

# 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-photovoltaic 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*

The theoretical background of our project is based on a paper we published in *Optics Express*<sup>i</sup>, which presented 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<sup>ii</sup>. 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.

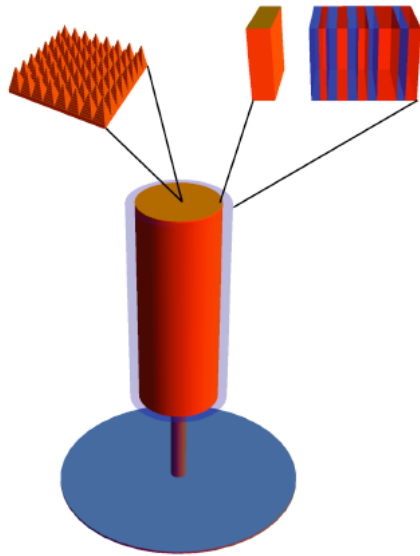


Fig. 1. A cylindrical geometry incorporating the Tungsten emitter and absorber that we have analyzed. The central Tungsten rod provides efficient solar absorber for sun light coming from the top, as well as thermal emission through the side of the rod. A concentric multi-layer dielectric film surrounding 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. Some of the current theoretical works aim to understand some of the

basic issues regarding fundamental entropy constraint of solar spectrum compression in these systems.

### E.2. Nanofabrication

Over the past year, Braun has focused on increasing the temperature stability of the two and three dimensional structures inspired by Fan from refractory metals such as tungsten. We have now demonstrated a tungsten photonic crystal, fabricated via template directed electrodeposition, which could be used as a selective emitter for thermophotovoltaics. Thermal stability up to 1400°C is demonstrated for the first time using a hafnium dioxide passivation layer (Fig. 2).

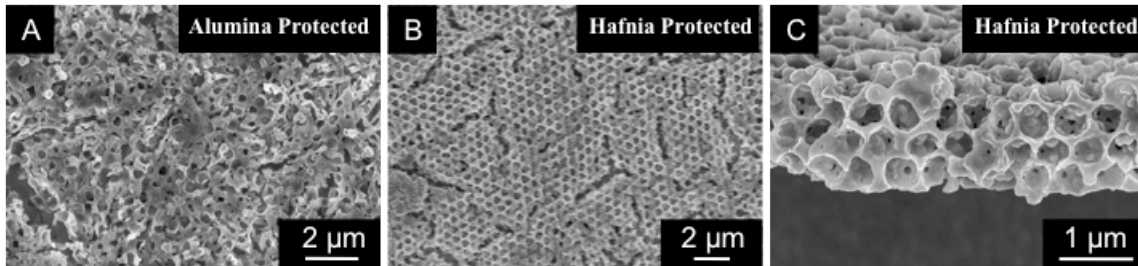


Figure 2. Tungsten inverse opals after heating to 1400°C for 12 hours. A) top surface of tungsten inverse opals protected with alumina. B) top surface and C) fractured cross section of tungsten inverse opals protected with hafnia.

Figure 3 describes the tungsten inverse opal fabrication procedure. A silica opal was used as a 3D template to direct the tungsten electrodeposition. The silica colloids were made using the well-known Stober method and the opals were assembled by vertical deposition. Before electrodeposition, the opals were coated with  $\text{HfO}_2$  by atomic layer deposition (10nm). The  $\text{HfO}_2$  was necessary to prevent lift-off from the tungsten substrate, and preserve the 3D order during electrodeposition. Following the tungsten deposition, the 3D silica/hafnia template was removed by HF etching (5% HF in 1:1 water:ethanol solution), and a fresh hafnia layer was deposited via ALD. Figure 4 shows a fracture cross-section of the as-deposited tungsten before template removal and a top view of the tungsten inverse opal after template removal.

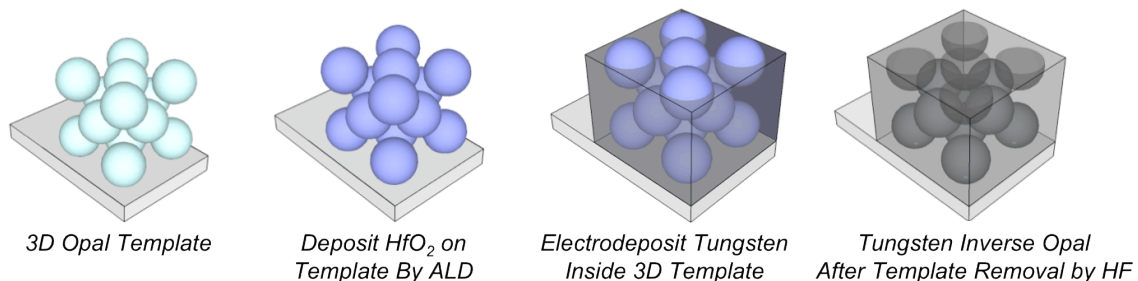


Figure 3. Process for creating thermally stable 3D tungsten structures.

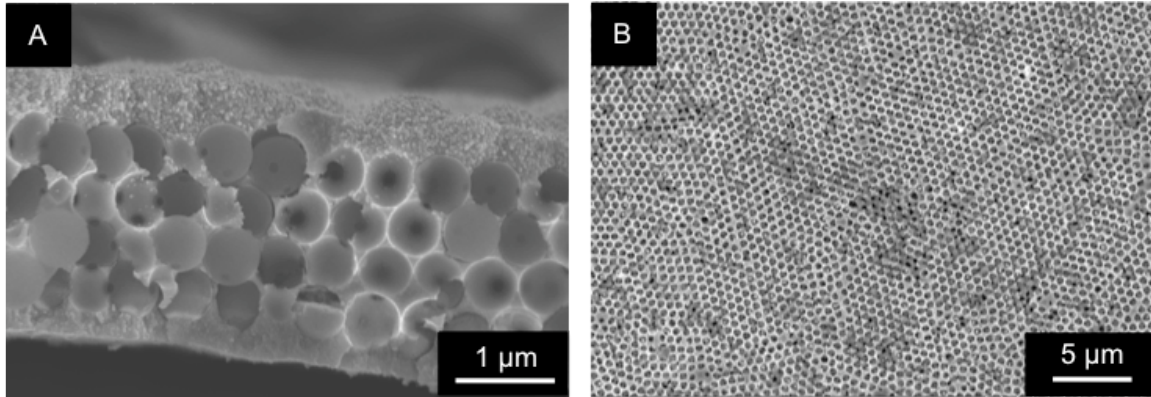


Figure 4. A) Fracture cross sectional micrograph after tungsten electrodeposition inside the 3D silica/hafnia template. B) Top surface of tungsten inverse opal after template removal by HF etching.

### E.3. Measurement

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 MgF<sub>2</sub>/36nm TiO<sub>2</sub>/11nm Mo/33nm TiO<sub>2</sub>/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.

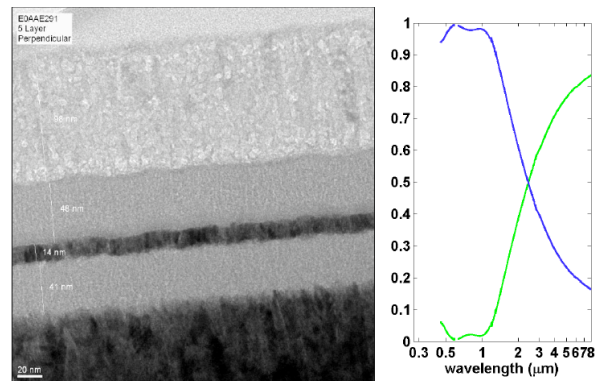


Figure 4. (Left) Cross-sectional TEM of the fabricated stacks. (Right) Emissivity (green) as a function of wavelength, showing the suppression of low-energy radiation.

### F. Progress and future plans

On the nanofabrication side, Braun's group plans to focus on measuring the optical properties of the high temperature 3D photonic crystals with a focus on the high temperature emissive behavior. Once these studies are completed, the whole team plans to measure the radiation emitted by these structures at high temperature, begin assembling these materials into TPV devices.

## G. Publications

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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6. K. A. Arpin, M. D. Losego, and P. V., “Braun Enhancing the Thermal Stability of Electrodeposited Tungsten Inverse Opals”, in preparation

## H. Contacts

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## I. References

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<sup>i</sup> 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).

<sup>ii</sup> 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).