic Photonic Crystals As Intermediate Absorber and Emitter

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B. Abstract

Our team aims to combine large-scale numerical simulations, with nanofabrication and characterization to develop the efficient intermediate absorbers and emitters that enables high efficiency solar thermo-photovolatic systems. In this year, continued progress has been made in developing designs that enable high efficiency TPV cells, as well as in experimental setup for fabricating and measuring of such devices.

C. Introduction

Thermal Photovoltaic (TPV) solar cells, where solar radiation is absorbed by an intermediate, which then emits thermal radiation towards a solar cell, is capable of achieving an extremely high efficiency using single-junction solar cells. The theoretical efficiency of 85% far exceeds the Shockley-Queisser limit. In order to approach such efficiency, however, there are very important constraints on the properties of the intermediate absorber and emitter. Until now, there is no known way to meet the requirements on the intermediate that are needed in order to reach efficiency beyond 30%.

The aim of our project is to exploit emerging opportunities in the area of nanophotonic structure such as photonic crystals for TPV applications. It has been recently shown that both the absorption and thermal emission properties of nanophotonic structure can be tailored with appropriate design. Here, we aim to show that such structures can indeed be designed to enable ultra-high efficiency TPV solar cells. Specifically, we will demonstrate that crystal structures can be produced with low-cost self-assembly fabrication techniques using abundant materials such as Tungsten, that the crystals can provide broad-band absorption over the entire solar spectrum, and that the intermediate can be designed to enhance overall cell efficiency

D. Background

This project builds upon significant expertise and previous accomplishments that this group has in the design of nanophotonic structures (Fan), low-cost fabrication techniques (Braun), as well as experience in solar cell applications (Peumans).

E. Results

E.1. Solar TPV system analysis

Over the past year, we have published a paper in Optics Express[1], presenting detailed theoretical and numerical design for solar TPV system utilizing nano-photonic absorber and emitter. As a concrete example of an overall system design, we consider a cylindrical geometry as shown in Fig. 1. The system consists of a tungsten rod. The top surface of the rod consists of a square array of nano pyramid. We have shown previously that the use of pyramid's allows broad-band, wide-angle absorption over the entire solar spectrum[2]. Thus, such a structure functions as a highly efficient absorber for high solar concentrations. The side of the rod is surrounded by a concentric multilayer dielectric film, which is thermally insulated from the central rod with vacuum layers. The use of such multi-layers creates a narrow band thermal emission from the rod. The use of the rod geometry ensures that the emitter has a much larger area compared with the absorber, satisfying the fundamental thermodynamic requirement on the area ratio that is essential for solar TPV applications. Using this geometry, our theoretical analysis indicates that such a system, with an ideal single junction cell at 0.7eV bandgap energy, is able to produce efficiency that is higher than the Shockley-Queisser limit.

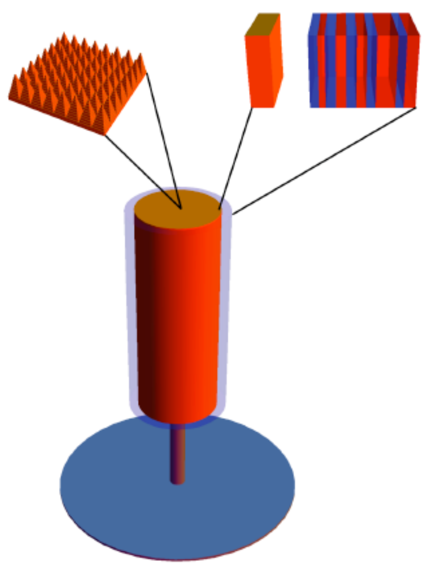

Fig. 1. A cylindrical geometry incorporating the Tungsten emitter and absorber that we have analyzed. The central Tungsten rod provides efficient solar absorber for sun light coming from the top, as well as thermal emission through the side of the rod. A concentric multi-layer dielectric film surrounding the rod is used to generate narrow-band thermal emission.

Our work represents the first realistic design of solar TPV absorber and emitter that enables one to overcome the Shockely-Queisser limit. This work should also provide strong stimulus to the experimental work in this area, some of which will be detailed in the sections below.

E.2. Nanofabrication

Over the past year, Braun has focused on methods for creating complex two and three dimensional structures inspired by Fan from refractory metals such as tungsten. The two dimensional structures are being formed using a microindentation of a polymer film using a modified AFM followed by sputter deposition of tungsten, and the three-dimensional structures are being fabricated via tungsten electrodeposition into complex three-dimensional templates, such as those formed by colloidal crystallization.

As an initial target, Braun's group is fabricating the tungsten pyramids proposed by Fan[2]. The pyramidal structure presents a number of complications when one considers the various standard fabrication technologies. Given the high aspect ratio and dense packing of the pyramids, it is difficult to create them through a traditional top-down lithographic strategy. We have thus decided to employ a much more flexible approach. In collaboration with Prof. W. King at UIUC, we are using nanoindentation to pattern a polymer film with a nearly arbitrary pattern which is limited only by the shape of the nanoindentor. Using a pyramidal shaped indentor, we create a polymer film consisting of a close-packed array of inverse pyramids, sputter tungsten into the inverse pyramids, electrodeposit additional metal on the back side to provide mechanical stability, and peal the resulting film off the polymer (Fig. 2). We are just beginning to interrogate the optical properties of these structures.

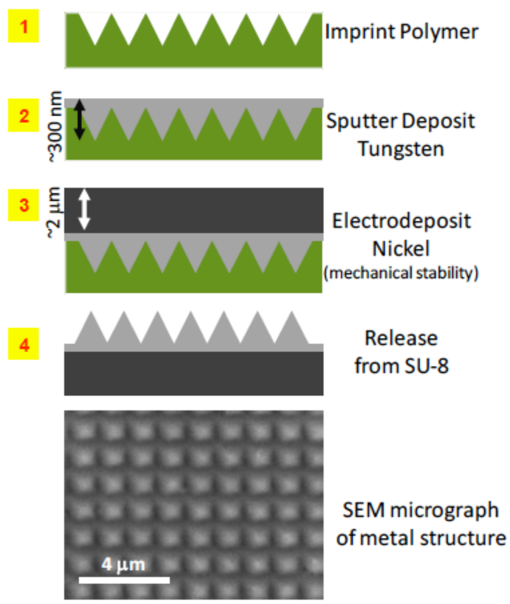

Figure 2. Process for creating metallic pyramids and SEM micrograph of the resulting structure.

Fabrication of 3D structures follows a considerably different pathway. First, a template with the desired inverse structure is formed. To date, we primarily form structures via colloidal crystallization, however should more complex designs be required, we can utilize optical holography. The open space in the template is then filled with a refractory metal such as tungsten via CVD or electrodeposition, and finally the template can be removed. See Fig. 3 for an SEM micrograph of a tungsten inverse opal created through this process.

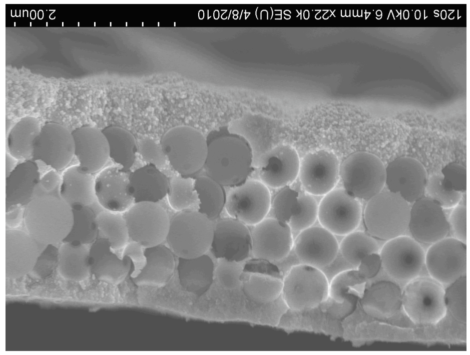

Figure 3. SEM of a tungsten inverse opal created by tungsten electrodeposition through a colloidal crystal followed by removal of the colloidal template.

E.3.   Measurement

Using the measurement facility that we have set up, as detailed in last year's report, we have started experimental measurement on thermal emission properties of nanophotonic structures. As an example, we have fabricated test stacks on stainless steel with layer structure (96nm MgF2/36nm TiO2/11nm Mo/33nm TiO2/150nm Mo/steel). These stacks were designed to have good spectral emissivity suppressing low-energy thermal emission. The experimental results for this stack are shown in Figure 4 below.

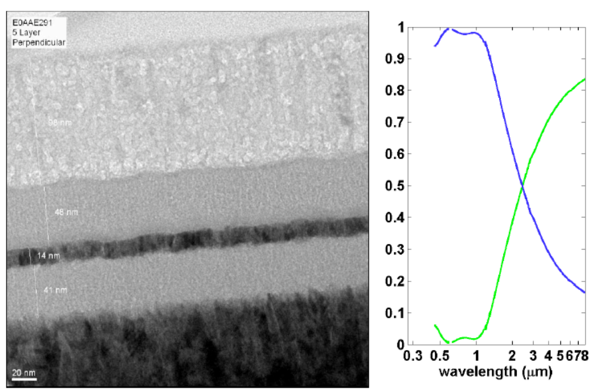

Figure 4. (Left) Cross-sectional TEM of the fabricated stacks. (Right) Emissivity (green) as a function of wavelength, showing the suppression of low-energy radiation.

F. Progress and future plans

On the nanofabrication side, Braun's group plans to continue to improve our fabrication processes to be able to match the structures simulated by Fan. Once the nanofabrication is completed, the whole team plans to measuring the radiation emitted by these structures at high temperature, using the facility that has already been set up in Peuman's lab, and begin assembling these materials into TPV devices.

G. Publications in this period

1. E. Rephaeli and S. Fan, “Absorber and emitter for solar thermo-photovoltaic systems to achieve efficiency exceeding the Shockley-Queisser limit”, Optics Express, vol. 17, no. 17, pp. 15145-15159 (2009).
2. N. P. Sergeant, O. Pincon, M. Agrawal, and P. Peumans, “Design of wide-angle solar-selective absorbers using aperiodic metal-dielectric stacks”, Optics Express, vol. 17, no. 25, pp. 22801-22812 (2009).
3. N. P. Sergeant, M. Agrawal and P. Peumans, High performance solar-selective absorbers using sub-wavelength gratings, Optics Express, vol. 18, no. 6, pp. 5525-5540 (2010).
4. M. Losego, H. Zhang, A. Gardner, W. P. King, P. V. Braun, “Nanoindentation as a Route to 3D Metal Nanostructures”, in preparation.

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I. References

[1] E. Rephaeli and S. Fan, “Absorber and emitter for solar thermo-photovoltaic systems to achieve efficiency exceeding the Shockley-Queisser limit”, Optics Express, vol. 17, no. 17, pp. 15145-15159 (2009).

[2] E. Rephaeli and S. Fan, “Tungsten black absorber for solar light with wide angular operation range”, Applied Physics Letters, vol. 92, art. No. 211107 (2008).