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Global Climate & Energy Project

STANFORD UNIVERSITY

Ultra-High Efficiency Thermophotovoltaic Solar Cells Using Metallic Photonic Crystals as Intermediate Absorber and Emitter

Investigators

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Objective

This research is investigating a novel design for thermophotovoltaic devices with the potential to boost their energy conversion efficiency beyond current efficiency records of about 30%. In the proposed design, the absorber and the emitter consist of tungsten photonic crystals whose properties can be tailored to provide broad-band absorption of light over the entire solar spectrum and to adjust the emission spectrum to match the absorption characteristics of a silicon photovoltaic cell. The absorber and the emitter are integrated within the intermediate to optimize thermal transfer.

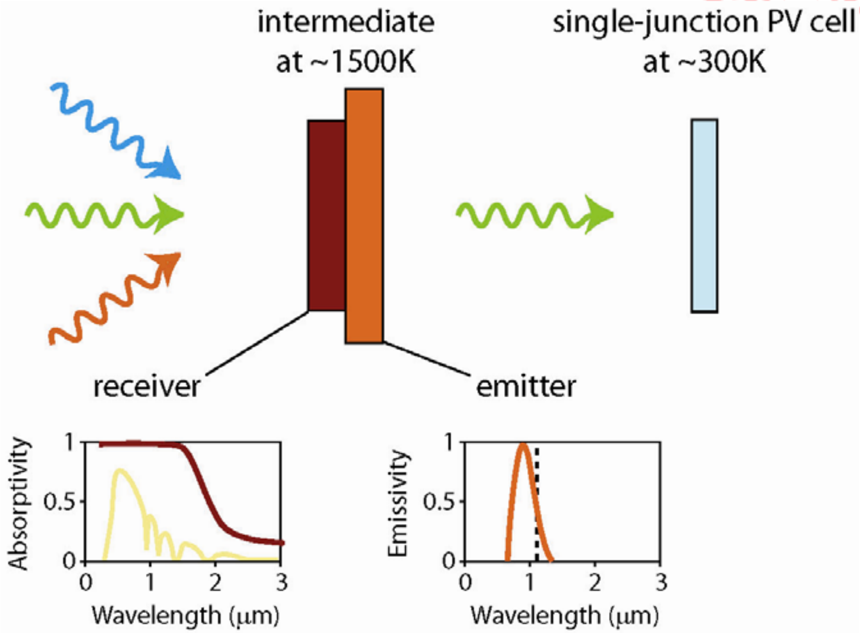

Figure 1: Schematic of the proposed thermophotovoltaic cell. The receiver and the emitter layers of the intermediate are shown together with their idealized absorption spectrum (including the solar spectrum in yellow) and emission spectrum (the dotted line indicates the PV cell bandgap energy level), respectively.

Background

The thermophotovoltaic (TPV) concept reduces the energy losses associated with the absorption of light in a conventional cell by tailoring the average energy of the photons absorbed by it. In this scheme (see Fig. 1), the solar cell is not directly exposed to the solar flux. Instead, an intermediate – consisting of two thermally connected layers, the absorber and the emitter – is positioned in front of the cell. The receiver heats up to a reasonably high temperature by absorbing sunlight. Subsequently, thermal energy is transferred to the emitter that illuminates the cell with narrow-band thermal radiation that better matches its absorption characteristics. Conventional TPV designs include a filter between the emitter and the cell to back-reflect the photons with energy lower than the cell bandgap. This way, their energy is recycled to maintain the temperature of the intermediate. The absorption and emission spectra of the intermediate can be manipulated to improve performance, limited by a theoretical efficiency maximum of 85% under direct illumination.

In the system studied in this project the receiver and the emitter are integrated within a single intermediate structure and consist of metallic photonic crystals that can be designed to tailor both the absorption and emission spectra as a function of the illumination conditions (direct or concentrated solar light) and of the bandgap of the PV cell, so that a filter is not required.

Approach

The tungsten photonic crystals forming the intermediate structure (see Fig. 2) are fabricated using low-cost techniques such as colloidal self-assembly and holographic patterning. Their structural parameters are optimized through extensive computational design in order to maximize optical absorption over the entire solar spectrum, narrow-band thermal emission, angular response, and thermal transfer between the absorber and the emitter.

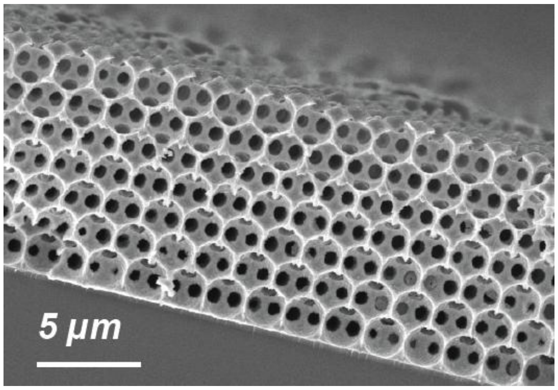

Figure 2: Scanning Electron Microscope picture of a representative nickel photonic crystal fabricated by electrodeposition using a self-assembled polystyrene opal template.

Initial designs of the absorber explore pyramidal structures that have the potential to confer the required black body characteristics over the entire solar spectrum. Narrow-band spectral emission is realized by using a connected metal network structure for the emitter. Initial simulations show that with the right choice of structural parameters, such as sample thickness, surface topography, and metal filling fraction, an emitter structure can be realized that emits most of its power right above the bandgap of a silicon cell.

Geometry also determines other critical properties such as the angular variability of absorptivity and emissivity, and the thermal transfer efficiency between the absorber and the emitter. While emission should be confined to a narrow angular range for maximal transmission to the silicon cell, the optimal angular behavior of the absorber depends on the operation conditions – high concentration or direct, non-concentrated sunlight. Initial prototypes are designed with omni-directional blackbody absorption characteristics to operate at high concentration. Finally, the efficiency of thermal transfer within the intermediate, which depends on the width ratio between the solar and the emission spectra, can be maximized by optimizing the absorber/emitter surface ratio.

Practical devices will require materials and structures capable of withstanding extended operation times at temperatures in excess of 2000^{o}C and frequent thermal cycling. Tungsten and other high melting-point materials (such as tantalum, molybdenum, and silicon carbides) are investigated. Alloying and thin-coating with specific protective layers are also explored to increase the device stability in these highly demanding operation conditions.