Highly Efficient Thermophotovoltaics Enabled by Photon Re-Use

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***Abstract* — Thin-film photovoltaic cells with high reflectivity in the below-bandgap spectral region are ideally suited for thermophotovoltaics. 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 theoretical thermophotovoltaic conversion efficiency in the presence of photon re-use. 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 optical cavity to be used for future efficiency measurements. Owing to recent advances in thin-film photovoltaics, thermophotovoltaic efficiencies above 50% may soon be realizable.

***Index Terms* – thermophotovoltaics, photovoltaics, photon re-use, thermal emission, optical cavity**

I. Introduction

Thermophotovoltaics (TPV) converts heat energy to electrical energy through the photovoltaic conversion of thermal radiation emitted by a hot object. Originally proposed in 1960 [1], thermophotovoltaics 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 thermophotovoltaics is a local hot object, typically at a much lower temperature. As a consequence, thermophotovoltaic systems are designed for a different set of incident spectra and illumination intensities than solar photovoltaic systems.

The local nature of the radiation source in thermophotovoltaics provides additional opportunities to enhance the energy conversion efficiency that are not possible in solar energy harvesting. In this paper, we present the unique advantages of recycling thermal radiation back to the heat source by enclosing the thermophotovoltaic system in a reflective optical cavity. This can be accomplished by using photovoltaic cells that are designed to have high reflectivity below the optical bandgap, allowing almost all of the unconverted photons to return to the source. The same feature of high sub-bandgap reflectivity has recently led to single-junction solar cells that approach the theoretical limits of voltage and efficiency [2]. Technological breakthroughs that enable a highly reflective PV cell, as well as the availability of photovoltaic materials with high internal luminescence quantum efficiency, can now be leveraged in the field of thermophotovoltaics, where we predict significant improvements in the efficiency of heat-to-electricity conversion.

We predict the theoretical efficiency limits for a thermophotovoltaic system utilizing 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 Re-Use

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 ~1.4 eV [3]. Meanwhile, the lower-temperature radiation sources relevant for thermophotovoltaics generally demand a substantially lower value of the bandgap. However, despite the disadvantage of a smaller voltage, the accessibility of the local source in thermophotovoltaics offers new means of spectral control. This suggests that the efficiency of thermophotovoltaic 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 means of a photonic crystal, so that only photons close to the bandgap of the photovoltaic cells are emitted [4-6]. However, a difficulty lies in carefully matching the emission spectrum to the absorptivity of the photovoltaic cell, while also maintaining high output power density.

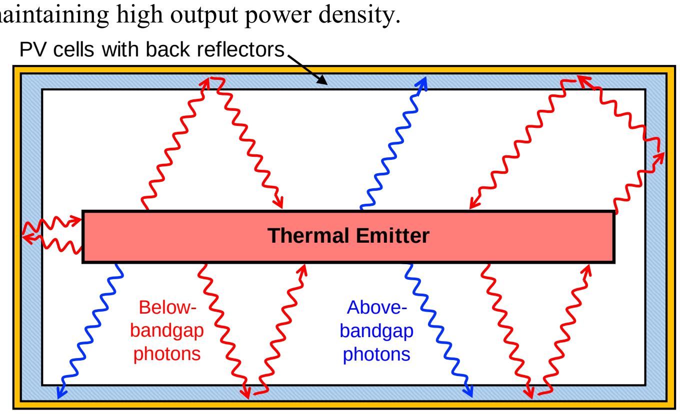

Fig. 1. Reflective thermophotovoltaic cavity: above-bandgap photons (blue arrows) are converted by the photovoltaic cells, while the unabsorbed below-bandgap photons (red arrows) are reflected from the cells and returned to the emitter.

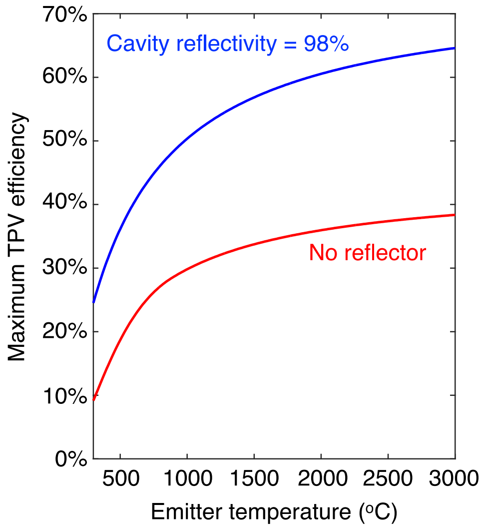

Fig. 2. Maximum attainable thermophotovoltaics efficiency vs. temperature with and without photon re-use, calculated with ideal material parameters and optimal bandgaps at every temperature.

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 in Fig. 1. Photons with energy above the bandgap are converted by the photovoltaic cell, while a highly reflective mirror on the rear side of the cell return the unabsorbed below-bandgap photons to the emitter. By reflecting the unabsorbed light, the energy in these photons can be used to reheat the source, rather than being lost. Thus, the internal radiation in the reflective cavity 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 thermophotovoltaic conversion efficiency is given by:

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

where J_{OP} and V_{OP} represent the current density and voltage of the cell at the maximum power point, E is the photon energy, $b(E,\ T_S)$ is the spectral irradiance (in W/cm^2/eV) from a blackbody source at temperature T_S, E_g is the cell bandgap, and R is the reflectivity of the cell for below-bandgap photons. For simplicity, complete absorption of above-bandgap radiation and constant sub-bandgap reflectivity are assumed in this expression. The second term in the denominator, which is absent from the Shockley-Queisser detailed-balance efficiency calculation [3], represents the portion of the thermal radiation that is returned to the source. By increasing the rear reflectivity of the cell R, large gains in thermophotovoltaic efficiency can be made. Since the below-bandgap photons are re-used rather

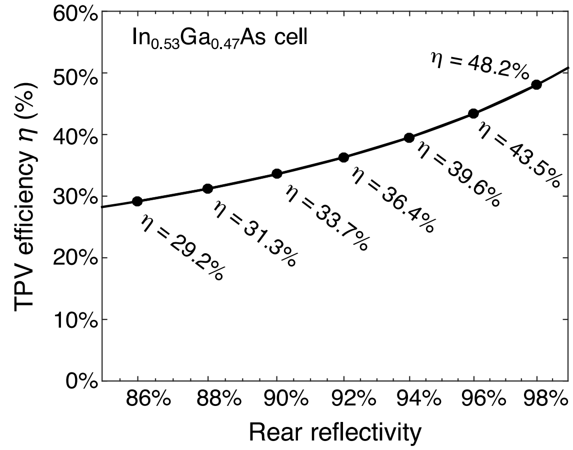

Fig. 3. Predicted thermophotovoltaic conversion efficiency using a $In_{0.53}Ga_{0.47}As$ photovoltaic cell for various values of rear reflectivity at a source temperature of 1200°C and a cell temperature of 20°C.

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 [7], which used a silicon cell and a source temperature of ~2000°C.

Fig. 2 compares the maximum achievable efficiency of a thermophotovoltaic system without photon re-use to that of a cavity thermophotovoltaic system with a below-bandgap reflectivity of R = 98%. For both cases, a photovoltaic cell with an optimal bandgap energy (not the same for the two curves) and unity external luminescence quantum efficiency has been assumed at every value of the emitter temperature. The presence of a highly reflective rear mirror provides a substantial increase in thermophotovoltaic efficiency at any value of the emitter 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 [8]. A suitable photovoltaic material for temperatures near 1200°C is $In_{0.53}Ga_{0.47}As$, a well-characterized material with a direct bandgap (~0.74 eV at room temperature) that is useful for a variety of optoelectronic applications. Fig. 3 shows the maximum achievable thermophotovoltaic conversion efficiency at 1200°C with this material as a function of the reflectivity of the rear mirror R (assumed constant with energy for simplicity). To find the voltage and current through the cell, published values of the radiative, Shockey-Reed-Hall, and Auger recombination lifetimes in $In_{0.53}Ga_{0.47}As$ [9] were used to calculate the internal luminescence quantum efficiency. A planar cell with n-type doping density of 10^{17} cm^{-3} and a thickness of 1.5 μm were chosen for this calculation. to maximize luminescence extraction (which increases open-circuit voltage, and favors a thinner cell) while providing sufficient absorption of above-bandgap photons. For a high reflectivity of R = 98%, close to 50% energy conversion efficiency is possible; a value that has not been approached previously in thermophotovoltaics.

Photovoltaic cells made from InGaAs alloys have previously been used in thermophotovoltaics, with at least one demonstration that similarly exploited the spectral selectivity of the band edge and used a gold rear mirror to reflect the unused photons. These experiments attained a maximum thermophotovoltaic conversion efficiency of 23.6% with a source temperature of 1039^{o}C and a bandgap of 0.6 eV [10-12]. The efficiency of these systems was ultimately limited by lower-than-desired cell 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 rear mirror reflectivity (>>90%) is pivotal for extracting internal luminescence from the cell, which in turn increases its open-circuit voltage and photovoltaic efficiency [2]. Developments along these lines led to the record-breaking GaAs solar cell by Alta Devices [13]. Epitaxial liftoff can be used to separate an InGaAs thin film from its substrate and attach it to a metal surface [14]. 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 rear reflectivity can now be brought to thermophotovoltaics, enabling very high thermophotovoltaic conversion efficiencies of ~50%.

IV. Experimental Realization of Thermophotovoltaic Cavity

A test-bed for the proposed thermophotovoltaic system has been constructed (see Fig. 4) to experimentally measure the thermophotovoltaic efficiency that is achievable using the concepts previously described. A reflective metal cavity surrounds the emitter, which is a strip of resistively heated graphite. Photovoltaic samples can be placed along the walls of the reflective chamber, facing either side of the emitter,

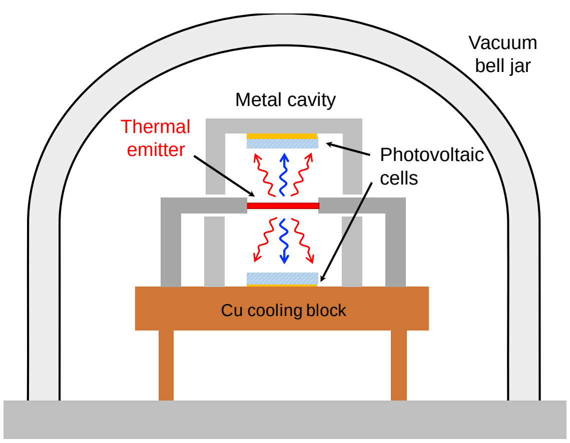

Fig. 4. Diagram of the thermophotovoltaic cavity showing the reflective chamber containing the graphite emitter and InGaAs photovoltaic samples.

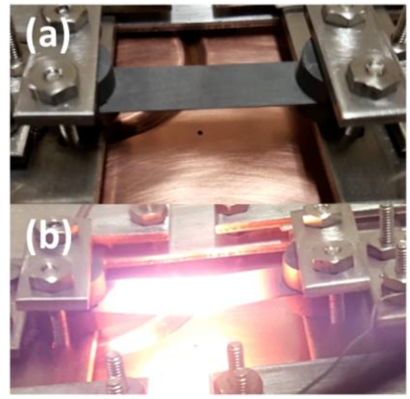

Fig. 5. The graphite ribbon emitter used in the experiments, at (a) 20^{o}C and (b) 1200^{o}C. The reflective chamber is not shown.

and are maintained at room temperature through contact with a water-cooled copper block to avoid degradation of open-circuit voltage. The relative positions of the emitter and photovoltaic samples can be adjusted. The 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. The vacuum environment minimizes heat loss to the surrounding media by conduction and convection.

As recognized in [12], if the walls of the thermophotovoltaic cavity are highly reflective, multiple reflections from the walls will cause most of the emitted photons to be eventually re-absorbed by the hot source. Therefore, the radiation inside the cavity rapidly equilibrates to the spectrum of a blackbody emitter in the presence of the reflective walls of the cavity. As a consequence, the emissivity of the emitter will not have a strong effect on the performance of the thermophotovoltaic system.

Preliminary experiments without any photovoltaic samples have demonstrated the effect of source reheating by recycled photons. As the emitter, we used a ceramic electric heater which radiates from one hot surface (232 cm^2, 0.85 emissivity). The photons are received and reflected by a copper block (316 cm^2) placed 1 mm away. When kept at a steady-state temperature of 1085^{o}C, the heater emits 16.2 W/cm^2 in thermal photons, but only requires 1.03 W/cm^2 of electrical input power to sustain that temperature, with the rest provided by reflected photons. This represents an effective cavity reflectivity of ~94%, which includes loss of light outside of the cavity. In the final thermophotovoltaic experiment, a graphite strip will be used as the emitter, shown in Fig. 5 at temperatures of 20^{o}C and 1200^{o}C as measured using an infrared pyrometer.

Following the convention set by [11], the relevant performance metric for our system is the ratio of the electrical power generated by the cell normalized by the optical power incident on the cell. This ratio represents the efficiency with which heat in the form of thermal radiation is converted into electrical power. Since this conversion step is the most relevant physical process for thermophotovoltaic systems, we define this ratio as the thermophotovoltaic heat-to-electricity conversion efficiency, our main figure-of-merit.

Validation of high reflectivity from the $In_{0.53}Ga_{0.47}As$ cells across the 1200°C blackbody spectrum will be important for the experimental demonstration of high thermophotovoltaic efficiency. With knowledge of source temperature T_S and the reflectivity spectrum of the cell $R(E)$ through spectrophotometry, we can predict the thermophotovoltaic conversion efficiency of the system using the following expression, which removes the major assumptions made in Equation (1):

$$\eta_{TPV} = \frac{I \cdot V}{F \cdot A_{cell} \cdot \int_0^\infty [1 - R(E)] \cdot b(E, T_S)\, dE} \qquad (2)$$

where I and V are the current and voltage extracted from the cell, A_{cell} is the area of the cell, and F is a dimensionless view factor which represents the fraction of light emitted by a patch of area A_{cell} on the emitter's surface that ultimately arrives on the cell. Since the emitter is surrounded by reflective surfaces, F can be greater than 1, with its precise value given by a simulation of the optical power flux in the reflective thermophotovoltaic cavity [12].

Extraction of the thermophotovoltaic efficiency from experiment will rely on calorimetric measurements across the water cooling tubes inside the copper block. With good thermal contact between the copper and the photovoltaic cell, these measurements can accurately determine the amount of heat generated in the cell. Combining this with measurements of the generated electrical power yields the total radiative power absorbed by the cell.

V. Conclusion

We have demonstrated that thermophotovoltaic heat-to-electricity conversion efficiencies approaching 50% can be achieved by using the photovoltaic band edge as a spectral filter, and through the re-use of unabsorbed photons to reheat the thermal source. Much as in the record-efficiency single-, double- [13], and quadruple-junction solar cells [15], which were designed for maximum reflection of luminescence, the rear reflectivity of the photovoltaic cell is also of utmost importance in attaining high thermophotovoltaic efficiency. A thermophotovoltaic 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 the high thermophotovoltaic efficiencies predicted by theory.

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