Highly Efficient Thermophotovoltaics Enabled by Photon Recycling

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***Abstract* — Thermophotovoltaic efficiencies above 50% may soon be realizable due to recent advances in thin-film photovoltaics. Highly efficient thin-film photovoltaics cells are highly reflective in the below-bandgap spectral region. In a thermophotovoltaic system, this allows the below-bandgap radiation to be reflected back to the emitter, so that their energy can be used to reheat the source, rather than being lost.**

In this work, we present a substantial improvement in the thermophotovoltaic conversion efficiency in the presence of photon recycling. We also predict the achievable conversion efficiency for a system that uses $In_{0.53}Ga_{0.47}As$ photovoltaic cells, and present an experimental cavity to be used for future efficiency measurements.

I. INTRODUCTION

Thermophotovoltaics (TPV) converts heat energy to electrical energy through the photovoltaic conversion of thermal radiation. TPV is distinguished from solar photovoltaics primarily by the nature of the thermal radiation source. Rather than the Sun, which is an approximate 5800K blackbody at a distance of 1.5 x 10^8 km from the Earth, the source used in TPV is a local hot object, typically at a much lower temperature. Therefore, TPV systems and devices are designed for a different set of incident spectra and illumination intensities than solar photovoltaic systems. The local nature of the radiation source also provides for additional methods to enhance the performance of the photovoltaic system that are not possible in solar energy harvesting.

The concept of TPV for direct heat-to-electricity conversion was originally proposed in the 1960s [1], though early experiments produced low efficiencies. On the other hand, the efficiency of solar photovoltaics has seen dramatic improvements in subsequent decades, due to technological advances in photovoltaic materials and devices as well as in photon management. Today, the highest-performing single-junction solar cells are approaching the theoretical limit of efficiency [2]. These breakthroughs can now be leveraged in the field of TPV, where we predict significant improvements in the efficiency of heat-to-electricity conversion.

In this paper, we present the unique advantages of recycling thermal radiation back to the source, a method of enhancing the photovoltaic efficiency by enclosing the TPV system in an optical cavity. We next describe predicted theoretical limits to TPV efficiency using thin-film $In_{0.53}Ga_{0.47}As$ cells, a suitable material for source temperatures near 1200°C. Finally, we present an experimental realization of an optical cavity that can be used to demonstrate the high TPV efficiencies achievable using $In_{0.53}Ga_{0.47}As$ cells.

II. ENHANCING THERMOPHOTOVOLTAIC EFFICIENCY BY PHOTON RECYCLING

The choice of bandgap in solar photovoltaics is governed by the spectrum of sunlight; incident photons with energy above the bandgap are inefficiently converted due to energy loss from carrier thermalization, while photons below the bandgap energy are not absorbed. Under 1-sun solar illumination, this leads to an optimal bandgap of ~1.4eV [3]. Meanwhile, the lower-temperature radiation sources involved in TPV generally demand a substantially lower value of the bandgap. However, despite the disadvantage of a smaller voltage, the accessibility of the local source in TPV offers new means of spectral control. This suggests that the efficiency of TPV systems is not necessarily limited by the same concerns that determine the efficiency limit of solar cells.

One suggested method of spectral control is to introduce selectivity in the emission spectrum of the source, by using a photonic crystal, so that only photons close to the bandgap of the photovoltaic cells are emitted [4]. However, a difficulty lies in carefully matching the emission spectrum to the photovoltaic band edge, while also maintaining high output power density.

An alternative method of spectral control is to exploit the spectral selectivity in the absorptivity of the photovoltaic cell itself. This can be achieved by enclosing both the source and the cells inside an optical cavity, as shown in Fig. 1. The most important component of this cavity is a highly reflective mirror on the back side of the photovoltaic cells, which allow the unabsorbed below-bandgap photons to be returned to the emitter. By recycling the unabsorbed light, the energy in these photons can be used toward reheating the source, rather than being lost. Thus, the internal radiation in the reflective cavity

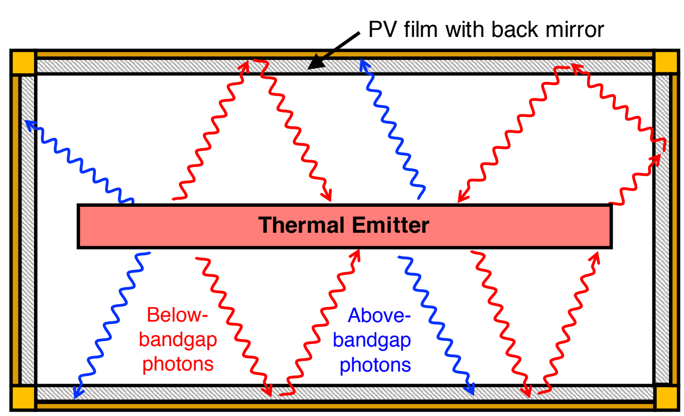

Fig. 1. Reflective thermophotovoltaic cavity: above-bandgap photons (blue) are converted by the photovoltaic cells, while the unabsorbed below-bandgap photons (red) are returned to the emitter.

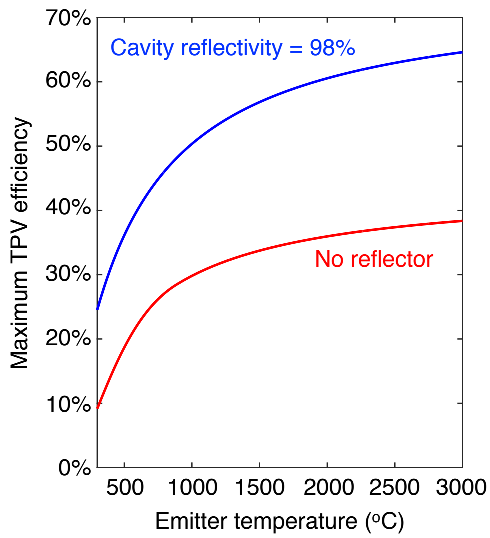

Fig. 2. Maximum attainable thermophotovoltaics efficiency vs. temperature with and without photon recycling, calculated by detailed balance methods.

provides a large fraction of the power necessary to maintain the emitter at a high temperature, reducing the power that needs to be drawn from an external heat source.

For a simple cavity with no external loss and comprising only of a source and reflective photovoltaic cells, the TPV efficiency is given by:

$$\eta_{TPV} = \frac{J_{OP} \cdot V_{OP}}{\int_0^{\infty} E b_s(E, T_S)\, dE - R \int_0^{E_g} E b_s(E, T_S)\, dE} \qquad (1)$$

where J_{OP} and V_{OP} represent the current and voltage of the cell at the maximum power point, E is the photon energy, $b_S(E, T_S)$ is the blackbody radiation flux (in photons/time/area/energy) for a source at temperature T_S, E_g is the cell bandgap, and R is the reflectivity of the cell for below-bandgap radiation. The above equation assumes complete absorption of above-bandgap photons, for simplicity. The second term in the denominator, which is absent from the Shockley-Queisser efficiency calculation, represents the portion of the thermal radiation that is returned to the source. By increasing the back reflectivity of the cell R, large gains in TPV efficiency can be made. Furthermore, since the below-bandgap photons are recycled rather than lost, the optimal bandgap shifts to a higher energy to minimize carrier thermalization. We note that this type of spectral control was implemented in [5], which used a silicon cell and a source temperature of ~2000°C.

Fig. 2 compares the maximum achievable efficiency of a TPV system without photon recycling to that of a cavity TPV system with a below-bandgap reflectivity of $R = 98\%$. For both cases, a photovoltaic cell with an ideal external luminescence yield ($\eta_{ext} = 1$) has been assumed at every value of the bandgap. The presence of a highly reflective back

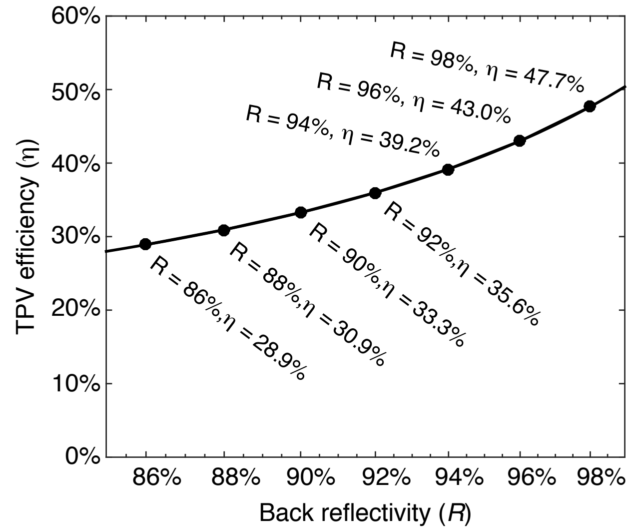

Fig. 3. Predicted TPV conversion efficiency using a $In_{0.53}Ga_{0.47}As$ photovoltaic cell for various values of back reflectivity.

mirror provides a substantial increase in TPV efficiency at any value of the source temperature.

III. Predicted Thermophotovoltaic Efficiency using $In_{0.53}Ga_{0.47}As$

For most applications making use of combustion (or nuclear reactors) to generate heat, a practical source temperature lies in the range from 1000°C to 1500°C. A suitable photovoltaic material for a temperature near 1200°C is $In_{0.53}Ga_{0.47}As$, a well-characterized material with a direct bandgap (~0.74eV at room temperature) that is useful for a variety of optoelectronic applications. Fig. 3 shows the maximum achievable TPV efficiency with this material as a function of the below-bandgap reflectivity R. Measured values of the radiative and non-radiative recombination lifetimes in $In_{0.53}Ga_{0.47}As$ [6] were used in the caluclation. For a high reflectivity of $R = 98\%$, close to 50% energy conversion efficiency is possible; a value that has not been approached previously in TPV.

An InGaAs alloy with a smaller bandgap of 0.6eV has been used for TPV demonstrations in the past, which similarly exploited the spectral selectivity of the band edge and used an Au back mirror. These experiments attained a maximum TPV efficiency of 23.6% [7], and were ultimately limited by low reflectivity owing to large parasitic absorption of low-energy photons in a thick InP substrate before the Au mirror. More recently, it has been realized in solar photovoltaics that very high back mirror reflectivity (>>90%) is necessary for high photovoltaic efficiency, and developments along these lines led to the record-breaking GaAs solar cell by Alta Devices [8]. Today, epitaxial liftoff can be used to separate an InGaAs thin film from its substrate and attach it to a metal surface [9]. A few microns of InGaAs is sufficient to absorb almost all of the above-bandgap radiation while minimizing parasitic absorption. Thus, the benefits of very high back reflectivity can now be brought to thermophotovoltaics, enabling very high TPV conversion efficiency of ~50%.

IV. Experimental realization of Thermophotovoltaic Cavity

An experimental test-bed for the proposed TPV system has been installed in a nuclear engineering laboratory at UC Berkeley. The test-bed (see diagram in Fig. 4) will be used in future experiments to ascertain the achievable TPV efficiency using the concepts previously described. The TPV cavity is enclosed in a vacuum bell jar equipped with a turbomolecular pump and a cryogenic trap, which provide a vacuum of 10^{-5} torr. This level of vacuum is sufficient to minimize heat loss to the surrounding media by conduction and convection. A reflective chamber surrounds the emitter, which consists of a strip of resistively heated graphite. The chamber sits on a reflective, water-cooled copper block. Photovoltaic samples can be placed along the walls of the reflective chamber, facing either side of the emitter, and are maintained at room temperature to avoid open-circuit voltage degradation. The relative positions of the emitter and photovoltaic samples can be adjusted.

Photographs of the graphite emitter at 20ºC and at 1200ºC are shown in Figure 5. $In_{0.53}Ga_{0.47}As$ photovoltaic cells, with a measured open-circuit voltage V_{OC} = 400mV under 1-sun solar illumination, will be used in this experiment. The system's TPV efficiency will be evaluated using Equation (1): the electrical power output from the photovoltaic cell will be compared with the optical power incident upon the cell that is not reflected back. The amount of non-reflected thermal radiation is determined by measuring the reflectivity spectrum of the cell with a spectrophotometer, then measuring the temperature of the emitter with an infrared pyrometer to infer the spectrum of thermal radiation. Calorimetric measurements across the water cooling lines on the copper block can be equivalently used to validate the amount of power absorbed by the cell, providing an alternative scheme to obtain the TPV efficiency.

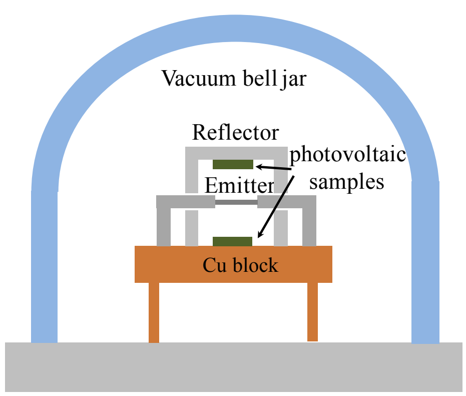

Fig. 4. Diagram of the TPV cavity showing the reflective chamber containing the graphite emitter and InGaAs photovoltaic samples.

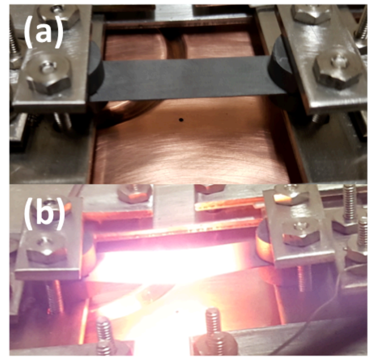

Fig. 5. The graphite ribbon emitter used in the experiments, at (a) 20ºC and (b) 1200ºC. The reflective chamber is not shown.

V. Conclusion

We have demonstrated that TPV conversion efficiencies approaching 50% can be achieved using the photovoltaic band edge as the spectral filter, and recycling unused thermal photons back to the source. The back reflectivity of the photovoltaic cells is of utmost importance in attaining high efficiency. A TPV chamber has been installed that will use $In_{0.53}Ga_{0.47}As$ photovoltaic cells to experimentally demonstrate the efficiencies achievable with this scheme. Future experiments are anticipated to produce high TPV conversion efficiencies.

References

[1] B. D. Wedlock, "Thermo-photo-voltaic conversion," *Proc. IEEE,* vol. 51, p. 694–8, 1963.

[2] O. D. Miller, E. Yablonovitch, and S. R. Kurtz, "Strong internal and external luminescence as solar cells approach the Shockley-Queisser limit," *IEEE J. Photovolt.,* vol. 2, no. 3, pp. 303–311, 2012.

[3] W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells," *J. Appl. Phys.,* vol. 32, pp. 510-519, 1961.

[4] Y. X. Yeng W. R. Chan, V. Rinnerbauer, J. J. Senkevich, J. D. Joannopoulos, M. Soljacic, and I. Celanovic, "Photonic crystal enhanced silicon cell based thermophotovoltaic systems," *Opt. Express.*, vol. 23, A157–A168, 2015.

[5] R. M. Swanson, "Silicon photovoltaic cells in thermophotovoltaic energy conversion," *IEEE Int. Electron Devices Meet.*, vol. 24, p/ 70-73, 1978.

[6] R. K. Ahrenkiel, R. Ellingson, S. Johnston, and M. Wanlass, "Recombination lifetime of $In_{0.53}Ga_{0.47}As$ as a function of doping density," *Appl. Phys. Lett.*, vol. 72, no. 26, p. 3470, 1998.

[7] B. Wernsman, R. R. Siergiej, S. D. Link, R. G. Mahorter, M. N. Palmisiano, R. J. Wehrer, R. W. Schultz, G. P. Schmuck, R. L. Messham, S. Murray, C. S. Murray, F. Newman, D. Taylor, D. M. DePoy, and T. Rahmlow, "Greater Than 20% Radiant Heat Conversion Efficiency of a Thermophotovoltaic Radiator/Module System Using Reflective Spectral Control," *IEEE Trans. Electron Devices*, vol. 51, no. 3, pp. 512–515, 2004.

[8] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 46)", *Prog. Photovolt. Res. Appl.*, vol. 23, pp. 805-812, 2015).

[9] E. Yablonovitch, "Extreme selectivity in the lift-off of epitaxial GaAs films," *Appl. Phys. Lett.*, vol. 51, pp. 2222-2224, 1987.