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Optimum semiconductor bandgaps in single junction and multijunction thermophotovoltaic converters

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ABSTRACT

The choice of the optimum semiconductor for manufacturing thermophotovoltaic (TPV) cells is not straightforward. In contrast to conventional solar photovoltaics (PV) where the optimum semiconductor bandgap is determined solely by the spectrum (and eventually the irradiance) of the incident solar light, in a TPV converter it depends on the emitter temperature and on the spectral control elements determining the net spectral power flux between the TPV cell and the emitter. Additionally, in TPV converters there is a tradeoff between power density and conversion efficiency that does not exist in conventional solar PV systems. Thus, the choice of the proper semiconductor compound in TPV converters requires a thorough analysis that has not been presented so far. This paper presents the optimum semiconductor bandgaps leading to the maximum efficiency and power density in TPV converters using both single junction and multijunction TPV cells. These results were obtained within the framework of the detailed balance theory and assuming only radiative recombination. Optimal bandgaps are provided as a function of the emitter and cell temperature, as well as the degree of spectral control. I show that multijunction TPV cells are excellent candidates to maximize both the efficiency and the power density simultaneously, eliminating the historical tradeoff between efficiency and power density of TPV converters. Finally, multijunction TPV cells are less sensitive to photon recycling losses, which suggest that they can be combined with relatively simple cut-off spectral control systems to provide practically-viable high performing TPV devices.

1. Introduction

Thermophotovoltaic (TPV) devices perform a direct heat-to-electricity conversion by using photovoltaic cells [1,2]. A basic TPV device comprises two elements: an emitter, which is heated by an external heat source, and a photovoltaic cell, referred to herein as a TPV cell, which is illuminated by the thermal radiation emitted by the emitter in order to produce electricity. In this arrangement, spectral control elements (selective emitters, filters, reflectors, etc) may be used to produce spectrally selective thermal radiation matching the TPV cell spectral response. This leads to a very high theoretical efficiency for TPV devices, approaching the Carnot efficiency in the limit of that TPV cells are illuminated by monochromatic light [3].

TPV technology offers a series of advantages compared with other heat engines: (1) it enables extremely high temperature operation, owing to the absence of physical contact between the hot and cold reservoirs, (2) it is a modular and scalable technology with an extremely low weight and volume, leading to extraordinary high specific power and energy densities, (3) it does not use moving parts, which minimizes the maintenance requirements and enables low noise operation, and (4) it may enable very high heat-to-electricity conversion efficiency, ideally as high as a Carnot engine.

The above characteristics combined with the many different possible sources of heat led to a broad range of applications for TPV technology, including heat recovery from high temperature industrial processes [4–6], combined heat and power for residential use [7–11], solar power [3,12–18], portable energy sources [8,19–21], space power [22–26], energy storage systems [16,25–27], among others.

The best experimental radiant heat to electricity conversion efficiency reported so far for a TPV device is of 23.6%, using a SiC emitter at 1039 °C and InGaAs (0.6 eV) single junction TPV cells conforming a monolithic interconnected module (MIM) [28]. Similar values have been reported by other authors by using GaSb (0.74 eV) single junction TPV cells [29] and InGaAsSb (0.53 eV) quaternary compounds [30,31]. Concerning power density, values of up to 2.5 W/cm^2 have been measured using SiC emitter at

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Nomenclature

A	area (cm^2)
A_c	TPV cell area (cm^2)
A_e	emitter area (cm^2)
c	speed of light in vacuum (cm/s)
$\dot{E}$	normal radiative energy flux (W/cm^{2}sr)
F_{ec}	emitter-to-cell view factor
$F_{cc}^{(e)}$	cell-to-cell view factor when the emitter is a shadowing element
h	Plank constant (cm^2 kg/s)
J_k	electrical current density generated by the k^{th} sub-cell, where $k=1$ corresponds to the top-cell (A/cm^2)
J	electrical current density generated by the TPV cell (A/cm^2)
J_{MP}	electrical current density generated by the TPV cell at the maximum power point (A/cm^2)
J_{SC}	short-circuit current density of the TPV cell (A/cm^2)
k	Boltzmann constant (cm^2 kg s^{-2} K^{-1})
n	number of sub-cells in the multijunction TPV cell
$\dot{N}$	normal photon flux (no. photons/cm^{2}sr-s)
n_{int}	TPV cell semiconductor refraction index
P_{out}	radiative power density outgoing from the emitter (W/cm^2)
P_{in}	radiative power density incoming to the emitter (W/cm^2)
P_{EL}	output electrical power density (W/cm^2)
q	electron charge (C)
Q_{in}	external heat input (W/cm^2)
T	temperature (°C)
T_e	emitter temperature (°C)
T_c	TPV cell temperature (°C)
V_k	voltage generated by the k^{th} sub-cell, where $k=1$ corresponds to the top-cell (V)
V	total output voltage generated by the TPV cell (V)
V_{MP}	output voltage generated by the TPV cell at the maximum power point (V)
V_{OC}	open-circuit voltage of the TPV cell (V)
ε_k	bandgap energy of the semiconductor used in the k^{th} sub-cell, where $k=1$ corresponds to the top-cell (eV)
ε_G	bandgap energy of the semiconductor used in a single homo-junction PV cell (eV)
ε_{ce}	cut-off energy of the emitter (eV)
η	conversion efficiency
η_{th}	thermal efficiency
η_{TPV}	TPV efficiency
μ	photon electrochemical potential (eV)
ρ_{BSR}	reflectivity of the semiconductor-BSR interface (for all wavelengths)

Abbreviations

MJC	multijunction cell
TPV	thermophotovoltaic
BSR	back surface reflector
1JC	single junction TPV cell
2JC	dual junction TPV cell
3JC	triple junction TPV cell

1450 °C and GaSb (0.74 eV) single junction TPV cells [32]. However, much higher efficiencies and power densities are achievable, at least theoretically, by TPV converters [1–3,33].

In order to increase the conversion efficiency and power density of current state-of-the-art TPV converters, research focuses on both optimizing the semiconductor TPV cell structure and on finding the proper arrangements for tuning the spectrum of the radiation exchanged between the TPV cell and the emitter. With respect to the latter, TPV converters may be classified according to the type of spectral control strategy: cut-off or narrow-band.

Narrow-band strategies attempt at creating a quasi-monochromatic radiative exchange between the emitter and a single junction TPV cell. Single junction PV cells have already demonstrated conversion efficiencies above 50% under monochromatic illumination using a laser light source [34]. Therefore, the current challenge of narrow-band TPV approach consists of developing the appropriate emitter element to produce high quality quasi-monochromatic thermal emission at high temperatures [35]. The key fundamental drawback of this approach, independently of its particular implementation, relies on the low output power density, which is related to the low density of photonic modes of the monochromatic light. Novel concepts based on near-field effects may enhance the monochromatic power density beyond the classical limits [36,37], but these concepts are still in a very early stage of development and are not considered in this study.

This work focuses on cut-off spectral control strategies in which the radiative exchange between the emitter and the TPV cell is restricted to those photons with energies above the TPV cell's bandgap. This arrangement provides higher power density and enables the use of simpler elements on the (hot) emitter side; thus it is more readily implementable in practice. The main drawback of this approach is the lower bound for the conversion efficiency. However, this study demonstrates that this drawback may be overcome by using multijunction TPV cells. Although experimental work on multijunction TPV cell structures has been presented previously [38–42], a thorough theoretical analysis on their potential for TPV energy conversion is missing.

This paper presents a global optimization of single junction and multijunction TPV devices comprising cut-off spectral control elements. The optimum semiconductor bandgap(s) are calculated as a function of the emitter and cell temperatures, and the quality of the spectral control (i.e. photon recycling efficiency). Optimums for both

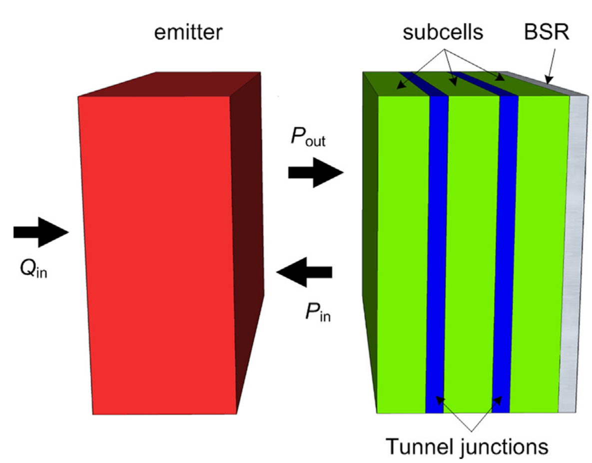

Fig. 1. Multijunction TPV converter with integrated BSR.